

Analysis of three unusual severe weather events over Delhi during May-June, 2018 using Dual-Pol Doppler Weather Radar and GNSS data

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सार – उच्च प्रभाव वाली मौसम की घटनाएं, जैसे कि गरज और धूल भरी आंधी, एक बदलती जलवायु के पहलू हैं जिनका समाज पर प्रतिकूल प्रभाव पड़ने की संभावना है। वर्ष 2018 के अप्रैल, मई और जून के महीनों के दौरान ऐसी कई गंभीर मौसम की घटनाओं ने दिल्ली और आसपास के क्षेत्रों को प्रभावित किया। मई-जून के दौरान मनाई गई तीन घटनाओं का विश्लेषण सी-बैंड पोलारिमेट्रिक डॉपलर वेदर रडार (डीडब्ल्यूआर) और से टिप्पणियों का उपयोग करके किया गया है। मौसम भवन, नई दिल्ली में स्थापित ग्रांड बेस्ड ग्लोबल नेविगेशनल सैटेलाइट (GNSS) रिसेविंग सिस्टम। यहां, डीडब्ल्यूआर प्रेक्षणों से विशेष रूप से पोलारिमेट्रिक प्रकृति के इन असामान्य घटनाओं के संबंध में डेटा का अध्ययन करने और जीएनएसएस प्राप्त प्रणाली से प्राप्त डेटा के साथ इसे क्रॉस सत्यापित करने का प्रयास किया गया है। 9 जून को छोड़कर सभी घटनाओं में 60 डीबीजेड से अधिक की परावर्तकता देखी गई थी, जब 54 डीबीजेड के आसपास अधिकतम परावर्तन के साथ एक स्क्वॉल लाइन बनाई गई थी और हवा का वेग कुछ अवसरों पर एक ही तारीख में 120 समुद्री मील तक बढ़ गया था और आम तौर पर अलग-अलग था। तूफान की अवधि के दौरान 45-60 समुद्री मील। इन तूफानों की ऊंचाई 9 जून को छोड़कर 12 किलोमीटर और 13.6 किलोमीटर के बीच भिन्न थी, जब डीडब्ल्यूआर द्वारा तूफान की ऊंचाई 15 किलोमीटर से अधिक देखी गई थी। यद्यपि 9 जून को अधिकतम परावर्तनशीलता थोड़ी कम थी, लेकिन बादलों की ऊर्ध्वाधर सीमा अधिक थी और इसलिए GNSS से IPWV का अनुमानित मूल्य अन्य के लिए 40 से 45 मिमी की सीमा में मूल्यों की तुलना में अधिकतम 67 मिमी था। तूफान की घटनाएँ एकल-पोल DWR टिप्पणियों के अलावा, दोहरे-पोल उत्पादों ने हाइड्रोमीटर के आकार, आकार और विविधता और उनके गैर-मौसम विज्ञान प्रकृति के संबंध में तूफानों की एक अधिक व्यापक सामग्री प्रस्तुत की। एक दोहरे पोल रडार की आंखों के माध्यम से विश्लेषण करते समय हाइड्रोमीटर की एकाग्रता के बारे में जानकारी भी एक सकारात्मक बिंदु रही है। इन कई झंझावातों पर उनकी कुछ महत्वपूर्ण विशेषताओं को सामने लाने के लिए चर्चा की गई है और डुअल-पोल डीडब्ल्यूआर सिस्टम और जीएनएसएस से प्राप्त आंकड़ों के बीच एक अच्छी मात्रा में समझौता देखा गया है।

ABSTRACT. High-impact weather events, such as thunderstorms and dust storms, are aspects of a changing climate that are likely to have an adverse effect on society. A number of such severe weather events struck Delhi and adjoining areas during the months of April, May and June of the year 2018. Three events observed during May-June have been analyzed using observations from C-Band Polarimetric Doppler Weather Radar (DWR) and ground based Global Navigational Satellite (GNSS) receiving system installed at Mausam Bhawan, New Delhi. Here, an attempt has been made to study the data regarding these unusual events from DWR observations especially of polarimetric nature and cross verify it with the data obtained from GNSS receiving system. Reflectivity of more than 60 dbZ was observed in all the events by the DWR system except on 9 June when a squall line formed with maximum reflectivity around 54 dBZ and the wind velocity increased upto 120 knots on the same date on few occasions and generally varied between 45-60 knots during the period of the storms. The height of these storms varied between 12 kms and 13.6 kms except on 9 June when the storm height was observed to be more than 15 kms by the DWR. Though the maximum reflectivity was a bit less on 9th June but the vertical extent of the clouds was greater and therefore the estimated value of IPWV from GNSS had a maximum of 67 mm as compared to the values in the range of 40 to 45 mm for other storm events. Apart from the single-pol DWR observations, the dual-pol products presented a more comprehensive ingredients of the storms in respect of the size, shape and variety of the hydrometeors and also their non-meteorological nature. The information regarding the concentration of hydrometeors has also been a positive point while analyzing through the eyes of a dual-pol radar. These multiple thunderstorms have been discussed to bring out some of their important features and a good amount of agreement has been observed between the data obtained from dual-pol DWR system and GNSS.

Key words – Doppler Weather radar (DWR), Global Navigational Satellite System (GNSS), Integrated Precipitable Water Vapour (IPWV), Differential Reflectivity (ZDR), Correlation Coefficient (CC), Differential Phase shift (Phi-DP), Specific Differential Phase (KDP).

1. Introduction

Thunderstorm is a meso-scale system of space scale ranging from a few kilometers to a few hundreds of kilometers and time scale of less than an hour to several hours. A severe thunderstorm includes some of the attributes among heavy rain shower, lightning, thunder, hail storm, dust storm, surface wind squall and down-burst. Low-level wind shear and atmospheric instability plays an important role in initiation and strengthening of meso-scale storms. Similarly, a dust storm is a meteorological phenomenon common in arid and semi-arid regions. Dust storms arise when a gust front or other strong wind blows loose sand and dirt from a dry surface. Fine particles are transported by saltation and suspension, a process that moves soil from one place and deposits it in another.

Pre-monsoon weather in India has always been vulnerable. Late April and May are the peak time for pre-monsoon weather activities that include dust storms, thunderstorms, lightning strikes, rain and thundershowers ranging from mild to severe levels. As a norm, India records four to five spells of intense thunderstorms and dust storms. However, meteorologically not more than two spells of extremely severe pre-monsoon storms are usually recorded every year. Occurrence of more than one severe storm within span of a week has been very rare in the country especially over north India. As has been the experience, very severe storms normally don't hit the same area twice with same intensity in the same season.

As per the international agreement, a thunderstorm day is defined as the one where thunder is observed by the observer. Confirming to the agreement in general in India, the thunder can be heard over a distance of 30-40 km from the source of the lightning.

Weather scientists have long been linking increased frequency of storms with a rise in temperature on account of global warming. The summer season of the year 2018 has been unusual with most of the places recording up to two degree higher temperatures than the average for the season. Rajasthan, Haryana, Punjab and parts of Jammu and Kashmir along with the neighbouring areas of Pakistan were facing the worst conditions of heat. The day temperatures were appreciably above normal in some parts of Himachal Pradesh, Rajasthan, west Madhya Pradesh, Saurashtra and Kutch, Konkan and Goa, central Maharashtra, Vidarbha and coastal Karnataka, and were above normal in some parts of east Madhya Pradesh, Gujarat and Marathwada. A trickle of moisture from the Bay of Bengal had found its way along the foothills of the Himalayas to these unstable regions. The unusually high temperature zones reacted violently when they came in

contact with moisture-laden air to create spells of dust storms.

1.1. Role of Doppler weather radar in thunderstorm studies

Doppler Weather Radar (DWR) provides an excellent quantitative analysis of severe weather events of any nature along with several derived products useful for research purpose. The research field programs (Staff, 1979; Doviak *et al.*, 1979; Wilson *et al.*, 1980) showed that significant nowcasting information can be obtained from Single Doppler radar. Also, various improvements in estimation of weather using polarimetric weather radars (Seling and Bringi, 1978; Ulbrich and Atlas, 1984; Sachidananda and Zrnic, 1987) have been demonstrated and documented. It has been acknowledged worldwide that DWR is an indispensable tool for the study of severe weather phenomena like thunderstorm, hailstorm, cyclone (hurricane) etc. Presently the identification of cyclones, gust fronts, downbursts and fronts can be easily accomplished by the forecasters monitoring and interpreting the DWR products. It is one of the most useful observational instruments for the detection of thunderstorm cell, monitoring of their development and prediction of their further propagation. Three base products available from DWR are:

(i) *Radar Reflectivity (Z)* : The amplitude of the echoes returned to the radar after being scattered from the hydrometeors is directly proportional to the sixth power of the rain drop diameter and therefore this parameter is mainly used for the quantitative estimation of precipitation contents, liquid water content, rainfall rate associated with a thunderstorm, vertical and horizontal developments of the cloud and to study the three dimensional structure of a thunderstorm cell.

(ii) *Radial Velocity (V)* : Using Doppler principle for electromagnetic waves, the radial component of the velocity of winds may be estimated by this parameter. Derived products from radial velocity data provide information on the direction of movement of the system, horizontal components of the wind velocity and wind shear. It has been well documented by Doviak *et al.*, (1979) and Wilson and Wilk (1981) that the radial wind information obtained from a single DWR can be used to derive and estimate the horizontal wind, wind shear and other products useful for the study of severe weather phenomena.

(iii) *Spectrum width (W)* : It is a measure of the amount of velocity dispersion within the radar sample volume and is proportional to the variation of speed and direction within a sample volume. This parameter is therefore a

measure of the variability of the velocity estimates. Some meteorological features or conditions associated with relatively high spectrum widths are Thunderstorms, shear regions, wind shear, turbulence, outflow boundaries and different fall speeds of different sized hydrometeors. It can also be used as a tool for quality control of velocity data.

Other polarimetric products available are :

(i) *Differential Reflectivity (ZDR)* : Seliga and Bringi, 1976 introduced ZDR as a new way of analyzing the hydrometeors. It is dependent upon the logarithm of the ratio of the power returned to the radar from the horizontal pulse to the power returned from the vertical pulse. If this ratio is greater than 1, then the feature being observed is wider than it is tall and the signal is positive; if this ratio is less than 1, the feature is taller than it is wide and the signal is negative. When the ratio is close to 1, the feature is approximately spherical. ZDR varies with raindrop sizes and shapes but is independent of particle concentration, whereas Z_H is directly proportional to particle concentration. Thus, for a given value of Z_H in rain, there is a range of possible ZDR values that can be observed depending on the drop size distribution (Kumijan, 2013).

(ii) *The Correlation Coefficient (CC)* : The correlation coefficient has been defined by (Doviak and Zrnice, 2006). It is a measure of how uniform the features being observed by the radar are. It ranges in value from 0 to 1. Pure rain or snow should have Correlation Coefficient values close to 1. If there is a mixture of precipitation like a mix of water, ice and snow and/or other forms of precipitation, the value of CC will be quite less than 1. Meteorological echoes will typically have Correlation Coefficient values higher than 0.8 with non-meteorological echoes (birds, insects, etc.) typically having values less than 0.8. The range of this product and all other dual - pol products can be varied upto 250 kms as per the selection by the radar operator.

