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ARTICLE

Thumb Rule for Nowcast of Dust Storm and Strong Squally Winds over Delhi NCR using DWR Data

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ABSTRACT

Squally winds are the natural hazards and are often associated with the severe thunderstorms (TS), which mostly affects plains of North West India during pre monsoon season (March to May). Squally winds of the order more than 60 kmph are very devastating. Under influence of these strong squally winds trees, electricity poles, advertisement sign boards fall, sometimes human life is also lost. The main objective of this study is to find out the thumb rule based on Doppler Weather Radar (DWR) Data to Nowcast the squally winds over a region. To detect thumb rule, five cases of thunder storm accompanied with squally winds ranging from (55 kmph to 110 kmph) are taken in to consideration. These TS's occurred over Delhi NCR (National Capital Region) during May - June 2018. Maximum reflectivity (Max Z) data of Delhi DWR, Cloud Top Temperature (CTT) data from INSAT and squally winds along with other weather parameters observed at Safdarjung and Palam observatories are utilized to find out the Thumb Rule. Based on the analysis, it is concluded that presence of a western disturbance (WD), presence of East-West trough from North-west Rajasthan upto East UP through south Haryana and very high temperature of the order of 40 degree Celsius over the nearby area are very conducive for occurrence of squally winds accompanied with thunderstorms. Thumb rule find out in this study is that, **squally winds of the order of 55 kmph or more will effect a station if a thunderstorm (having Max Z echo with vertical extension of cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station) moving towards station is present in one to two hour before images of Doppler Weather Radar.**

1. Introduction

Squally winds are the natural hazards and are often associated with the strong thunderstorms (TS), which mostly affects plains of North West India during pre monsoon season (March to May). Squally winds of the order more than 60 kmph are very devastating. Under influence of these strong squally winds trees, electricity poles, advertisement sign boards fall, sometimes human life is also lost. As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height was not much higher at that time it means less convection gives more dust at the surface. There is both updraft and downdraft accompa-

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nied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching towards the observatory which further enhance the wind speed and thus squally winds are reported at the observatory.

A squall is a sudden strong rise in wind speed which generally lasts for some minutes. **As per IMD definition squall is the wind that has to rise by at least 16 knots to a speed of greater than 22 knots and to last for at least one minute**. Squally weather is meant to cover occasional or frequent squalls with rain or persistent type of strong **gusty winds** (mean **wind** speed not less than 20 knot) accompanied by rain. Such conditions are associated with severe thunderstorms, low pressure systems or onset and strengthening of monsoon.

Thunderstorm climatology over Indian region based on climatological data from 450 observatories [9]. The study has brought out higher (100-120 days) annual frequency of thunderstorm as compared to those given by earlier studies (80-100 days). The highest annual frequency (100-120 days) is observed over Assam and Sub Himalayan West Bengal in the east and Jammu region in the north. The lowest frequency (less than 5 days) is observed over Ladakh region. Kerala records highest (80-100 days) thunderstorm frequency of thunderstorm over peninsula. Udhampur observatory (132 days) in Jammu sub-division records highest number of thunderstorms in the country followed by Kumbhigram (Silchar) observatory (129 days) in south Assam and Hasimara (123 days) in Sub Himalayan West Bengal. In the plains Saurashtra and Kutch record lowest number (less than 15 days) of thunderstorm in the country. Under the Severe Thunderstorm Observation and Regional Modelling (STORM) programme reviewed the status of convective activity over Indian region and discuss the two important severe thunderstorms using Doppler Weather Radar (DWR) that occurred on 30 May, 2014 in New Delhi and 21 April, 2015 in Purnia, Bihar [4]. These two events caused lot of damage to life and property due to strong winds/gusts associated with the thunder squalls that affected these areas. Thunderstorm with squall was reported at Meteorological Office at Palam airport in New Delhi on 30 May, 2014 with wind speed in gust reaching 115 kmph .Similarly on 21 April, 2015 Doppler Weather Radar at Patna reported a micro burst signature at where the peaking winds of 49.1 m/s were observed. It is analysed that the thermodynamic indices variation over eastern Indian region associated with pre-monsoon thunderstorms for 20-year period (1987-2006), showing a rise in humidity over the period, decrease in thunderstorm frequency over the study period unveiling the climate change over the region [5]. A series of destructive windstorms on 16 July 1980 from Chicago to Detroit, the nature of the windstorms was confirmed to be downbursts and microburst characterized by multiple scales of airflows with their horizontal dimensions extending tens of meters to hundreds of kilometres and. an attempt was made to estimate the wind speed based on three types of airborne objects and presented linkage between cloud-top features and wind effects on the ground [2]. The hail storm phenomena over Chennai in the year 2002 based on the data received from Doppler Weather Radar, Chennai was analyzed [8]. 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 confirms that hails of 19 mm was more probable with 0.80 probabilities. Utilisation of 'Aerostat' system a part of the air defence radar network, adopted by the Indian Air Force DWR images for nowcast of thunderstorms/dust storms over NW India during pre-monsoon and SW monsoon seasons was studied [1]. In this study, It has been found that the DWR is a very good tool to track the movement of significant weather echoes around the airfields, which can be very helpful in issuing appropriate warnings/advisories with sufficient lead time. An attempt was made to use INSAT Infrared and Visible imageries and found that by and large Eastern India (Jharkhand, Orissa, Sub Himalayan West Bengal and Bangladesh) is responsible for the initiation of convection [10]. Development occurs as the cells propagate over the neighbouring areas of Bangladesh and NE India. It is suggested that half hourly to hourly monitoring of convection can be accomplished by using INSAT imagery, along with multiple overlapping radar coverage; only effective way for effective warning is nowcasting using satellite and multiple radar coverage.

