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Severe dust storm/thunderstorm activity over Uttar Pradesh on 13th May, 2018 - A case study

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सार – उत्तर प्रदेश में मॉनसून पूर्व ऋतु में गरज के साथ वर्षा, धूल भरी आँधी, तूफानी हवाएँ और ओलावृष्टि आदि की अधिकता होती है। ये तूफान आमतौर पर संवहन और नमी अभिसरण के साथ स्थानीय रूप से विकसित होते हैं और डॉपलर मौसम रेडार में एकल कोशिकाओं के रूप में देखे जाते हैं, लेकिन येगर्ज के साथ तूफान कभी-कभी आते हैं। सिनॉप्टिक स्केल सिस्टम जैसे चक्रवाती परिसंचरण/ट्रफ के रूप में पश्चिमी विक्षोभ, कम/चक्रवाती परिसंचरण या उत्तर-पश्चिम-दक्षिणपूर्व उन्मुख गर्त से जुड़े होते हैं जिससे इन तूफानों की स्थानिक सीमा और गंभीरता में काफी वृद्धि होती है। इस शोध पत्र में, 13 मई 2018 को राज्य में बड़े पैमाने पर हुई धूल भरी आँधी/तूफान गतिविधि का विश्लेषण किया गया है, जिसमें उत्तर प्रदेश में 49 से अधिक मनुष्यों और बड़ी संख्या में पशुधन की मृत्यु हो गई। इस अध्ययन का उद्देश्य इस गतिविधि के संभावित गतिशील और थर्मोडायनामिक पहलुओं का पता लगाना था। अध्ययन से पता चलता है कि उच्च अधिकतम तापमान (>40 °C), उच्च CAPE (>1000), अधिकतम योग का कुल सूचकांक (>50) और उच्च नकारात्मक लिफ्टेड सूचकांक मान (<-5) पश्चिमोत्तर भारत के अधिकांश मैदानी भाग में थाजो प्रचंड तूफान गतिविधि के लिए पर्यावरण थर्मोडायनामिक रूप से अत्यधिक अनुकूल था। दक्षिण उत्तर प्रदेश में नमी असंतुलन रेखा स्पष्ट रूप से देखी गई और इसके उत्तर में नमी की मात्रा अधिक रही। इसके अलावा 0000 UTC GFS द्वारा दिन में 925 hPa पर हवा के विश्लेषण से उत्तर प्रदेश में 30-35 नॉट्स के क्रम की प्रबल दक्षिण-पूर्वी हवाओं का संकेत मिला, जिसके परिणाम स्वरूप इस क्षेत्र के निचले स्तर में अधिक नमी का प्रवेश हुआ। निम्न स्तर का विंड शीयर भी अधिक था और यह लगभग 25-30 नॉट्स था जैसा कि व्योमिंग साइट से दिन के 1200 UTC के लिए लखनऊ के स्क्यू-टी ग्राम से स्पष्ट है और साथ ही 13 मई, 2018 को ECMWF के ERA अंतरिम दैनिक डेटा का उपयोग करके 1200 UTC के विंड शीयर का विश्लेषण किया गया था। ये विशेषताएँ सिनॉप्टिक स्थितियों के साथ मिलकर; मध्य और ऊपरी स्तरों पर पश्चिमी विक्षोभ (डब्ल्यूडी) और दक्षिण हरियाणा एवं आसपास के क्षेत्र में एक चक्रवाती परिसंचरण (साइक्लोनिक सर्कुलेशन) के साथ-साथ निचले स्तरों में इस चक्रवाती परिसंचरण से फैली एक पूर्व-पश्चिमी ट्रफ ने इस क्षेत्र में प्रचंड गर्ज के साथ तूफान वाली गतिविधि के लिए वातावरण को अत्यधिक अनुकूल बना दिया।

ABSTRACT. Pre-monsoon season over Uttar Pradesh is characterized with thunderstorms accompanied with rain, dust storms, gale winds and hail storms etc. These storms generally develop locally in association with convection and moisture convergence and seen as single cells in Doppler Weather Radar, but sometime these thunderstorms are associated with synoptic scale systems, *viz*., Western Disturbance as cyclonic circulation/trough, induced low/cyclonic circulation or northwest-southeast oriented trough, thereby increasing the spatial extent and severity of these thunderstorms significantly. In the present study, Duststorm/Thunderstorm activity that occurred over the state on large scale on 13th May, 2018 and which claimed more than 49 human lives and large number of livestock in Uttar Pradesh has been analyzed. The purpose of this study was to find out probable dynamic and thermodynamic aspects of this activity. The study indicates that the environment was highly favourable thermodynamically for severe thunderstorm activity with high maximum temperatures (>40 °C), high CAPE (>1000), high Total Total Index (>50) and high negative Lifted Index values (<-5) over most parts of the northwest Indian plains. The moisture discontinuity line was clearly noticed over south Uttar Pradesh with high moisture contents towards its north. Also 0000 UTC GFS wind analysis of the day at 925 hPa indicated strong southeasterlies of the order of 30-35 kts over Uttar Pradesh resulting high moisture incursion in the lower levels over this region. The Low level wind shear was also high and was about 25-30 kt as evident from Skew-T gram of Lucknow for 1200 UTC of the day taken from Wyoming site as well as 1200 UTC wind shear analysis using ERA Interim daily data of ECMWF on 13th May, 2018. These features together with synoptic conditions, *viz*.; Western Disturbance (WD) in mid and upper levels and a Cyclonic Circulation (cycir) over south Haryana & neighbourhood as well as an east-west trough extending from this cycir in the lower levels made the environment highly favourable for severe thunderstorm activity over the region.