(iii) *Specific Differential Phase (KDP)* : It is the difference between the horizontal and vertical pulses of the radar as they propagate through a medium such as rain or hail and are subsequently attenuated. Due to differing shapes and concentration, most targets do not cause similar phase shifting in the horizontal and vertical pulses. When the horizontal phase shift is greater than the vertical, the differential phase shift is positive; otherwise, it is negative. Stating in a different, horizontally oriented targets will produce a positive differential phase shift, whereas vertically-oriented targets produce a negative differential phase shift. While this correspondence between positive values (horizontal) and negative values (vertical) is analogous to Differential Reflectivity (ZDR),

there is a crucial distinction; differential phase is dependent on particle concentration. That is, the more horizontally oriented targets are present within a pulse volume, the greater the positive differential phase shift. Thus a high frequency of small raindrops could yield a higher differential phase value than a lower concentration of larger raindrops. Differential phase shifting is mostly unaffected by the presence of hail, and shifts in snow and ice crystals are typically near zero degrees. Non-meteorological echoes (birds, insects, and so forth) produce highly variable differential phase shifts. Ryzhkov and Zrnice, 1995; Zrnice and Ryzhkov, 1996; Sachidananda and Zrnice, 1986 suggested emerging evidences of advantages of KDP over reflectivity Z, like the effect of lesser magnitude of the variations in drop size distribution in the case of KDP in contrast to reflectivity Z.

In this paper, capabilities of DWR have been analyzed to study the occurrence and movement of storms over Delhi and its neighbourhood. An analytical study of three thunderstorms which occurred during pre-monsoon period of the year 2018 has been performed using reflectivity, velocity data and also dual-polarization products generated by DWR, Delhi along with GNSS data and rainfall data over Delhi. Thunderstorms during the months of April, May and June of 2018 have also been recorded and analyzed for interpretation of dual-polarized products and their agreement with GNSS parameters.

1.2. Classification of storms

The thunderstorms have generally been classified in the following categories :

1.2.1. Based on structure

- (a) Single cell storm
- (b) Multiple cell storms
- (c) Squall line

1.2.2. Based on DWR estimated reflectivity and vertical extent

- (a) Severe thunderstorm
- (b) Moderate thunderstorm
- (c) Weak thunderstorm
- (d) Very weak thunderstorm

The classification of storms based on structure, based on DWR estimated reflectivity and vertical extent have been described in a paper (Pradhan *et al.*, 2012).

2. Data and methodology

2.1. Doppler Weather Radar

A combination of products generated by the Doppler Weather Radar has been utilized to study the internal structure of the storm. India Meteorological Department (IMD) installed & commissioned two C-Band polarimetric DWRs at New Delhi & Jaipur during the year 2011 (November) & 2012 (January) respectively. These two C-Band polarimetric DWR stations are located in and around the national capital of India for continuous surveillance of severe weather systems coming from the west. These are C-Band radars (5 cm wavelength) operating at 5625 MHz, transmitting a peak power of about 250 KW using Klystron as amplifying device. The unambiguous range for reflectivity measurement in surveillance mode is 400 km and maximum unambiguous radial wind estimates (using velocity unfolding technique) within 250 km radius is 64 m/s (230 km/hr). With the installation of these radars in the north and north-western parts of India, round the clock weather observation and analysis capabilities of IMD have been enhanced to a great extent. DWR generates voluminous data related to observed weather phenomena by performing a volume scan of duration 10-11 minutes. The time for a volume scan may be varied as per requirement of the data. A sequence of reflectivity, direction, velocity and polarimetric data of a number of thunderstorms has been collected at every 10-11 minutes interval during the period (May-June) of the year 2018 and analyzed and evaluated with GNSS data. IRIS software has been supplied by the manufacturer for deriving the products from the base data.

Thunderstorms in north India over and around the National Capital Region, Delhi during pre-monsoon period usually follow a fixed pattern based on the thermodynamic instability and the wind direction. Since speed and direction of wind around New Delhi are always available from the DWR derived products like Plan Position Indicator (PPI_V) and VVP_2, forecasters can easily issue the nowcasting by observing the initiation and development of the system and its direction of movement. Alongwith the single pol derived products of DWR, the polarimetric products have also been analyzed. An analysis of DWR recorded observations of three particular thunderstorm events during May to June, 2018 has been performed in the present work. The thunderstorm events have been analyzed using DWR data for intensive study. The data from GNSS system for the same period has also been evaluated and analyzed and an attempt has been made to cross verify both the data along with the rainfall data.

A brief of the few products of IRIS software used in this radar by M/S Vaisala, Finland is given below :

2.1.1. Max Z (Maximum Reflectivity)

The reflectivity of the radar clearly tells in great detail about the reflectivity of the storm. This is a derived product from volume reflectivity data, which gives a three dimensional view of the cloud. The algorithm calculates reflectivity in each vertical column of the cloud and finds the maximum reflectivity in that column. The reflectivity is presented in pseudo colours and scale is shown to the right of the product. The overall three dimensional cloud is presented in the form of a composite of three partial images into a single imagery. The partial images are:

(i) A top view as the highest measured reflectivity values in Z - direction. This image shows the highest reflectivity value for each vertical column seen from the top of the cartesian volume.

(ii) A north-south view of the highest measured reflectivity values in Y - direction. This image is appended above the top view and shows the highest measured reflectivity value for each horizontal line scan from north to south. The height of the cloud can be observed with respect to reflectivity from this image.

(iii) An east-west view of the highest measured values in X - direction. This image is appended to the right of the top view and shows the highest measured reflectivity value for each horizontal line scan from east to west. This image is also an indicator of height of the cloud and avoids the overlapping of the clouds in N-S projection, if any.

2.1.2. VVP_2 (Volume Velocity processing)

Waldtenfel and Corbin (1979) proposed a technique to derive horizontal winds from radial velocity observed by single DWR over a limited area of about 50 km around the radar. A vertical profile of horizontal winds up to 10 km may be derived at equal steps selectable by users. This product displays the horizontal wind velocity and the wind direction in a vertical column of the radar site. This means that for local observations for winds over an area of 50 km this product (VVP_2) may be taken as a standard product. A linear wind field model is used to derive the additional information from the measured radial velocity data.

2.1.3. Hydrometeor classification

It is an algorithm that uses “fuzzy logic” to identify the predominant hydrometeor in the radar beam. The Hydrometeor Classification Algorithm uses base

reflectivity, differential reflectivity (ZDR), correlation coefficient (CC), specific differential phase (KDP), base velocity and differential phase shift (Phi-DP) radar products to determine the precipitation type of what is being observed. It also distinguishes non-precipitation echoes from the precipitation echoes. The classes of precipitation detected by the algorithm in C-Band DWR installed at New Delhi are hail, graupel, snow, wet snow, rain and no met. Hydrometeor Classification Algorithm (HCA) is useful for identifying precipitation type, hail detection, biological target detection, ground clutter removal for every radar elevation angle. Vivekanandan *et al.*, 1999 documented the use of fuzzy logic approach to delineate different hydrometeor classification types.

2.2. GNSS Meteorology

India Meteorological Department (IMD) established a network of 25 ground based Global Navigation Satellite System (GNSS) receivers collocated with meteorological sensors for continuous monitoring of integrated precipitable water vapour (PWV) which is useful for weather events monitoring. GNSS data are processed using the Trimble Pivot Platform (TPP) software to estimate PWV at every 15 minutes interval. To reduce the multipath effects a 5° elevation cut-off angle was fixed and Modified Hopfield the New Mapping functions (NMFs) (Niell, 1996) are used to map the signal path delay from zenith direction to other elevation angles. The GNSS ZTD estimates are obtained using the TPP software at 15 minutes interval with a processing window (sliding window) of 9 hours [Foster *et al.*, 2005]. Zenith Hydrostatic Delay (ZHD) estimates at each GNSS receiver are calculated using surface pressure data measured from the surface meteorological sensor assuming the hydrostatic equilibrium, as given by [Davis *et al.*, 1985]. GNSS-derived IPWV have been widely used in meteorological applications such as data assimilation into numerical models, climate studies and weather forecasting (Bevis *et al.*, 1992, 1994; Devis *et al.*, 1985). The GNSS-estimated PWV reflects the inflow and outflow of water vapor in a vertical column atmosphere above a certain region (Fontaine *et al.*, 2003; Wang *et al.*, 2013). GNSS-PWV has a relationship with the measured rainfall. Several studies have been done to analyze the potential of GNSS-derived PWV to forecast rainfalls. Benevides *et al.*, 2015 reported GNSS-PWV to forecast rainfalls and the forecasted correct rate was about 75%. It is observed that in pre-monsoon seasons, the GNSS PWV increases but fluctuates due to convection and turbulence in the atmosphere. In pre-monsoon season GNSS-PWV varies between 30 mm and 55 mm and when the southwest monsoon approaches the stations, PWV increases further and reaches to an average value of

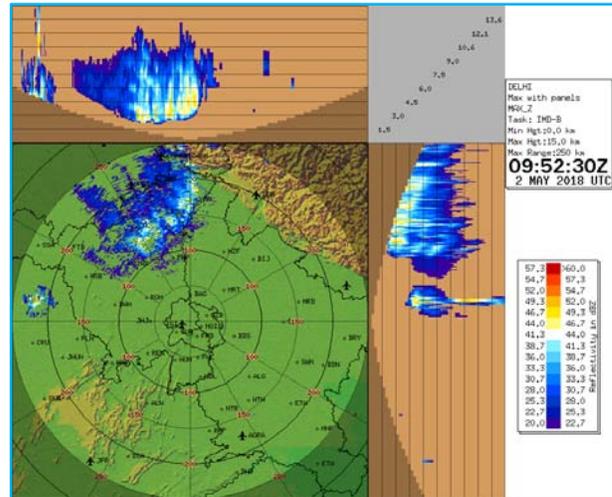


Fig. 1. MAX_Z (0952 UTC)

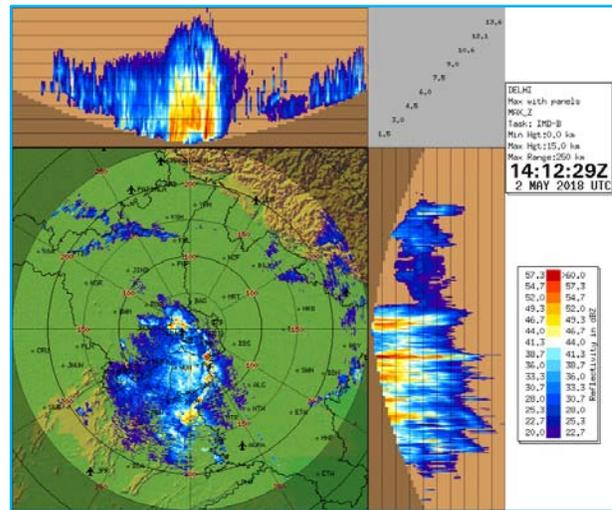


Fig. 2. MAX_Z (1412 UTC)

60 mm or more (Puviarasan *et al.*, 2015). IMD GNSS derived PWV is most commonly validated with collocated GPS Sonda PWV observations over Indian region. Correlation coefficient is found to be above 0.85, bias is less than 5 mm except for Thiruvanthapuram. Root mean square error between values are less than 5 mm at all stations. It is also found that the accuracy of the calculated PWV data from GNSS is high (Yadav *et al.*, 2020).