It was observed that a major challenge in meteorology is the forecasting of winds owing to their highly chaotic nature. However, wind forecasts, and in particular daily peak wind gust forecasts, provide the public with a general sense of the risks associated with wind on a given day and are useful in decision making [3]. In this project a peak wind gust prediction scheme based on output from the North American Mesoscale (NAM) model are used in a support vector regression (SVR) algorithm trained to predict daily peak wind gusts for ten cities commonly impacted by hazardous wind gusts and with interests in wind energy. SWIRLS nowcast system was implemented for nowcsat of thunderstorm and associated quantitative precipitation forecast during Commonwealth Games 2010 at New Delhi. In this system MOVA ("Multi-scale

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Optical flow by Variational Analysis") a latest algorithm uses optical flow, is used in motion detection in image processing, and variational analysis to derive the motion vector field. In this study it is concluded that, MOVA can better depict the actual storm motion vector field as compared with TREC and GTrack [6]. Mesoscale model (ARPS) is implemented with real-time assimilation of DWR data in India Meteorological Department (IMD) for real-time nowcast of weather over Indian region using Three-dimensional variational (ARPS3DVAR) technique and cloud analysis procedure for real-time data assimilation in the model. Results show that in both the cases, Cloudburst events of September 15, 2011, and thunderstorm event of October 22, 2010, ARPS3DVAR and cloud analysis technique are able to extract hydrometeors from radar data which are transported to upper levels by the strong upward motion resulting in the distribution of hydrometeors at various isobaric levels. Dynamic and thermodynamic structures of cloudburst and thunderstorm are also well nowcast in real time [7].

The main objective of this study is to find out the thumb rule based on Doppler Weather Radar (DWR) Data to Nowcast the squally winds over a region. To detect thumb rule, five cases (02 May, 07 May, 13 may, 01 June and 09 June 2018) of thunder storm accompanied with squally winds ranging from (55 kmph to 110 kmph) are taken in to consideration. These TS's occurred over Delhi NCR (National Capital Region) during May - June 2018. Maximum reflectivity (Max Z) data of Delhi DWR, Cloud Top Temperature (CTT) data from INSAT and squally winds along with other weather parameters observed at Safdarjung and Palam observatories are utilized to find out the Thumb Rule.

Data used in this study is described in section 2, Methodology to find out thumb rule for squally winds are described in section 3, Section 4 deals with the analysis and discussion of five cases of strong squally winds and finally results are concluded in the section 5.

2. Data Set

In order to study the Dust storm / thunder storm accompanied with squally winds of five cases data has been collected from following stations:

(A) **Synoptic data** at three hourly intervals are taken from Regional Weather Forecasting Center (RWFC), New Delhi.

(B) **METAR data** at 30 minute interval is collected from of Palam and Safadarjung observatories of Delhi.

(C) S- Band **Doppler Weather RADAR (DWR)** images has been collected from radar station situated at IMD Head Quarter, Lodi Road, New Delhi (lat. 28.58 ^{0}N, long. 77.22 ^{0}E) having time and space resolution of 10 minutes and 1 km respectively.

(D) In order to study the formation, weakening, intensification and movement of thunderstorm Satellite images of **INSAT-3D-IMAGER (INFRARED)** are collected from Satellite division of IMD New Delhi

3. Methodology

AS our main objective is to find out the thumb rule to nowcast (1-2 hour advance) the strong squally wind (> 60kmph) associated with Thunderstorm / Duststorm based on DWR observations, **the following criteria has been fixed / chosen to nowcast the squall (wind speed >60 kmph) in this study.**

(1) Presence of a Thunder cell in the previous images of DWR (1-2 hour before).

(2) Distance of Thunder cell should be (100 -150 km) from the station observing squall.

(3) Direction of movement of Thunder cell (towards or away) from the station

(4) Vertical extension thunder cell >7 km,

(5) Maximum Reflectivity (at 1 km height) >45 dBz

Apart from these above mentioned criteria presence of following Synoptic condition is also checked in all the cases (1) A western disturbance (WD) (2) East-West trough from North-west Rajasthan upto East UP through south Haryana (3) Very high temperature of the order of 40 degree Celsius over the nearby area

4. Analysis & Discussion

In order to verify the above criteria discussed in the section 3, five cases (02 May, 07 May, 13 may, 01 June and 09 June 2018) have been considered for investigating the high speed squally winds (**wind speed >60 kmph**) accompanied with these Duststorm (DS) / Thunderstorm (TS) which occurred over the study domain.

4.1 Case Study 1: (02 May 2018)

DS with squall (Two cell storm) was reported on 02 May 2018 at 1645-1647 IST (1115 UTC). Squall approached with wind speed of 59 kmph from northerly direction at Safadarjung and that at Palam also with speed of 59 kmph, but from easterly to southerly direction associated with DS (Table 1). If we see the DWR images at the time when squall was reported, there is no echo over the station, but nearest echos are seen around 80-90 km towards North-West of the Delhi. Based on Synoptic condition, satellite images and Radar images analysis is carried out here.

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Table 1. Observations at Safderjung (SFD) and Palam (PLM) stations on 2 May 2018

Station	Speed of Squall (kmph)	Direction	Time Of occurrence of Squall (IST)	Maximum Reflectivity (dBz)	Maximum Height of convective cell (km)	Distance of station from maximum Reflectivity (km)	Weather	Rain (mm)	Maximum Temperature (^{0}C)
SFD	59	N-NE	1645-1647	49-52	11	80-90	Dust Storm	1.3	37.6
PLM	59	E-SE	1645-1647	49-52	11	80-90	Dust Storm	1.4	38.7

4.1.1 Synoptic Analysis

Figure 1 shows that on 02 May 2018 there was WD (western disturbance) as a trough in mid and upper tropospheric levels with its axis at 7.6 km above MSL running roughly along long 64° E to the north of lat 30° N. The Cyclonic circulation over south Haryana and neighborhood persisted and extended up to 1.5 km above MSL. An east-west trough extended up to 1.5 km above MSL from NW Rajasthan to Manipur across the cyclonic circulation over Haryana, UP, the CYCIR over Gangetic West Bengal and Assam and Meghalaya. Max. Temp 47.7 C recorded at Bundi (Rajasthan). At 12UTC of 02 May 2018 CAPE value was 2696 Joule/kg and CINE value was -150 Joule/kg. This indicates that atmosphere was unstable and favorable for development of TS.

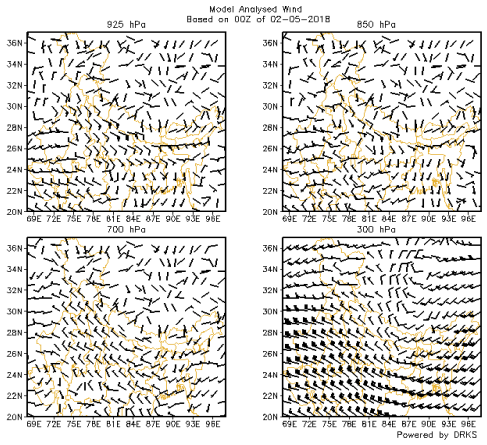

Figure 1. Wind pattern over Delhi region on 02 May 2018

4.1.2 Satellite Analysis

Table 2 depicts that cloud associated with TS/DS seen in North-West of Delhi and its adjoining regions around 1030 UTC. Satellite analysis also shows that there was TS activity occurring over Delhi NCR region and moving from north-west of Delhi to south-eastwards. Table 2 depicts that lowest cloud top temperature (CTT) of storm cell during this period was -50 degree Celsius at 17:00 IST (1130 UTC). This indicates that there was possibility of occurrence of moderate thunderstorm.

Table 2. Cloud Top Temperature (CTT) on 02 May 2018

Time of Thunderstorm (IST)	Direction of cloud patch	CTT (^{0}C)	Intensity of TS
1600	NW	-50	Moderate
1700	NW	-50	Moderate
1730	NW	-30	

4.1.3 RADAR Analysis

Table 1 describe that DS with squall (Two cell storm) was reported on 02 May 2018 at 1645-1647 IST (1115UTC). Squall is moving with wind speed of 59 kmph from northerly direction at Safadarjung and that of Palam with 59 kmph but from easterly to southerly direction associated with DS. Blowing dust (BLDU) with wind was reported as weather and rain was also observed at that time. DWR Images shown in the figure 2 for the duration 0952 UTC to 1152 UTC depicts that, there is no echo in the radar image at the location of station (i.e. Safadarjung and Palam) at the time when squall was reported, nearest echo was around 80-90 km away from Delhi in North-West direction. Radar images also show that there an was echo having vertical extension up to 12 km with reflectivity (Max Z) 49-52 dBz at an approximate distance of 80 km from the observatory.

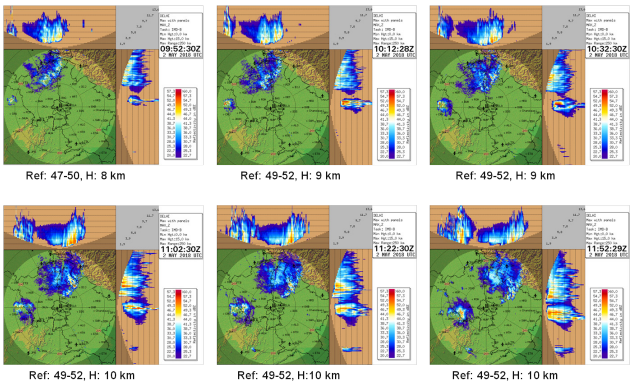

Figure 2. DWR images observed on 02 May 2018

Analysis of DWR images approximately one hour before (at 0952 UTC) depicts that nearest echo at this time was around 120-130 km away from the observatory in North-West direction having vertical extension up to 10 km with reflectivity (Max Z) 47-50 dBz. As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height was not much higher at that time it means less convection gives more dust at the surface. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching

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towards the observatory which further enhanced the wind speed and thus squall was reported at the observatory. This shows that squall (1115 UTC) over a station is reported, when a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension up to 10 km with reflectivity (Max Z) 47-50 dBz.

Thus, Synoptic analysis indicates that there was WD (western disturbance) as a trough in mid and upper tropospheric levels as well as the value CAPE is favorable for the development of TS/DS. Satellite analysis indicates that severe TS over Delhi NCR along with RADAR analysis which also indicates presence of severe TS. All these analysis shows that there was **intense TS** activity over Delhi NCR, which was reported in the weather report.

Thus TS/DS accompanied with the **squall** of speed 60 kmph (approx) is realised over Safderjung and Palam, when there is no echo at the observatory, however a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension **cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station (Figure 2).**

4.2 Case Study 2: (07 May 2018)

DS accompanied with squall of wind speed 70 kmph at Safadarjung and Palam was reported from north-westerly direction at 2303-2306 IST (1730 UTC) on 07 May 2018 (Table 3). Based on Synoptic condition, satellite images and Radar images, analysis was carried out.