3. Analysis

3.1. Analysis of Thunderstorm on 2 May, 2018

3.1.1. Maximum reflectivity (MAX_Z)

The Maximum reflectivity image at 0952 UTC (Fig. 1) of 2 May, 2018 shows the formation of a convective cloud system at a distance of about 220 km

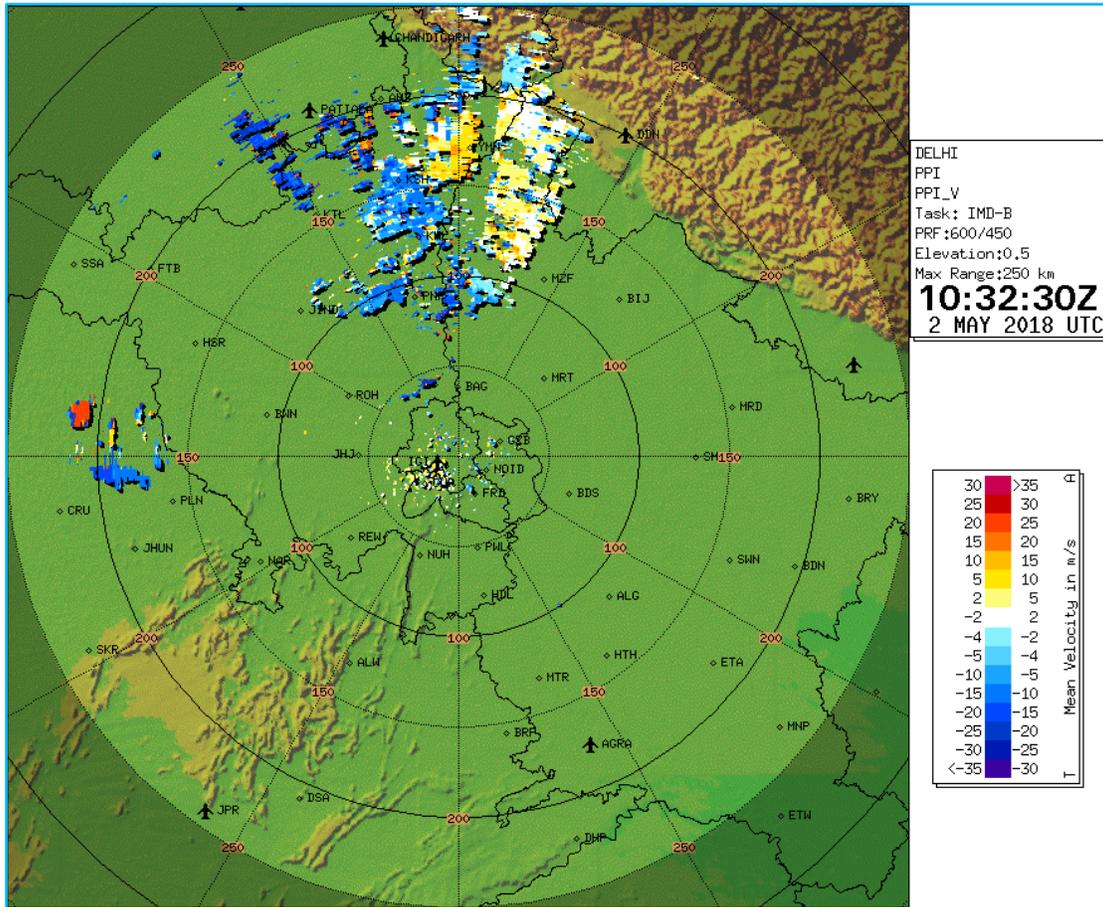


Fig. 3. PPI_V (1032 UTC)

West of Delhi. The system propagated eastwards, was over Delhi at 1412 UTC with maximum reflectivity shooting upto 55 dBZ bringing good amount of rainfall. Another larger system was seen to the north moving over Patiala, Kurukshetra, Panipat, Muzzafarnagar, Bijnore and other surrounding places. Significant reflectivity in the system indicates good amount of moisture present in the system which resulted in lot of thunderstorm activity with consequent destruction. The reflectivity associated with the thunderstorm over Delhi was in the range of 54.7 - 57.3 dBz (Fig. 2) indicating a high precipitation content within the clouds and the vertical extent of the clouds associated with the thunderstorm was observed upto 13.6 kms when over Delhi.

During the eastward propagation of first system from 0952-1412 UTC, lot more thunderstorm clouds developed in the southeasterly direction and by 1412 UTC a larger system could be seen mainly to the south of Delhi which was embedded with a number of severe thunderstorms. During this time the larger system to the north (near Patiala) propagated eastwards and gradually dissipated.

TABLE 1

Variation of radar beam height with range at fixed elevation

Elevation Angle (Deg)	Range (km)	Height (km)
0.5	50	0.58
0.5	100	1.46
0.5	150	2.63
0.5	200	4.1
0.5	250	5.85

3.1.2. Plan Position Indicator (Velocity) (PPI-V)

The velocity observations are analyzed using PPI_V image at 0.5 deg elevation. The velocity signatures of the thunderstorm were first observed at 1032 UTC (Fig. 3) for the first system moving towards Delhi. The velocity presentation in this thunderstorm system clearly shows a circulation (blue color as wind component towards the radar and the red color as moving away from radar). At

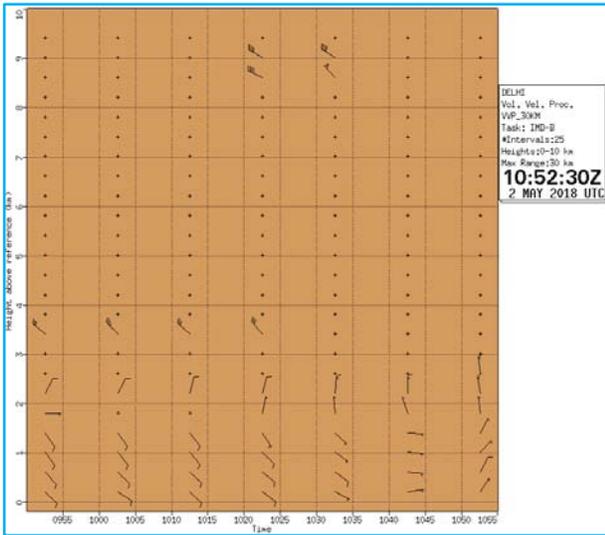


Fig. 4. VVP_2 (1052 UTC)

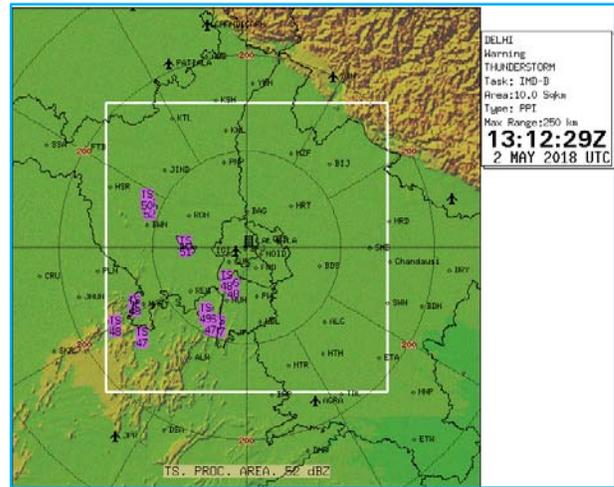


Fig. 6. TS-Warning (1312 UTC)

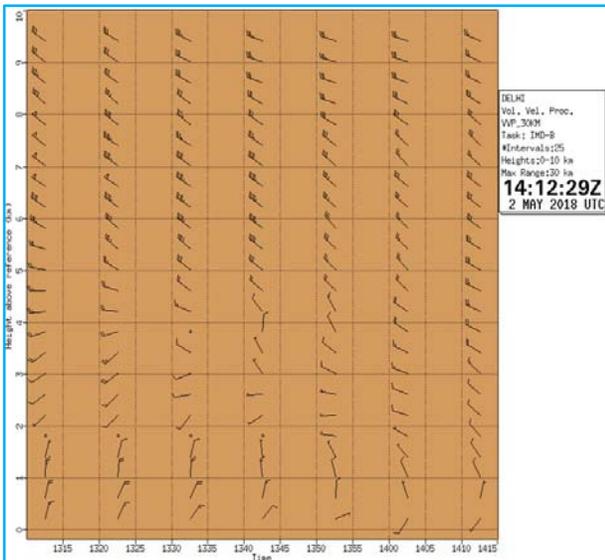


Fig. 5. VVP_2 (1412 UTC)

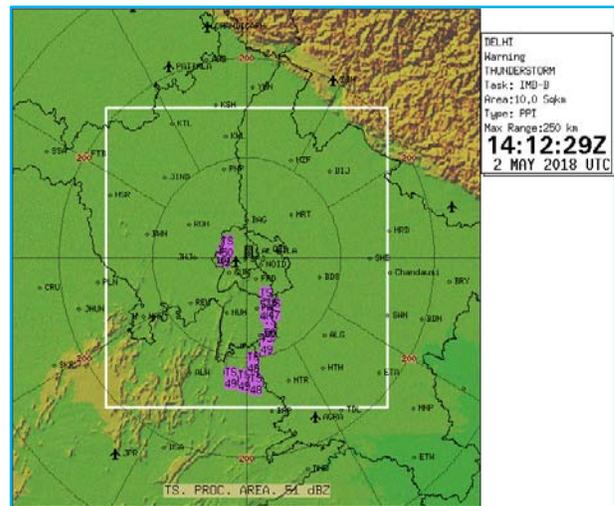


Fig. 7. TS-Warning (1412 UTC)

this distance the radar beam was at a height of slightly more than 4.1 km (beam elevation at 0.5 deg) and therefore, the velocity is related to this height as per Table 1.

3.1.3. Volume Velocity Processing (VVP_2)

The vertical profile of the wind (VVP_2) over Delhi provides an idea of the prevailing winds in the region at various levels up to 10 km with a step of 1.0 km. The movement of the clouds may be estimated up to a very good accuracy by this product. In normal weather during this season, a SE/SSE/E wind direction is observed over

Delhi and therefore as can be analyzed by VVP_2 image at 1052 UTC (Fig. 4), a SE/E wind is existing over Delhi at lower levels of height upto 1.5 kms before the first signs of the thunderstorm can be observed. At 1052 UTC, high winds at upper levels can be seen coming from west side which increased in intensity and at 1412 UTC the vertical profile from a height of 2 kms upto 10 kms is completely westerly (Fig. 5) which was exactly the time at which the thunderstorm was passing over Delhi.