Table 3. Observations at Safdarjung (SFD) and Palam (PLM) stations on 7 May 2018

Station	Speed of Squall (kmph)	Direction	Time Of occurrence of Squall (IST)	Maximum Reflectivity (dBz)	Maximum Height of convective cell (km)	Distance of station from maximum Reflectivity (km)	Weather	Rain (mm)	**Maximum Temperature (C)**
SFD	70	NW-W	2303-2306	47-50	9	70-80	Dust storm	3.4	36.2
PLM	70	NW-W	2303-2306	47-50	9	70-80	Dust storm	4.4	38.4

4.2.1 Synoptic Analysis

Figure 3 shows that on 07 May 2018 there was a Western Disturbance (WD) as a cyclonic circulation over Jammu and Kashmir and adjacent Himachal Pradesh at 3.1 km above MSL. Another WD was lying as an upper air cyclonic circulation over Pakistan and neighborhood at 3.1 km above MSL with the trough aloft at 5.8 km above MSL roughly running along 70°E to North of lat. 30°N. A trough extended from North-West Rajasthan to central Madhya Pradesh across NW Rajasthan at 0.9 km above MSL. Maximum temperature was recorded was 45.5°C at Phalodi (Rajasthan) on 7 May 2018. At 12UTC of 07 May 2018, CAPE value was 479 Joule /kg and CINE value was -33 Joule/kg. This indicates that atmosphere was unstable and favorable for development of TS.

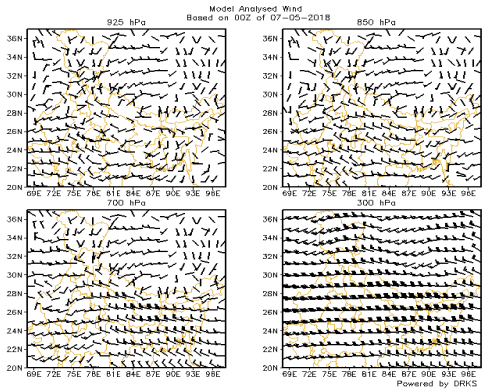

Figure 3. Wind pattern over Delhi region on 07 May 2018

4.2.2 Satellite Analysis

Table 4 depicts that on 07 May 2018 there was development of TS/DS around 2130 IST (16:00 UTC) in North West of Delhi. Satellite analysis shows that there was TS activity occurring over Delhi NCR region and moving from north-east of Delhi to south-westwards. Table 4 describes that the lowest cloud top temperature (CTT) of storm cell during this period was -50 degree Celsius at 23:00 IST indicating possibility of occurrence of moderate thunderstorm.

Table 4. Cloud Top Temperature (CTT) on 07 May 2018

Time of Thunderstorm (IST)	Direction of cloud patch	CTT (^{0}C)	Intensity of TS
2130	NE	-50	Moderate
2200	NE	-50	Moderate
2230	NE	-50	Moderate

4.2.3 RADAR Analysis

Table 3 describe that DS accompanied with squall of wind speed 70 kmph at Safdarjung and Palam was reported and winds were coming from north-westerly direction at 2303-2306 IST (1730 UTC) on 07 May 2018. Dust storm along with strong wind and rain was reported as weather and rain was also observed at that time. Radar images shown in the figure 4 for the duration (1602 UTC to 1832 UTC) depicts that there was no echo at the observatory when squall was reported nearest echo was at a approximate distance of 70 km from the observatory having vertical extension up to 10 km with reflectivity (Max Z) 47-50 dBz. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds

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also thunder storm was approaching towards the observatory. It further enhanced the wind speed and thus squall was reported at the observatory, when actual Thunder cell was 70-80 km away from observatory as per table 3 on 07 May 2018.

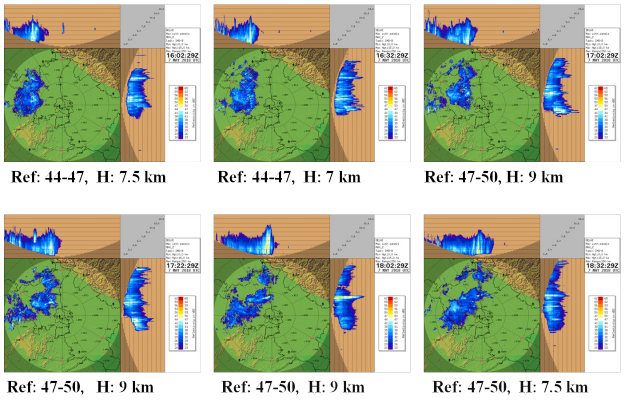

Figure 4. DWR images observed on 07 May 2018

Analysis of DWR images approximately one hour before (at 1602 UTC) depicts that nearest echo at this time was around 110-120 km away from the observatory in West North-West direction having vertical extension up to 7.5 km with reflectivity (Max Z) 44-47 dBz. As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height was not much higher at that time it means less convection gives more dust at the surface. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching towards the observatory which further enhanced the wind speed and thus squall was reported at the observatory. This shows that squall (1730 UTC) over a station is reported, when a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension up to 7.5 km with reflectivity (Max Z) 44-47 dBz.

Synoptic analysis indicates that there was WD (western disturbance) as a cyclonic circulation (CYCIR) with trough as well as the value CAPE is favorable for the development of TS/DS. Satellite analysis indicates that severe TS over Delhi NCR along with RADAR analysis which also indicates presence of severe TS. All these analysis shows that there was intense TS activity over Delhi NCR, which was reported in the weather report.

Thus TS/DS accompanied with the **squall** of speed 70 kmph (approx) is realised over Safderjung and Palam, when there is no echo at the observatory, however a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension **cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station (Figure 4).**

4.3 Case Study-3: (13 May 2018)

DS/TS accompanied with squall with wind speed 109 kmph (north- easterly) at Safadarjung and 96 kmph (North Easterly direction) at Palam was reported on 13 May 2018 at 1644-1646 IST (1115 UTC) and 1633-1634 IST (1105 UTC) as described in the Table 5. Based on Synoptic condition, satellite images and Radar images analysis is carried out here.

Table 5. Observations at Safderjung(SFD) and Palam (PLM) on 13 May 2018

Station	Speed of Squall (kmph)	Direction	Time Of occurrence of Squall (IST)	Maximum Reflectivity (dBz)	Maximum Height of convective cell (km)	Distance of station from maximum Reflectivity (km)	Weather	Rain (mm)	Maximum Temperature (^{0}C)
SFD	109	NE	1644-1646	57-60	11	Over the station	DS/TS	8.7	42.2
PLM	96	NE	1633-1634	57-60	11	Over the station	DS/TS	11.8	43.2

4.3.1 Synoptic Analysis

Figure 5 depicts that on 13 May 2018 there was WD lying as a cyclonic circulation (CYCIR) over Jammu and Kashmir and neighborhood at 3.1 km above MSL with trough aloft along long 74° E to the north of lat. 34° N. Another CYCIR lay over south Haryana and neighborhood and extended up to 0.9 km above MSL. The N-S trough ran from above CYCIR to Central Maharashtra across East Rajasthan and West Madhya Pradesh and extended up to 0.9 km above MSL. Another WD is also seen as a trough in mid-tropospheric westerly with its axis at 5.8 km above MSL ran along long 60 °E to the north of lat 30 °N. Maximum Temperature recorded over northwest India was 46.6 C at Bundi (Rajasthan). At 12 UTC of 13 May 2018 CAPE value was 2660 Joule/kg and CINE value was -316 Joule/kg. This indicates that atmosphere was unstable and favorable for development of severe TS.

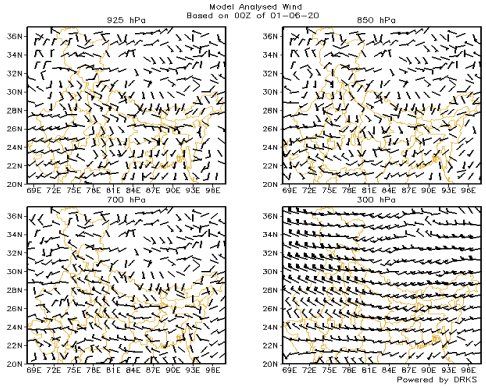

Figure 5. Wind pattern over Delhi region on 13 May 2018

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4.3.2 Satellite Analysis

Analysis based on satellite images for the duration 1630 IST to 1730 IST are shown in the table 6, depicts that on 13 May 2018 there was development and movement of intense TS/DS around 1630 IST (1100 UTC) in South to South-west of Delhi region.

Table 6. Cloud Top Temperature (CTT) on 13 May 2018

Time of Thunderstorm (IST)	Direction of cloud patch	CTT (^{0}C)	Intensity of TS
1630	SW	-30	-
1700	SW	-50	Moderate
1730	SW	-30	Moderate

Satellite analysis shown in the table 6 also depicts that there was TS activity occurring over Delhi NCR region and moving from south-west of Delhi to north-eastwards. Lowest cloud top temperature (CTT) of storm cell during this period was -50 degree Celsius at 17:00 IST. This indicates that there was possibility of occurrence of moderate thunderstorm.

4.3.3 RADAR Analysis

Table 5 shows that DS accompanied with squall with wind speed 109 kmph (North - easterly direction) at Safdarjung and 96 kmph (North-easterly direction) at Palam was reported on 13 May 2018 at 1644-1646 IST (1115 UTC) and 1633-1634 IST (1105 UTC). Analysis of the radar image shown in the figure 6 depicts that at the time of squall was reported, there is an echo having maximum reflectivity 57-60 dBz with vertical extension 11 km over the observatory.

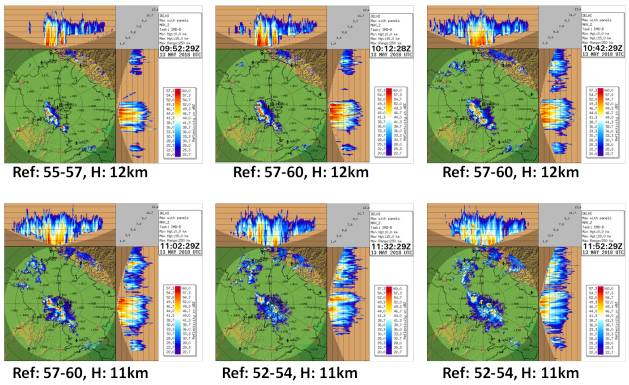

Figure 6. DWR images observed on 13 May 2018

Analysis of DWR images approximately one hour before (at 0952 UTC) depicts that nearest echo at this time was around 80-90 km away from the observatory in southwest direction having vertical extension up to 12 km with reflectivity (Max Z) 55-57 dBz. As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height was not much higher at that time it means less convection gives more dust at the surface. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching towards the observatory which further enhanced the wind speed and thus squall was reported at the observatory. This shows that squall (1105 UTC & 1115 UTC) over a station is reported, when a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension up to 12 km with reflectivity (Max Z) 55-57 dBz at a distance of 80-90 km in southwest direction.

Synoptic analysis indicates that there was WD (western disturbance) as a cyclonic circulation (CYCIR) with trough as well as the value of CAPE was favorable for the development of TS/DS. Satellite analysis indicates that severe TS over Delhi NCR along with RADAR analysis which also indicates presence of severe TS. All these analysis shows that there was intense TS activity over Delhi NCR.

Thus TS/DS accompanied with the **squall** of speed 109 and 96 kmph (approx) is realised over Safderjung and Palam respectively, when there is an echo present over the observatory, however a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension **cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station (Figure 6)**.