3.1.4. Thunderstorm warning (TS - warning)

A thunderstorm warning product (TS-warning) shows the locations where the reflectivity of the system is extreme, coupled with a high vertical extent of the clouds. A protected area is earmarked around the location of

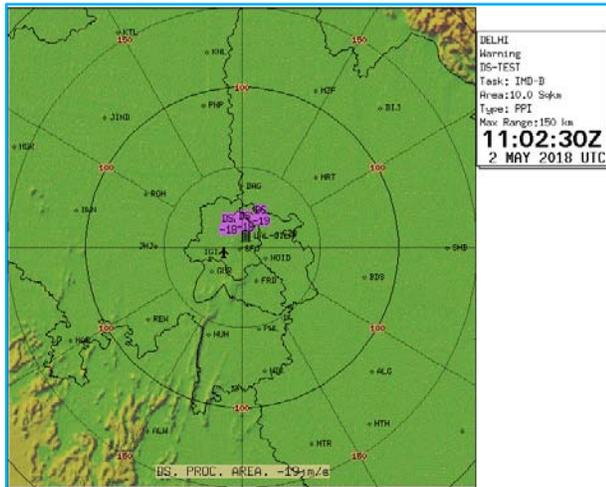


Fig. 8. DS-Warning (1102 UTC)

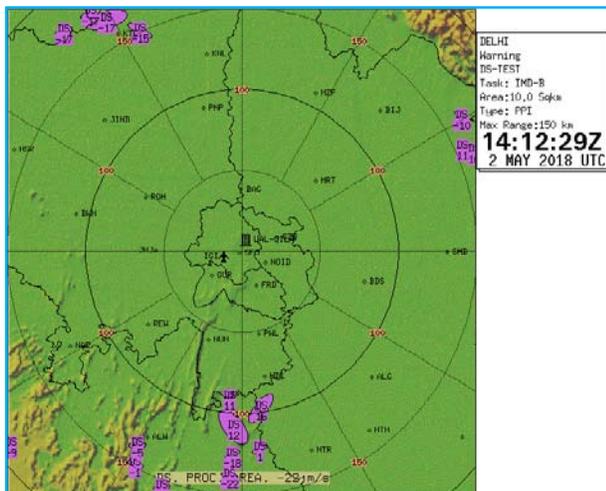


Fig. 9. DS-Warning (1412 UTC)

DWR and the display at the bottom of the image shows the maximum reflectivity in dBz of the associated weather system existing within the protected area. The protected area mainly gives an idea to the operational people about any system existing in close vicinity of the area under focus in terms of the reflectivity and wind speed which aids the operational people to be more alert. In the present analysis, a protected area has been designated by the user around Delhi as the location of the national capital which this DWR serves is of paramount importance and any instance of high reflectivity in the weather system is flagged and instantly disseminated in the nowcast and shared with the concerned operational forecasters in the associated user divisions.

In Fig. 6, it may be seen that the maximum reflectivity existing in the weather system when it enters the protected area is observed to be 52 dBz while in Fig. 7

the maximum reflectivity existing in the storm is observed as 51 dBz. By analyzing the other products like MAX_Z and PPI_Z, the user will get a rough idea that the maximum reflectivity existing in the storm is around or more than 50 dBz but with the use of this TS-warning protected area product, the exact value of the maximum reflectivity can be obtained and hence will aid the forecaster in better analyzing the damage potential of the weather system under observation. The thunderstorm warning at the locations affected by the weather system is indicated by pink spots with the word TS with reflectivity in dBz below it. Fig. 6 shows thunderstorm warning at 1312 UTC with reflectivity shooting up to a high of 52 dBz. As the system passes over Delhi at 1412 UTC, the spots affected by the thunderstorm along with the reflectivity are shown in Fig. 7.

3.1.5. Duststorm warning (DS - warning)

The duststorm warning product (DS-Test) shows the locations to be affected by the dust storm and uses the velocity of the system along with the vertical extent of the associated clouds. The whole range of 150 kms around the location of DWR is set as the protected area. Display at the bottom of the image shows maximum velocity of the winds associated with the dust storm existing within the weather system. The locations to be affected by dust storm are indicated in pink colour with the acronym DS written over the pink spots and the velocity of the winds shown below it. By analyzing PPI_V, the user may get an idea of the direction and speed of the weather system as PPI_V only shows the radial velocity associated with the weather system and not the true velocity. Similarly, VVP_2 shows the horizontal winds existing within 30 kms radius of the location of the DWR. But, by using DS-warning product as is done in the present study, the exact value of the velocity associated with the dust storm can be obtained along with their location. This additional information is very useful for issue of more precise nowcasts by timely indicating the damage potential of the dust storm. As can be seen in Fig. 8, the warning for duststorm is being shown by the radar along with the velocity associated at different instances of the storm. Negative speed shows storm moving towards the DWR and positive velocity shows the storm moving away. The maximum velocity at any instant of the duststorm was observed to be 22 m/s as can be seen in Fig. 9.

3.1.6. GNSS parameters

The GNSS parameters especially the precipitable water vapour (PWV), gave some indication of the ensuing weather activity on 2 May, 2018. Well in advance before the formation of thunderstorm, GNSS PWV over Delhi increased from 35.31 mm at 0900 UTC to 42.23 mm at

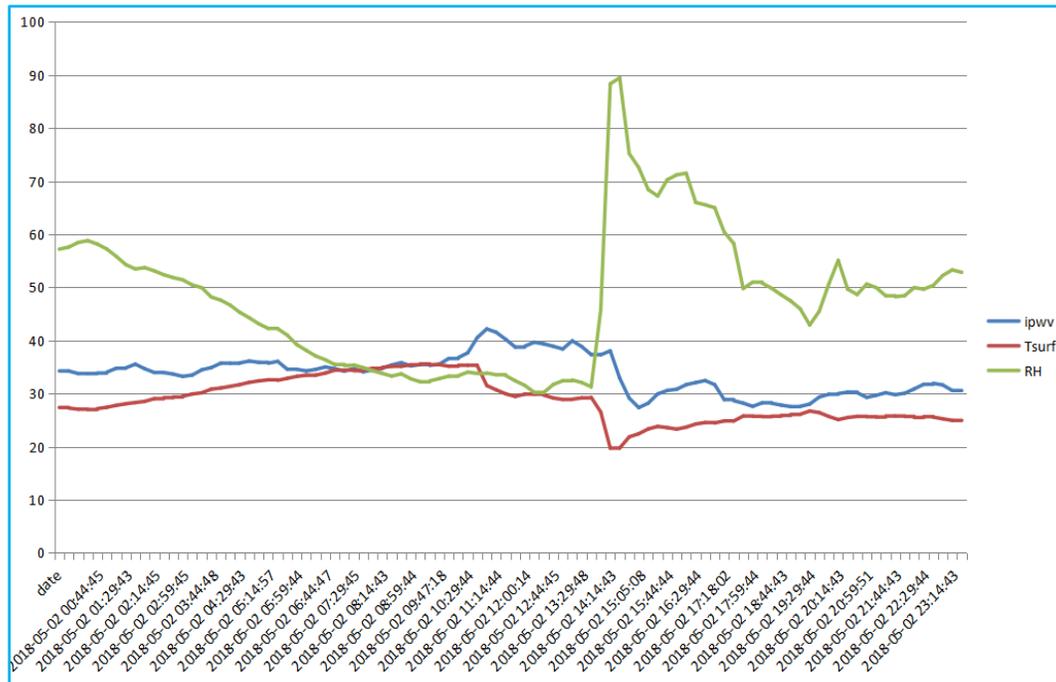


Fig. 10. GNSS Parameters (1412 UTC)

TABLE 2

Rainfall recorded at IMD observatories on 2 May, 2018

S. No.	Met. sub/district/division	Rainfall recorded (mm)
1.	Lodi Road	15.2
2.	Safdarjung	14.4
3.	Delhi University Observatory	0.4
4.	Aya Nagar	0.8
5.	Jafarpur	5.0
6.	Palam	3.4
7.	Najafgarh	13.0

1200 UTC (Fig. 10) and decreased thereafter. As the thunderstorm struck Delhi after 1200 UTC, the shooting up of the PWV since 0900 UTC gave indications of the approaching weather as high values of PWV mean that more water is available for potential rainfall and more often than not translates into heavier rainfall. Relative humidity also showed a decreasing trend since morning and stabilized around 0900 UTC only to again shoot up just after the storm hit the national capital. Surface temperature increased slightly from morning to noon as it behaves normally and went from around 28° C to 35° C and just around 1030 UTC when the sky began to turn

overcast, it dropped to 30 °C which further decreased to around 20 °C after the storm started dissipating.

3.1.7. Rainfall recorded on 02May, 2018

Table 2 shows the amount of rainfall received in Delhi on 2 May, 2018 and reported by the meteorological observatories. It is observed that the maximum amount of rainfall was recorded at Lodi Road, Safdarjung and Najafgarh which are located in the central and western parts of Delhi. According to the classification of rainfall intensity by India Meteorological Department, the rainfall of 15.2 mm, 14.4 mm and 13.0 mm recorded at the three stations is classified as moderate but the said amount of rainfall poured in a very short time causing devastation of life and property in and around the national capital.

3.1.8. Combined inference of the storm on 2 May, 2018

For the analysis of the storm on 2 May, 2018, the common DWR products like MAX_Z, PPI_V, VVP_2 have been used to differentiate the analysis of the two storms discussed later which are analyzed using dual-pol parameters. Two more products have been utilized to analyze the system which are not quite common and are not available on IMD's website for the general public. These products (TS-warning and DS-warning) provide a very clear picture of the weather system especially to the

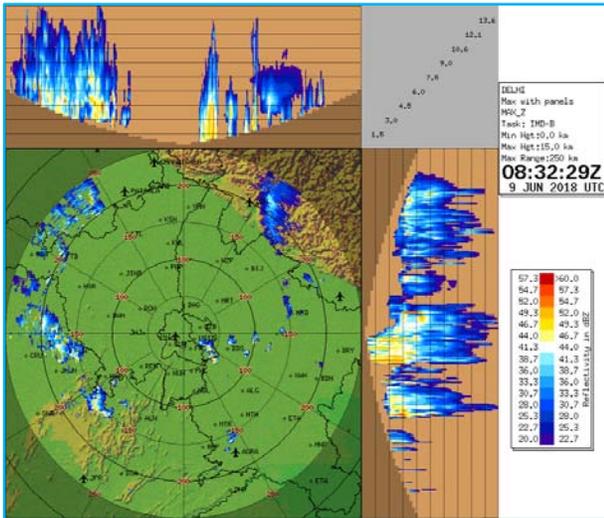


Fig. 11. MAX_Z (0832 UTC)