4.4 Case Study-4: (01 June 2018)

Table 7 describes that Dust Storm accompanied with squall having wind speed of 98 kmph at SFD with northerly to north- easterly direction and at 105 kmph at PLM also northerly direction was reported during 2012 IST-2014 IST (1440 UTC). Based on Synoptic condition, satellite images and Radar images analysis was carried out.

Table 7. Observations at Safderjung (SFD) and Palam (PLM) stations on 01 June 2018

Station	Speed of Squall (kmph)	Direction	Time of occurrence of Squall (IST)	Maximum Reflectivity (dBz)	Maximum Height of convective cell (km)	Distance of station from maximum Reflectivity (km)	Weather	**Rain (mm)**	**Maximum Temperature (^{0}C)**
SFD	98	N-NE	2012-2014 (1440 UTC)	49-52	12	70-75	HZ	0.7	42.1
PLM	105	N	2012-2014 (1440 UTC)	49-52	12	60-70	HZ	0.2	43.6

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4.4.1 Synoptic Analysis

Figure 7 depicts that on 01 June 2018, there was a WD as a cyclonic circulation (CYCIR) over central Pakistan and adjoining Punjab at 700 hPa and associated CYCIR was lying over central Pakistan and adjoining north-west Rajasthan extending up to 1.5 km above mean sea level (MSL). A trough ran through this CYCIR to northeast Jharkhand across north-east Rajasthan, south UP and south Bihar at 0.9 km above MSL. Another CYCIR lay over NE Rajasthan and neighborhood at 1.5 km above MSL. Maximum Temperature recorded over northwest India was 49.7 ^{0}C at Churu (Rajasthan). At 00UTC of 01 June 2018, CAPE value was 842 Joule /kg and CINE value was -418 Joule/kg. This indicates that atmosphere was unstable and favorable for development and occurrence of TS.

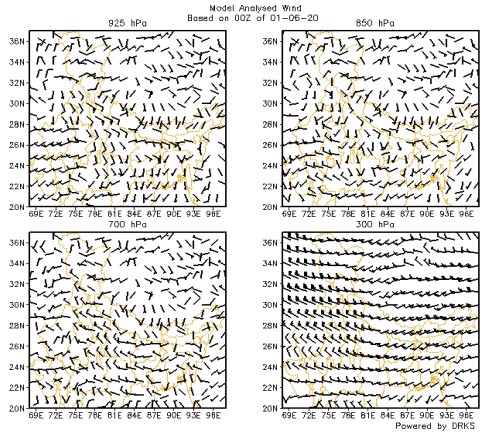

Figure 7. Wind pattern over Delhi region on 01 June 2018

4.4.2 Satellite Analysis

Table 8 depicts that TS/DS started developing around 2010 IST (1440 UTC) in North of Delhi and adjoining regions. Satellite analysis (Table 8) illustrate that there was TS activity occurring over Delhi NCR region and moving from north of Delhi to south-eastwards. Lowest cloud top temperature (CTT) of storm cell during this period was -80 degree Celsius at 20:00 IST. This indicates that there was very good chances of occurrence of severe thunderstorm.

Table 8. Cloud Top Temperature (CTT) on 01 June 2018

Time of Thunderstorm (IST)	Direction of cloud patch	CTT (^{0}C)	Intensity of TS
1930	N	-50	Moderate
2000	N	-80	Severe
2030	NW	-50	Moderate

4.4.3 RADAR Analysis

Table 7 shows that Dust storm accompanied with squall (wind speed of 98 kmph recorded at Safadarjung from northerly to north- easterly direction and 105 kmph recorded at Palam from northerly direction) was reported at 1440 UTC (2012- 2014 IST). RADAR images shown in the figure 8 at the time of occurrence of squall depicts that there was no echo over the location of station on radar (i.e. Safadarjung and Palam observatory), nearest echo was at a approximate distance of 70 km from the observatory having vertical extension up to 11 km with reflectivity (Max Z) 52-54 dBz to the north of Delhi. In fact for this case thunder cell never touched the Safdarjung and Palam observatory during the course of its movement.

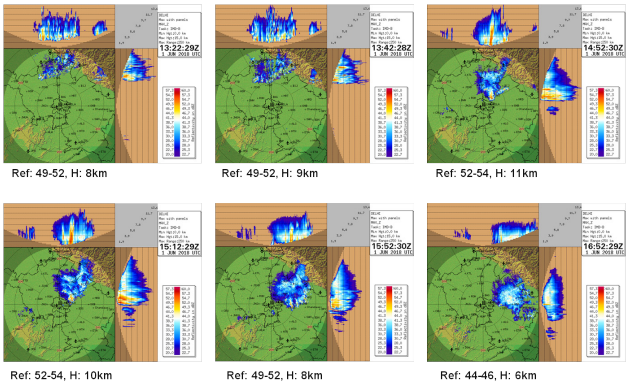

Figure 8. DWR images observed on 01 June 2018

Analysis of DWR images approximately one hour before (at 13:22 UTC) depicts that nearest echo at this time was around 150 km away from the observatory in North-West direction having vertical extension up to 8 km with reflectivity (Max Z) 49-52 dBz. This thunder cell continues to move southeastwards and figure 8 depict that at 13:42 UTC there was an echo around 120 km having vertical extension up to 9 km with reflectivity (Max Z) 49-52 dBz in northwest of Delhi. As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height was not much higher at that time it means less convection gives more dust at the surface. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching towards the observatory which further enhanced the wind speed and thus squall was reported at the observatory. This shows that squall is reported over Delhi at 1440 IST (2010 UTC), when a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension up to 8 km with reflectivity (Max Z) 49-52 dBz.

Synoptic analysis indicates that there was WD (western disturbance) as a cyclonic circulation (CYCIR) with

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trough as well as the value of CAPE was favorable for the development of TS/DS. Satellite analysis indicates that severe TS over Delhi NCR along with RADAR analysis which also indicates presence of severe TS. All these analysis shows that there was intense TS activity over Delhi NCR.

Thus TS/DS accompanied with the **squall** of speed 98 and 105 kmph (approx) is realised over Safderjung and Palam respectively, when there is an echo present over the observatory, however a thunder cell is present in the previous images of radar (1-2 hour before) with vertical extension **cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station (Figure 8).**

4.5 Case Study 5: (09 June 2018)

Table 9 depicts that DS/TS accompanied with rain and squall was reported at 1711-1713 IST at safderjung and at 1715-1717 IST at Palam. Squall having wind speed 96 kmph from westerly direction at Safdarjung observatory and that of 104 kmph at Palam observatory from north westerly to westerly direction is reported at that time. Based on Synoptic condition, satellite images and Radar images analysis is carried out.

Table 9. Observations at Safderjung (SFD) and Palam (PLM) stations on 09 June 2018

Station	Speed of Squall (kmph)	Direction	Time of occurrence of Squall (IST)	Maximum Reflectivity (dBz)	Maximum Height of convective cell (km)	Distance of station from maximum Reflectivity (km)	Weather	Rain (mm)	Maximum Temperature (^{0}C)
SFD	96	W	1715-1717	52-54	13	70-80	Gust	6.5	40.5
PLM	104	NW-W	1711-1713	52-54	13	70-80	Gust	8.9	42.1

4.5.1 Synoptic Analysis

Figure 9 shows that on 09 June 2018 there was a WD lying as a cyclonic circulation (CYCIR) over north Pakistan and adjoining Jammu & Kashmir at 700 hPa and associated CYCIR was lying over central Pakistan and adjoining north-west Rajasthan extending up to 1.5 km above mean sea level (MSL). There was a east-west trough extending from Punjab to Gangetic west Bengal and extending up to 1.5 km above MSL. Maximum Temperature recorded over northwest India was 44.6 ^{0}C at Churu (Rajasthan). At 12 UTC of 09 June 2018 CAPE value was 2624 Joule/kg and CINE value was -97 Joule/kg. This indicates that atmosphere was very unstable and favorable for development of TS.

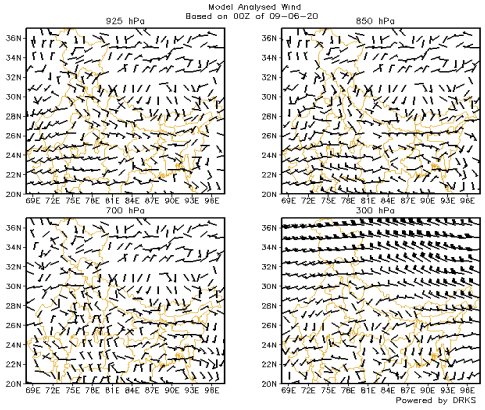

Figure 9. Wind pattern over Delhi region on 09 June 2018

4.5.2 Satellite Analysis

DS/TS started developing around 16:00 IST (10:30 UTC) in North-West of Delhi and its adjoining regions. Satellites analysis (Table 14) shows fully developed clouds associated with thunderstorm has covered most part of Punjab, Haryana and north Rajasthan during 16:30 IST -17:30 IST. Satellite analysis (Table 10) shows that there was TS activity was occurring over Delhi NCR region and moving from north of Delhi to south-eastwards. Lowest cloud top temperature (CTT) of storm cell during this period was -80 degree Celsius during 16:30 IST to 17:30 IST. This indicates that there was very high possibility of occurrence of severe thunderstorm over Delhi NCR.

Table 10. Cloud Top Temperature (CTT) on 09 June 2018

Time of Thunderstorm (IST)	Direction of cloud patch	CTT (^{0}C)	Intensity of TS
1630	NW	-80	Severe
1700	NW	-80	Severe
1730	NW	-80	Severe

4.5.3 RADAR Analysis

On 09 June 2018, Dust storm (DS) accompanied with squall was reported at 1715 -1717 IST (11:45 UTC). Squall was reported with wind speed 96 kmph from westerly direction at Safdarjung and that of 104 kmph at Palam observatory, with wind from north westerly to westerly direction. Gusty winds, squall and thundering associated with DS was reported (Table 9). In this case when squall is reported, figure 10 depicts that there is an echo overhead at the observatory (Safadarjung and Palam) with reflectivity (Max Z) 52-54 dBz with vertical extension up to 13 km.

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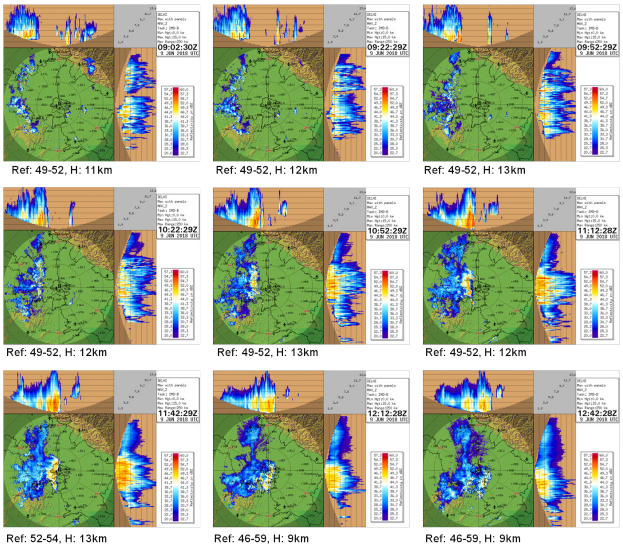