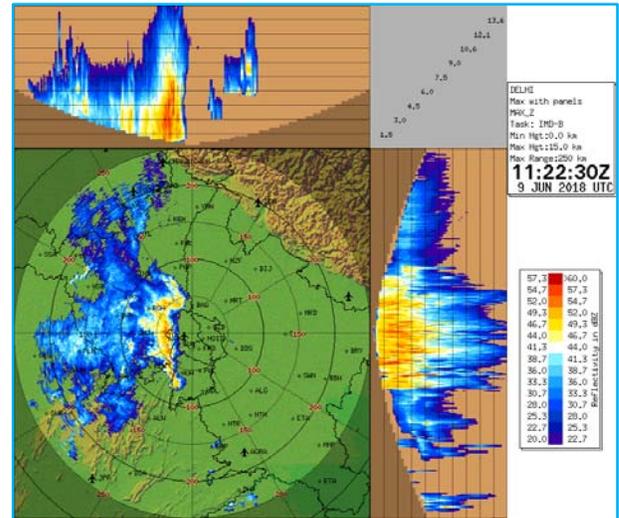


Fig. 13. MAX_Z (1122 UTC)

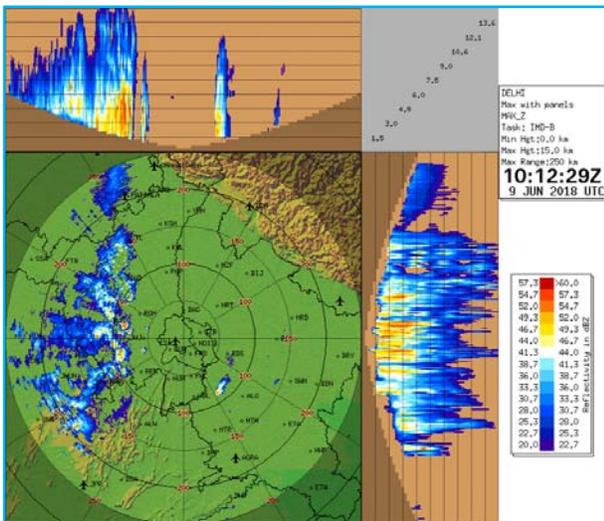


Fig. 12. MAX_Z (1012 UTC)

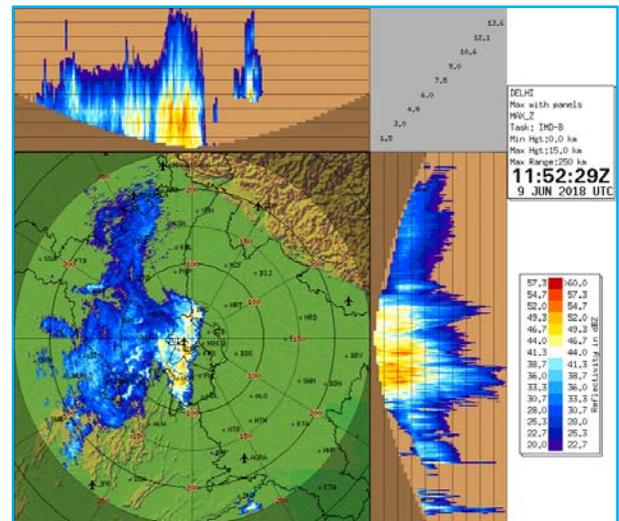


Fig. 14. MAX_Z (1152 UTC)

operational people who are continuously monitoring the storm and issuing nowcast.

Analyzing the GNSS parameters and DWR products together and comparing them, it can be observed that the DWR products present the picture of the system in real time while giving a very limited information beforehand in the form of wind speed and direction. However, the GNSS parameters, when used in conjunction with the DWR products are found to be more useful to alert the operator using the variation in PWV which may give an indication of some instability and disturbance in the atmosphere. The increase in the value of PWV is generally associated with heavy rainfall. The sudden rise in the value of RH just when the storm struck Delhi with

accompanying decrease in the value of PWV is also as expected.

The passing of a storm to the north of Delhi at about 100 kms to 220 kms over Patiala, Kurukshetra, Karnal, Panipat and nearby areas can be seen with the variation of PWV where the PWV over Delhi increased slightly just when the storm passed over the said areas. The increase in the PWV and decrease in RH over Delhi as measured by the GNSS receiver indicated that another system was about to strike Delhi which eventually passed over Delhi.

The variation of parameters in GNSS and the observations of DWR showed consistency to a good degree and these two tools may be used together to

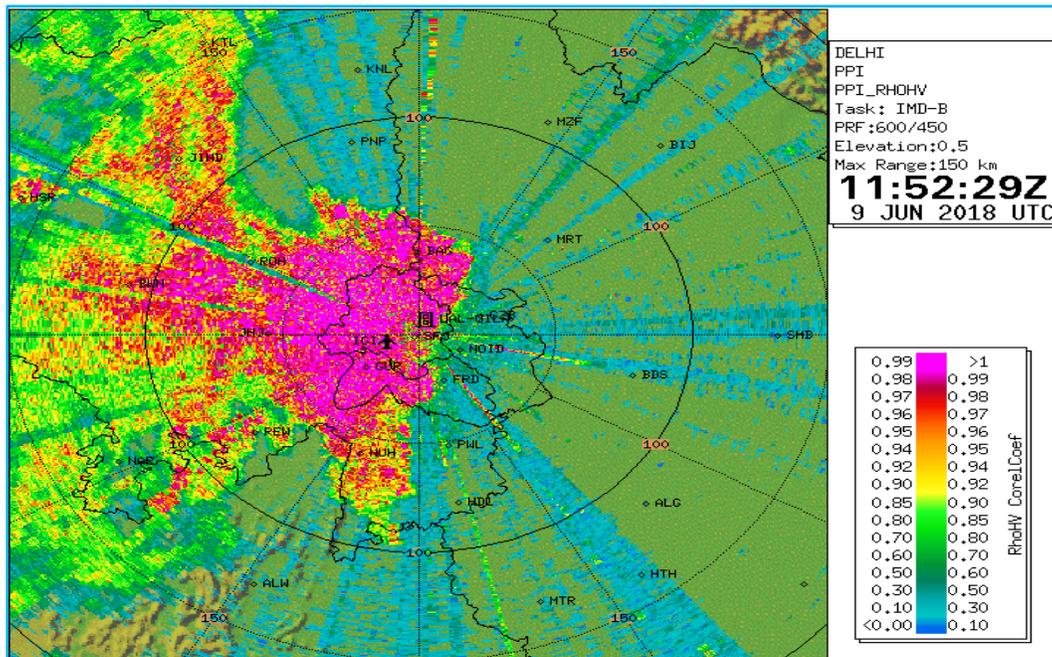


Fig. 15. CC (1152 UTC)

present a different picture of the weather event approaching the station where these are installed.

On 2 May, 2018, India Meteorological Department (IMD), the nodal agency of Government of India for all weather related events, observed thunderstorms / duststorms with squally/gusty winds over Delhi, Haryana, Chandigarh, Uttar Pradesh, East Rajasthan. The department had also indicated that these thunderstorms were the most lethal in six years. In terms of casualties, nearly 130 persons were reported dead in the May 2 weather-related incidents. Adequate timely warnings were given by IMD about these events.

3.2. Analysis of thunderstorm on 09 June, 2018

3.2.1. Maximum reflectivity (MAX_Z)

A severe convective storm, comprising of thunderstorm accompanied with dust storm, with winds gusting upto 96 kmph, struck the national capital region and surrounding areas around 1120 UTC on 9 June, 2018. The first signatures of the storm were visible at 0832 UTC in MAX_Z image (Fig. 11). Few separate smaller convective weather systems passed to the north of Delhi from west to east earlier during the day. The system that struck Delhi came from north-west/west direction, building up gradually on its way to Delhi (Fig. 12), increased in strength as indicated by very high reflectivity along with a very high vertical extent (height of 15 kms can be seen in the N-W projection in MAX_Z image,

Fig. 13). The system struck Delhi around 1152 UTC (Fig. 14) bringing good amount of rain preceded by the dust storm. The high amount of water content is indicated by the high reflectivity of clouds (red colour) and also the height where the reflectivity is high. The system was able to be tracked in a good manner with the help of DWR.

3.2.2. Correlation coefficient (CC)

The Correlation Coefficient is one of the six base products of a polarimetric DWR which gives additional information about the size, shape and variety of hydrometeors. The single polarimetric radar has three base products. CC is one among the three additional base products generated by a polarimetric DWR and gives extra information about the nature of the hydrometeors present in any severe weather system. It is a measure of how uniform the targets being observed by the radar are. It varies in the range of 0 to 1. Meteorological echoes will typically have Correlation Coefficient values higher than 0.8 with the uniform meteorological echoes having values greater than 0.97 and non-uniform meteorological echoes having values between 0.8 and 0.97. Non-meteorological echoes (birds, insects, etc.) typically have values less than 0.8. It can be seen in the images that there is some interference (bluish-green colour) which is quite predominant in the images of CC. Since the value of CC corresponding to bluish-green colour lies between 0.1-0.5, this interference is coming from non-meteorological echoes. When the storm is over Delhi at 1152 UTC (Fig. 15), the echoes are pink in colour and corresponds to

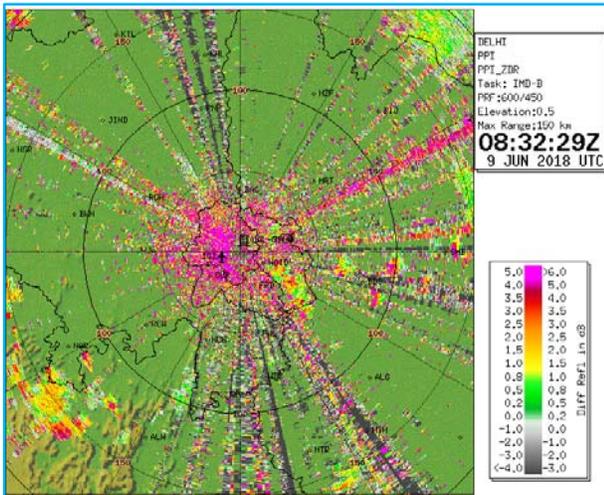


Fig. 16. ZDR (0832 UTC)

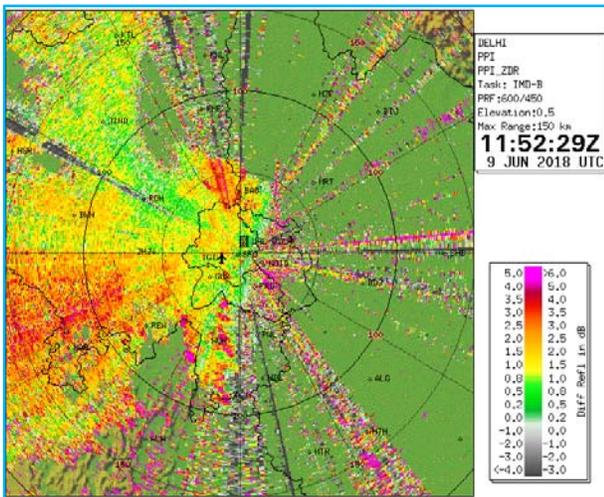


Fig. 17. ZDR (1152 UTC)

a value of 0.99 and 1 and hence the precipitation is pure rain. The green echoes correspond to a CC values from 0.7 to 0.9 while the yellow echoes correspond to CC values from 0.9 to 0.92 indicating a precipitation type like hail, melting snow etc but these echoes are coming from a particular height as the height of radar beam varies with distance as per Table 1. Here, it can be observed that with the use of a single polarized radar, we will only be able to estimate the danger potential of the severe weather system but with the use of the polarimetric product CC, the type of hydrometeor can also be known. Whether the hydrometeor is rain or hail can be estimated by matching the colour at a particular point in the product image against the value as available in the scale on the right side of the image. Also, this product is very useful to differentiate between non-meteorological echoes and the

TABLE 3

Physical interpretation using CC

Non-meteorological (Birds, insects, etc)	Meteorological (Non-uniform) (Hail, melting snow, etc)	Meteorological (Uniform) (Rain, snow, etc)
Low CC (< 0.8)	Moderate CC (0.80 to 0.97)	High CC (> 0.97)

Table Source : NWS, US

meteorological echoes. All the echoes whose values are less than 0.8 are non-meteorological in nature.

3.2.3. Differential Reflectivity (ZDR)

Differential Reflectivity is also among the six base products obtained from a polarimetric DWR. It is dependent upon the logarithm of the ratio of the power returned to the radar from the horizontal pulse to the power returned from the vertical pulse. If this ratio is greater than 0, then the target being observed is wider than it is tall and the signal is positive; if this ratio is less than 0, the target is taller than it is wide and the signal is negative. When the ratio is close to 0, the target is approximately spherical. As the storm is approaching towards Delhi (Fig. 16), few of the echoes are pink and red in colour with ZDR values observed upto 6 indicating a large size of the rain drops, i.e., as the value of ZDR increases, the size of the rain drops also increases. As the storm has reached over Delhi at 1152 UTC (Fig. 17), the echoes are yellow in colour corresponding to ZDR value of around 1 typically representing the precipitation as rain.

Table 4 may be referred for physical interpretation of the products based on the ZDR values. As the colour coding can be seen on the scale available on the right hand side of Fig. 16, most of the hydrometeors present in the system when it is over Delhi are pink in colour matching against the value greater than 6.0 in the scale and signifying large rain drops with the presence of hail. In Fig. 17, at 1152 UTC, the ZDR values of the hydrometeors present over Delhi is greenish-yellow signifying small rain drops existing in the weather system.

3.2.4. GNSS parameters

Fig. 18 shows the variation in GNSS parameters on 9 June, 2018 when a severe thunderstorm which was preceded by a mild duststorm hit the national capital and surrounding areas. The PWV was continuously increasing in value barring some two to three dips in its curve till the time the storm struck Delhi. And as we know, more the

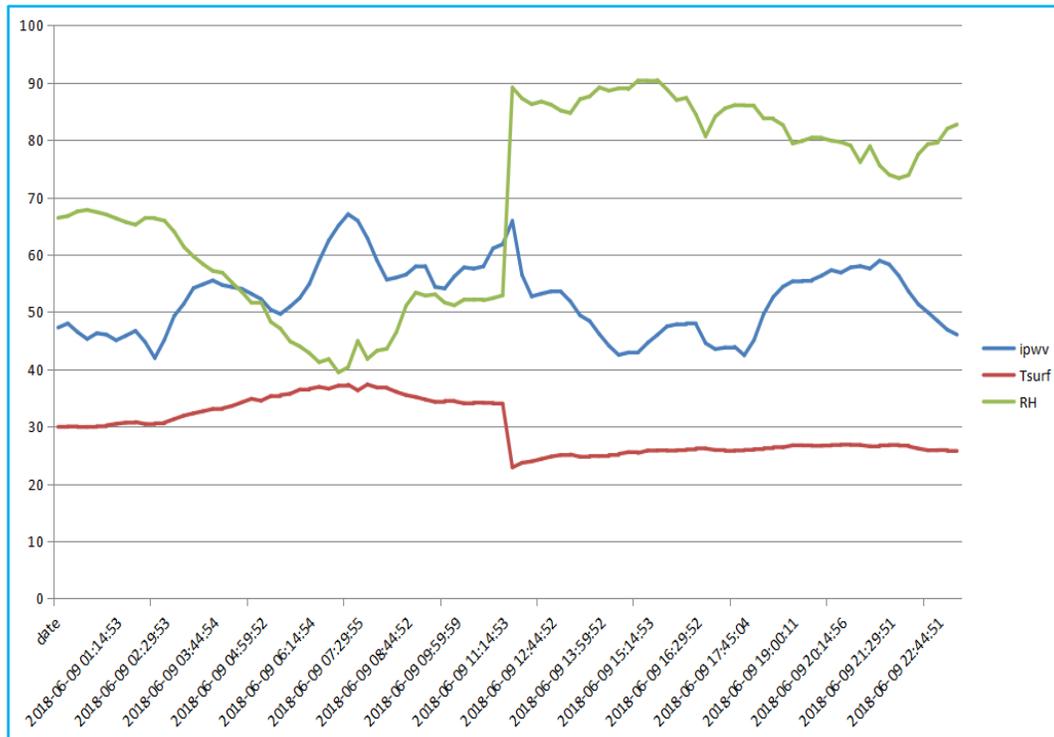


Fig. 18. GNSS parameters

TABLE 4

Physical interpretation using ZDR

Spherical (Small rain drops and large hail)	Horizontal (large hail drops, melting hail, insects, etc.)	Vertical (<i>i.e.</i> , vertically oriented ice crystals, sometimes large hail)
$Z_h \sim Z_v$	$Z_h > Z_v$	$Z_h < Z_v$
ZDR ~ 0 dB	ZDR > 0 dB	ZDR < 0 dB

Table Source : NWS, US

value of PWV, more is the potential of the cloud system to create rainfall. A wide variation in RH can be seen from its variation curve in Fig. 18. The value of RH was around 68% in the morning which decreased continuously and reached its lowest value at around 0700 UTC when the value of PWV was at its peak of 67 mm. The surface temperature increased from morning to noon as it generally increases and dipped by 12 °C after the storm started dissipating.

3.2.5. Rainfall recorded on 9 June, 2018

Table 5 shows the amount of rainfall received in Delhi on 9 June, 2018 and reported by the meteorological observatories. It is observed that the unusually high amount of rainfall occurred at Dhansa in the western part of Delhi and good amount of rainfall was also recorded at Jafarpur, Palam, Najafgarh, Ayanagar and Delhi University which are spread all over Delhi which means

TABLE 5

Rainfall recorded at BID observatories on 9 June, 2018

S. No.	Met. sub/district/division	Rainfall recorded (mm)
1.	Lodi Road	4.8
2.	Safdarjung	4.7
3.	Delhi University Observatory	13.9
4.	Aya Nagar	17.3
5.	Jafarpur	35.0
6.	Palam	27.4
7.	Najafgarh	19.0
8.	Pusa	6.0
9.	President House	3.6
10.	Delhi Ridge	11.1
11.	Mungeshpur	10.0
12.	Dhansa	67.4

good amount of rainfall all over the territory of the national capital.

3.2.6. Combined inference of the storm on 9 June, 2018

The analysis of the storm that hit Delhi on 9 June, 2018 has been done using polarimetric products Correlation Coefficient (CC) and Differential Reflectivity (ZDR) along with the most common product MAX_Z. The reason for using CC product before ZDR or any other dual-pol product is that all the dual polarization products that are being generated by C-Band DWR are showing some interference which manifests itself in the form of false echoes. Products derived from use of single-pol data do not have this problem. It appears that problem is due to transmission of alternately horizontal and vertical pulses used in the technology. In spite of this interference, it is possible to interpret dual-pol products and derive some useful information like the way CC has been used ahead in this paragraph to differentiate meteorological echoes from non-meteorological echoes. The echoes which are bluish-green in colour corresponds to a CC value of 0.1 - 0.5 and as any CC value below 0.8 is non-meteorological in nature, these interference echoes are taken as non-meteorological. The corresponding places in ZDR where interference echoes as in CC are visible are also taken as non-meteorological. As can be seen in Fig. 15, the CC value of the pink echoes is more than 0.97 signifying the presence of uniform rain drops. For yellowish echoes, whose value is less than 0.97 but greater than 0.8, the echoes are non-uniform, probably hail, and are located at an approximate height of 1.46 to 2.63 kms as the beam is

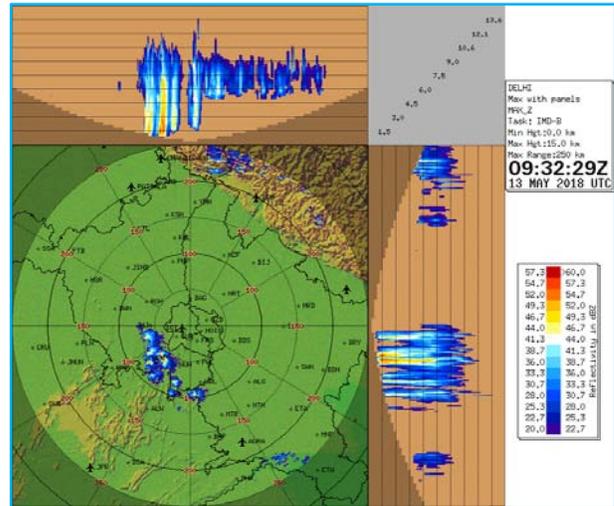


Fig. 19. MAX_Z (0932 UTC)

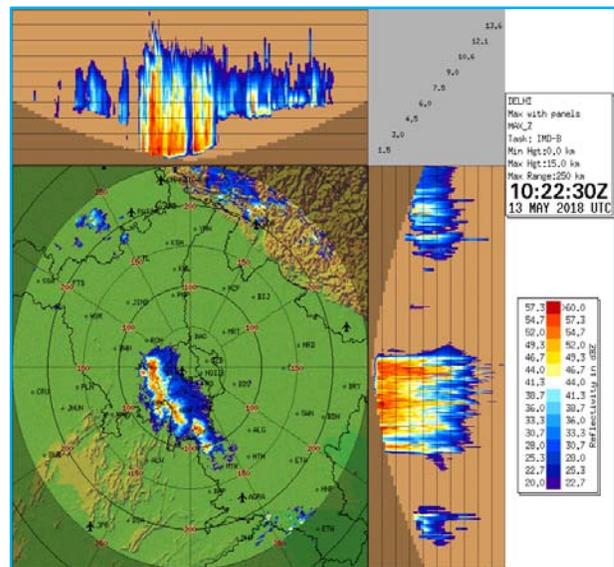


Fig. 20. MAX_Z (1022 UTC)

at that particular height at an elevation of 0.5° as per Table 1. Similarly, as per the ZDR values, most hydrometeors have a value of greater than 5 signifying drops of large diameter. So, these dual-pol parameters are giving additional information about the size, shape and variety of the hydrometeors.