Figure 10. DWR images observed on 09 June 2018

Analysis of DWR images approximately one-two hour before (from 09:02 UTC onwards) depicts that at 1430 IST **(09:02 UTC)** nearest north-south oriented echo was around 170-180 km away from the observatory in West direction having vertical extension up to 12 km with reflectivity (Max Z) 49-52 dBz. This thunder cell continues to move eastwards towards Delhi and figure 10 depict that at 1550 IST **(10:22 UTC)** system intensified in to squall line and was around 100 km having vertical extension up to 12 km with reflectivity (Max Z) 49-52 dBz towards west of Delhi. The squall line continues to move further eastwards and was over head at the observatories (Safadarjung and Palam) at 1712 IST (1142 UTC) with reflectivity (Max Z) 52-54 dBz with vertical extension up to 13 km. At this time squall (96 and 104 kmph) was reported. The squall line continues to move eastwards and crossed Delhi around 1812 IST (1242 UTC). As the squall and DS are mostly associated with the downdraft of any thunder cell or clouds, as the cloud's height in this case very heigh i.e. 12 km right from the beginning at 0902 UTC and there was very high convection, which has given more dust as well as light rainfall at the surface. There is both updraft and downdraft accompanied with TS and downdraft associated with strong gusty winds, also thunder storm was approaching towards the observatory which further enhanced the wind speed and thus squall was reported at the observatory. In this case squall as well as squall line simultaneously affected both the stations. This shows that squall is reported over Delhi at 1712 IST (1142 UTC), when a thunder cell is present in the previous images of radar (2 hour before) with vertical extension up to 12 km with reflectivity (Max Z) 49-52 dBz.

Synoptic analysis indicates that there was a trough as well as the value CAPE is favorable for the development of TS/DS. Satellite analysis indicates that severe TS over Delhi NCR along with RADAR analysis which also indicates presence of severe TS. All these analysis shows that there was intense TS activity over Delhi NCR.

Thus TS/DS accompanied with the **squall** of speed 96 and 104 kmph (approx) is realised over Safderjung and Palam respectively, there is an intense convective cell is present over the observatory, however analysis shows that a thunder cell is present in the previous images of radar (2 hour before) with vertical extension **cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station (Figure 10).**

Thus table 11 depicts that the **criteria fixed / chosen in Methodology (section 3) for squall (speed >55) is fulfilled in all the cases. Analysis of all the five cases illustrates that Squally winds of the order of 55 kmph or more will effect a station if a thunderstorm (having Max Z echo with vertical extension of cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station) moving towards station is present in one to two hour before images of Doppler Weather Radar.**

Table 11. Testing of criteria fixed / chosen in Methodology (section 3) for squall (speed >60)

S. No	Date of Squall over Delhi	Presence of WD	East-West trough from North-west Rajasthan upto East UP through south Haryana	Temperature 40 (approx) degree Celsius over the nearby area	Presence of a Thunder cell in the previous images of DWR (1-2 hour before)	Distance of Thunder cell should be (100 - 150 km) from the station	Direction of movement of Thunder cell (towards or away) from the station	**Vertical height of thunder cell >7 km**	**Maximum Reflectivity (at 1 km height) >45 dBz**	**Remarks/ Speed of observed squally winds (kmph)**
1	02 May 2018	Yes	Yes	Yes, Bundi (47.7 degrees)	yes	Yes 120-130	Towards station	Yes, 10 km	Yes, 47-50 dBz	All criteria fulfilled SFD 59 PLM 59
2	07 May 2018	Yes	Yes	Yes, Phalodi (45.5 degrees)	yes	Yes 110-120	Towards station	Yes, 7.5 km	Yes, 44-47 dBz	All criteria fulfilled SFD 70 PLM 70
3	13 May 2018	Yes	Yes	Yes, Bundi (46.6 degrees)	yes	Yes 80-90	Towards station	Yes, 12 km	Yes, 55-57 dBz	All criteria fulfilled SFD 109 PLM 96
4	01 June 2018	Yes	Yes	Yes, Churu (49.7 degrees)	yes	Yes 140-150	Towards station	Yes, 8 km	Yes, 49-52 dBz	All criteria fulfilled SFD 98 PLM 105

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5	09 June 2018	Yes	Yes	Yes, Churu (44.6 degrees)	yes	Yes 170-180	To-wards station	Yes, 12 km	Yes, 49-52 dBz	All criteria fulfilled SFD 96 PLM 104

5. Conclusions

Based on the analysis carried out on five pre monsoon thunderstorm weather events and testing of criteria fixed to nowcast squally winds (>55 kmph) as depicted in the Table 11; a Thumb rule is find out:

(1) Squally winds of the order of 55 kmph or more will effect a station if a thunderstorm (having Max Z echo with vertical extension of cell >7 km, reflectivity >45 dBz and at a distance of more than 100 km from the station) moving towards station is present in one to two hour before images of Doppler Weather Radar.

(2) It is also concluded that following synoptic condition are also present in all the cases and are very conducive for occurrence of squally winds accompanied with thunderstorms (i) A western disturbance (WD) (ii) East-West trough from North-west Rajasthan upto East UP through south Haryana (iii) Very high temperature of the order of 40 degree Celsius over the nearby area.

Above mentioned thumb rule in association with the synoptic conditions can be used to nowscast the strong squally winds associated with severe TS at least 1-2 hours in advance. Such type of nowcast are very useful for Public, aviation services, Sport events, Rail & road transport services and power sectors, etc

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