As the first signatures related to the storm were seen by the DWR at 0832 UTC (Fig. 11), the PWV also reached its peak value at that time (Fig. 18) and decreases slightly after the storm hit Delhi which shows a good agreement between the DWR and GNSS equipment. Just at 1200 UTC, the storm strikes the heart of the national capital, again a peak in the value of PWV can be seen

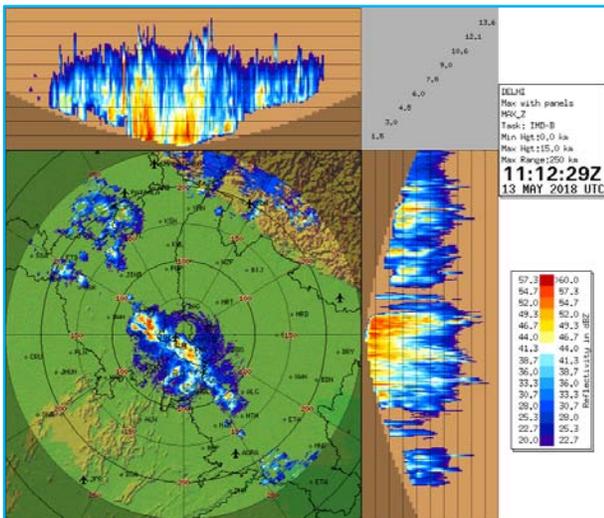


Fig. 21. MAX_Z (1112 UTC)

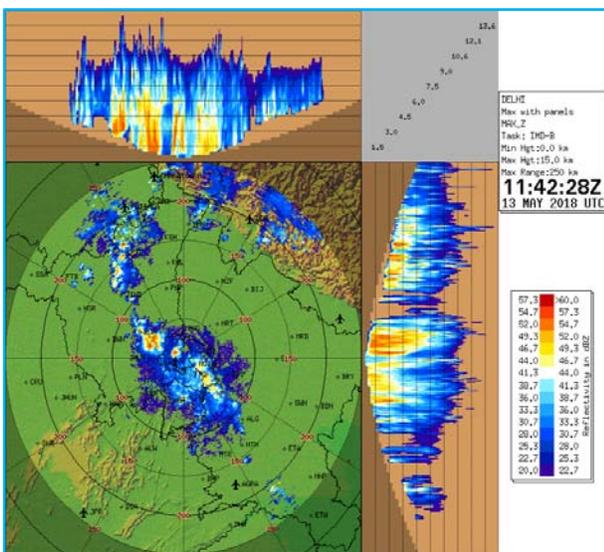


Fig. 22. MAX_Z (1142 UTC)

which decreases quickly after the storm has passed signifying the rainfall over Delhi has taken place as more PWV value signifies more potential of rainfall. The value of RH peaked from 52% to 90% just after the rainfall and the surface temperature decreased from 34 °C to 23 °C.

In this case also, it can be said that the DWR products used during the analysis of the storm on 09 Jun, 2018 presented a different picture than the first case but the closeness with GNSS parameters can be seen here also.

India Meteorological Department (IMD) had also forecasted the possibility of thunderstorms on 9 Jun, 2018.

As per several news reports, intense thunderstorm accompanied with dust storm blacked out several parts of Delhi-NCR and killed more than 26 people in Uttar Pradesh.

3.3. Analysis of thunderstorm on 13 May, 2018

3.3.1. Maximum reflectivity (MAX_Z)

A severe storm accompanied by squalls with associated wind speed of up to 109 kmph, battered Delhi and neighbouring areas on 13 May, 2018 throwing life of common people out of gear. The first indications of a storm developing were visible in MAX_Z image at 0932 UTC (Fig. 19) approximately 70 kms range in Southwesterly direction as seen from Delhi radar image. The storm increased in intensity in no time and at 1022 UTC (Fig. 20) a fully developed storm with reflectivity upto 60 dBz and height in excess of 13.5 kms can be seen. The sky turned cloudy at around 1630 IST and gusty winds swept the national capital. The storm blew over Delhi from South-West direction at a highest speed of 70 kmph as observed by DWR. Very high reflectivity of around 55dBz can be seen over Delhi at 1142 UTC (Fig. 22).

3.3.2. Differential Phase Shift (Phi-DP)

It is the difference in phase shift between the horizontal and vertical pulses of the radar as they propagate through a medium such as rain or hail and are subsequently attenuated. Due to differing shapes and concentration, most targets do not cause similar phase shifting in the horizontal and vertical pulses. When the horizontal phase shift is greater than the vertical, the differential phase shift is positive; otherwise, it is negative. While this correspondence between positive values (horizontal) and negative values (vertical) is analogous to Differential Reflectivity (ZDR), there is a crucial distinction : differential phase is dependent on particle concentration. That is, the more horizontally oriented targets are present within a pulse volume, the greater the positive differential phase shift. Thus a high frequency of small raindrops could yield a higher differential phase value than a lower concentration of larger raindrops. Differential phase shifting is mostly unaffected by the presence of hail, and shifts in snow and ice crystals are typically near zero degrees. As can be seen in Fig. 23 at 1302 UTC when the system was over Delhi, the echoes shown are bluish-green in colour which corresponds to a phase shift of around 30° - 40° between the horizontal and negative received pulses giving an additional information on the shape and concentration of hydrometeors.

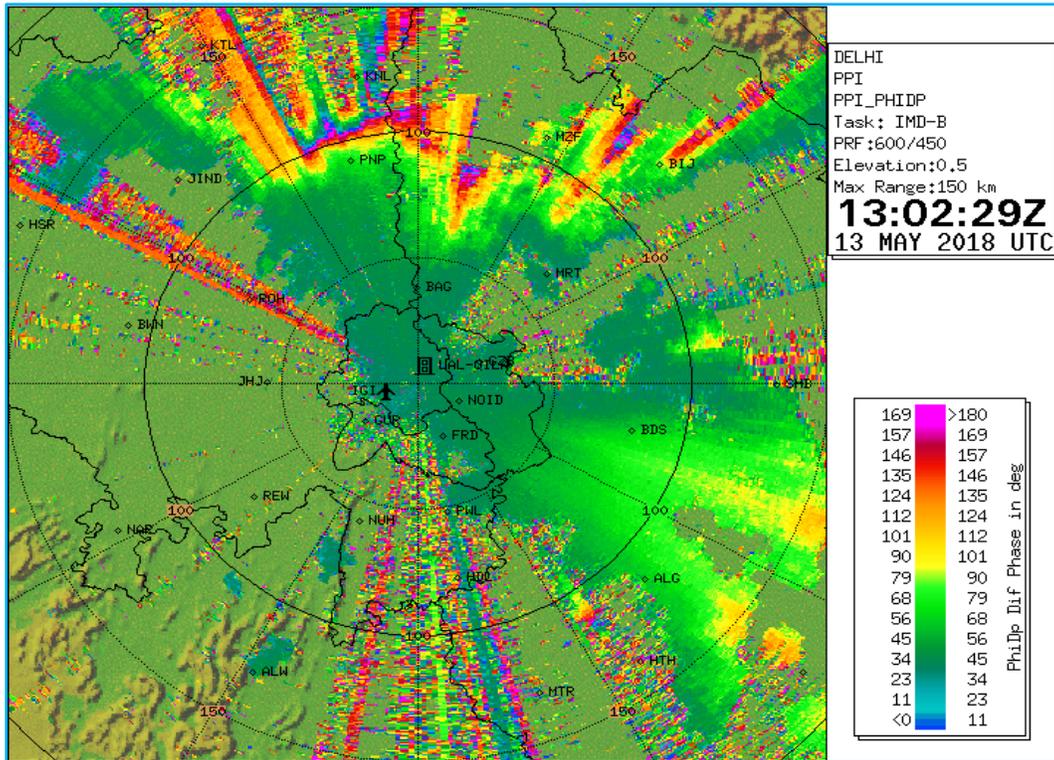


Fig. 23. Phi-DP (1302 UTC)

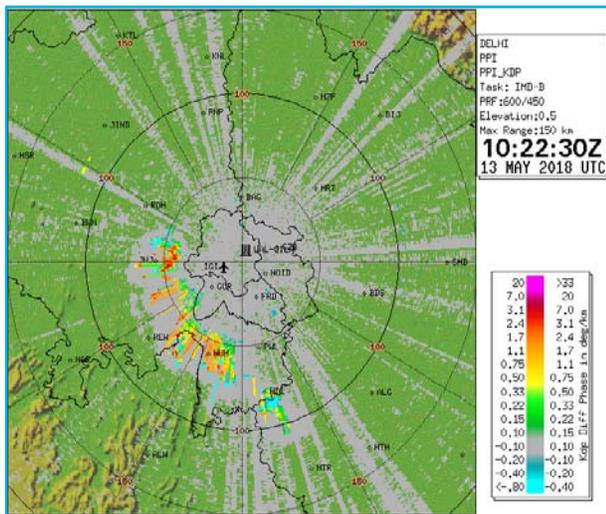


Fig. 24. KDP (1022 UTC)

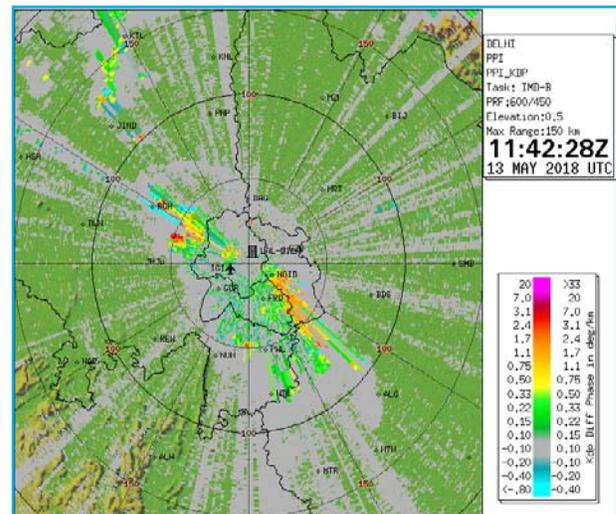


Fig. 25. KDP (1142 UTC)

3.3.3. Specific Differential Phase (KDP)

Specific Differential Phase (KDP) is defined as the range derivative of the differential phase shift along a radial. While Phi-DP gives the output in degrees, KDP, which is a derived product from Phi-DP, shows the

gradient or change per km and gives the output in deg/km. As a result, it is easier to interpret and more user friendly as compared to Phi-DP. Areas of heavy rain will typically have high KDP due to the size or concentration of the drops. KDP is useful for identifying areas where the heaviest rainfall is pouring. Hail and snow/ice crystals

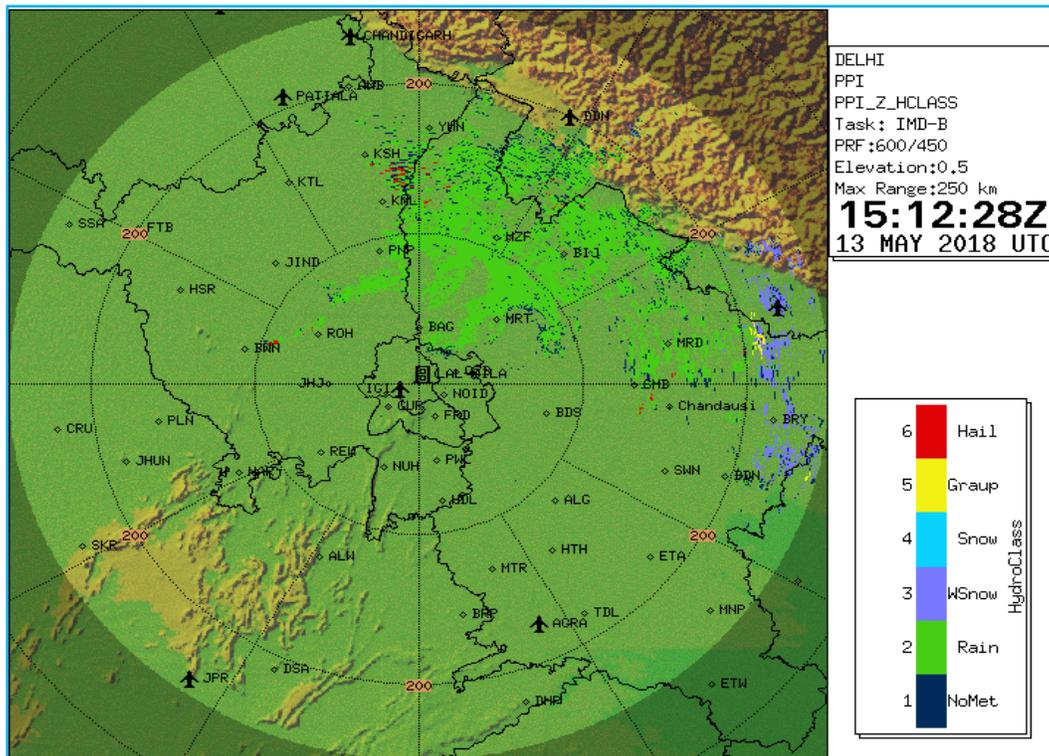


Fig. 26. H-Class (1512 UTC)

TABLE 6

Physical interpretation using KDP

S. No.	Form of precipitation	Interpretation
1.	Hail	KDP near 0 (except near 3 for melting)
2.	Snow	KDP typically between -1 and +0.5
3.	Rain	KDP between 0 and +5 (larger number indicates larger drops and/or increased drop concentration)

Table Source : NWS, US

have no preferred orientation and will yield KDP values near zero degrees. Non-meteorological echoes will result in noisy KDP values. Considering the image at 1022 UTC (Fig. 24), when the storm was at an approximate distance of 50 kms from Delhi, the KDP values of the echoes range from negative to large positive with the red echoes corresponding to KDP values of upto 7 deg/km signifying the presence of large-sized drops as per the interpretation stated in Table 6. As the storm hits Delhi (Fig. 25), the echoes shown in KDP values are spread over a large area. Since there is a wide variation of KDP values, the hydrometeors may contribute in different kind of precipitation and the echoes which are showing high KDP

values have high very high concentration of the hydrometeors. The areas showing higher KDP values correspond to the areas receiving heavy rain rate and more liquid precipitation. The interference is also showing the products which are noisy KDP values and must be ignored as per analysis of the CC product.

3.3.4. Hydrometeor classification (H-Class)

The hydrometeor classification algorithm uses several radar products to determine the precipitation type of what is being observed. The caution here to be kept in mind is that this algorithm is determining the precipitation type at the beam height and not at the surface. If we analyze the hydrometeor classification product in Fig. 26 at 1512 UTC for the storm that struck Delhi and UP on 13 May, 2018, it can be observed that the echoes shown at over 100 kms to the east of Delhi over Bareilly and Pantnagar Airport are of the color which corresponds to the precipitation type of Wet Snow. The height of the echoes at 0.5° elevation is around 1.9 kms as per Table 1. It is to be kept in mind that this precipitation when strikes the ground may or may not change the precipitation type and there was no observation of falling of snow in Bareilly on 13 May, 2018 which means that Wet Snow at around 2 kms height changed to rain when it reached the surface.

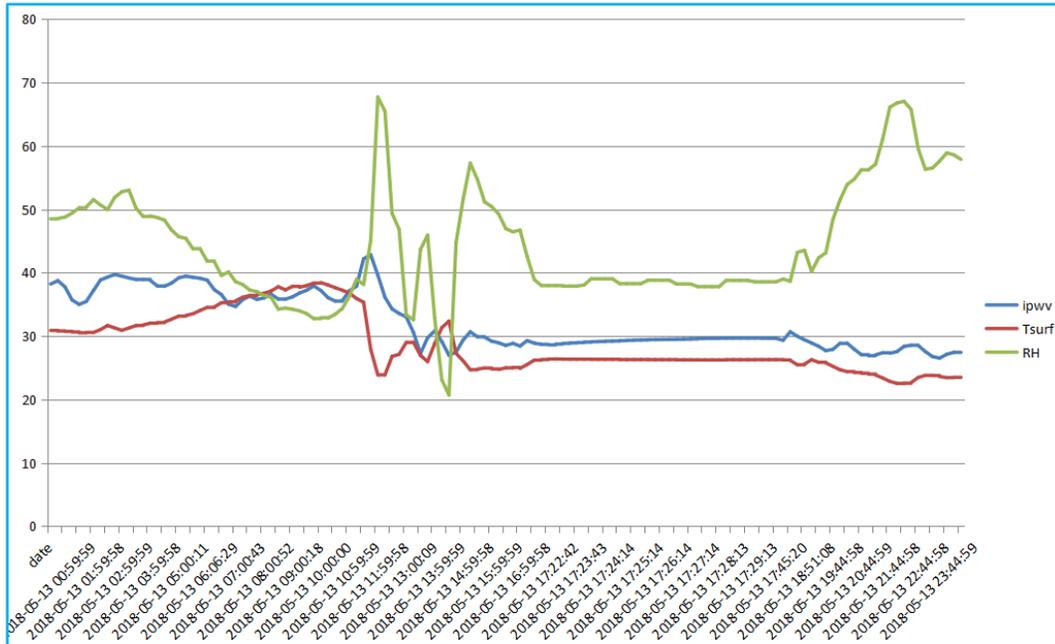


Fig. 27. GNSS parameters

TABLE 7

Rainfall recorded at BID observatories on 13 May, 2018

S. No.	Met. Sub/District/Divison	Rainfall Recorded (mm)
1.	Lodi Road	4.1
2.	Safdarjung	4.2
3.	Delhi University Observatory	1.8
4.	Aya Nagar	8.0
5.	Jafarpur	1.0
6.	Palam	1.2
7.	Najafgarh	1.0
8.	Pusa	3.0
9.	President House	3.8
10.	Delhi Ridge	1.3

3.3.5. GNSS parameters

Monitoring the GNSS parameters on 13 May, 2018, one can conclude from the value of RH that just before any storm is about to hit Delhi, its value shows the downward trend as it has shown in the analysis of the previous two storms and just after the storm hits the place, its value shoots up considerably. Here also the value of RH increased drastically from 38% to 68% in less than an hour (Fig. 27). Not much can be inferred from PWV here as it remains under 40 before the striking of the storm at

Delhi and expectedly increases quickly as the storm strikes. The surface temperature also behaves expectedly as observed by GNSS equipment as it increases from morning to afternoon and drops after the storm hits Delhi.

3.3.6. Rainfall recorded on 13 May, 2018

Table 7 shows the amount of rainfall received in Delhi on 13 May, 2018 and reported by the meteorological observatories. It is observed that no excessive rainfall has been recorded by any of the observatories with none reporting more than 10 mm of rainfall. The highest rainfall of 8.0 mm has been recorded from Aya Nagar.

3.3.7. Combined inference of the storm on 13 May, 2018

The analysis of the storm on 13-May-2018 has been done by using less common dual-pol products like Phi-DP (Differential Phase Shift) and KDP (Specific Differential Phase) as these two products give a more different picture of the storm than the earlier used products. The difference between the two being that in the latter the phase shift is the range derivative along the radial of the former. Using these two different products also tells the concentration of the hydrometeors in a pulse volume. Analyzing the Phi-DP values in Fig. 23, the initial parts of the system are showing higher values of Phi-DP implying more concentration of hydrometeors and as the system moves over Delhi, the echoes showing high values of Phi-DP

reduces to a less area as with the rainfall the concentration of hydrometeors in the system decreases.

Another product used in the analysis is the Hydrometeor classification (H-Class) which makes use of the other dual-pol products to give the type of precipitation at a particular height and elevation. But it is to be kept in mind that the type of precipitation is determined at a particular height which may change as the precipitation falls on the ground.

As the initial signatures of the storm are visible on the DWR products, the value of PWV also starts increasing towards its peak. It continuously increases and reached the peak just before the storm struck Delhi. Thereafter, it decreased but it gave the signal that there is a scope of good amount of rainfall which ultimately poured.

India Meteorological Department (IMD) also indicated in its advisory a day earlier that a thunderstorm accompanied with gusty winds is very likely at isolated places over Delhi, Haryana, West Uttar Pradesh and parts of Rajasthan. The loss due to the storm was also not less as many people were killed, around 70 flights were diverted and metro services were also disrupted for a short time.

4. Conclusions

The analysis of three storms over Delhi during the pre-monsoon season of 2018 using dual-polarized products showed DWR's increased capability of giving information about the development of severe weather system in respect of the size, shape and variety of the hydrometeors existing in the weather system. The role of ZDR (Differential Reflectivity), CC (Correlation Coefficient), Phi-DP (Differential Phase Shift), KDP (Specific Differential Phase) and H-class (Hydrometeor classification) has been found to be very useful in obtaining more precise information about the nature of precipitation. The information available from the polarimetric DWR is more pronounced in the context of retrieving additional information. In this respect, the polarimetric DWR shows a quantum jump over the single-polarized DWR. The maximum reflectivity values in all the three storms discussed in this study has been 54 dBZ and reaching even more than 60 dBZ in two storms signifying the severity of the system with the PPI(V) and VVP_2 giving information about the gustiness of the wind. Also, the interpretation of the dual-polarized products of the polarimetric DWR like ZDR, CC, Phi-DP and KDP when used in conjunction of each other has been very useful in the detailed analysis in context of knowing the form of precipitation, *viz.*, rain, snow, graupel, etc. or

non-precipitation echoes. The C-Band polarimetric DWR installed at New Delhi is one of the first polarimetric DWRs installed in the country in 2011 and provides valuable additional meteorological information about the size, shape and variety of hydrometeors which is not available with the single horizontally polarized DWR installed before.

As per the analysis of GNSS parameters during pre-monsoon season especially on 2nd May, 9th June and 13th May of 2018, the GNSS-derived PWV indicated the occurrence of thunderstorm activity over Delhi 2-3 hours in advance. It was also found that in the month of May, PWV values in excess of 40 mm and surface temperature values between 35 to 40 °C and in the month of June, PWV values greater than 45 mm and surface temperature values between 37 and 45 °C gave an indication of the coming severe weather activity over Delhi.

The observations made by the variation of various parameters of GNSS especially the PWV conforms to a satisfactory degree with the observations made by the DWR and the two tools can be used simultaneously for predicting the development of any severe weather event expected to strike in 2-3 hours.

5. Future scope of work

As more numbers of C-Band and X-Band Polarimetric Doppler Weather Radars are being installed in various parts of India by IMD and many more are expected in the near future including polarimetric S-Band DWR, this study will provide a better understanding of the interpretation of dual-pol products to other scientists of IMD and other organizations and also to the research students for improvement in the accuracy of nowcasting.

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