Key words – Western Disturbance, Doppler Weather Radar (DWR), Convective Available Potential Energy (CAPE), Sub-Tropical Westerly Jet (STWJ).

1. Introduction

Thunderstorms are more common weather phenomena over the state in pre-monsoon season. Thunderstorms during the pre-monsoon season (March to June) help ameliorate high surface temperatures over this region during this season. However in recent years, a few thunderstorms left a trail of destruction which will be remembered for years. Some of the thunderstorms are very destructive and are associated with duststorms, gale winds, lightening, hailstorms and occasionally heavy rain. Loss of human lives and livestock as well as damage to crops worth millions of rupees are associated with these severe weather events.

March, April and May months are categorized as Pre-Monsoon season. Northward movement of sun increases the solar insolation & results into gradual rise of surface temperatures from the month of March which continues till onset of pre-monsoon showers in the month of June. Intense heating over the state occurs in the second fortnight of April and entire May when the maximum temperatures more than 40 °C continuously persist for many days in different pockets of the Uttar Pradesh and adjoining states. Heating of the land create convection, which is an important factor for the formation of thunderstorms.

2. Data used

Uttar Pradesh has a network of 12 departmental and 18 part time observatories situated over different parts of the state (Fig. 1). Departmental observatories are run by staff and officers of India Meteorological Department whereas part time observatories are run with the coordination of state government staff. These observatories record synoptic observations at different synoptic hours and transmit to Meteorological Centre Lucknow. In addition to these observatories, data of two Indian Air Force observatories *viz*., IAF Agra and IAF Chakeri (Kanpur) are also received at Met Centre. For present study, thunderstorm data received from these 30 observatories have been used. Since, it is difficult to record all dust storms/thunderstorms by existing low density network, so rainfall received from raingauges installed in various tehsils under control of Uttar Pradesh Government have also been utilized as an evidence of current weather phenomena under study. Daily rainfall is collected from the tehsil offices at Meteorological Centre. To maintain the quality of the data these stations are inspected periodically by MC Lucknow staff.

The primary tools for detecting convective storms are weather radar, lightning detectors and satellite imagery (Ray *et al*., 2017). Due to insufficient observational network, reporting of all events of Squalls,

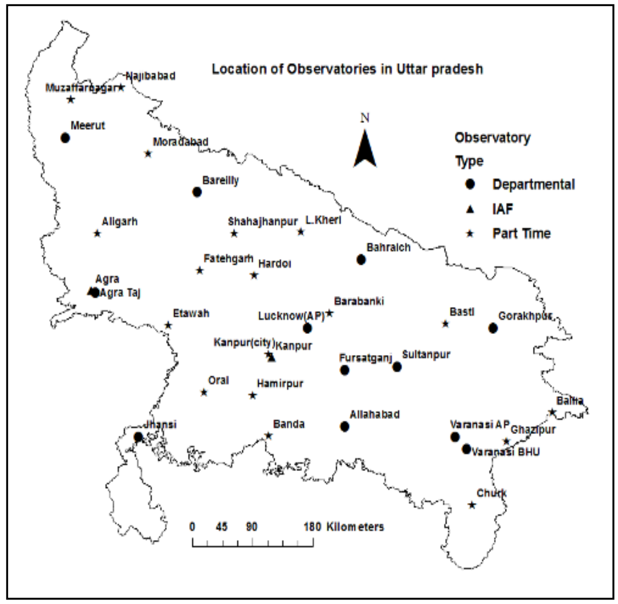


Fig. 1. Observational Network in Uttar Pradesh

Gale winds, Hailstorms etc. is almost impossible. To ensure proper reporting of all thunderstorm occurrences for both operational and climatological point of view, it was suggested by Ajit Tyagi (2007) to establish at least one full time current weather observatory in each district. However, Doppler Weather Radar (DWR) helps monitor the formation and movement of Thunderstorms. Uttar Pradesh has one S-band DWR installed at Lucknow. But due to Earth curvature effect, its effective range is limited to 250 km around the radar location. Augmentation of more Doppler Weather Radars in the state will be very helpful in monitoring of Thunderstorms and thus issue warnings more precisely.

Cloud CT-BT images obtained from SATMET division at IMD HQ New Delhi, DWR data of Lucknow, the gridded rainfall data at the resolution of 0.25° × 0.25° Lat./Long. based on rain gauge observational network of the India Meteorological Department (Rajeevan *et al*., 2005) are used for comparison of spatial distribution of convective rainfall. ERA Daily Interim reanalysis data of ECMWF (https://apps.ecmwf.int/datasets/) have also been used for preparing Convective Available Potential Energy (CAPE) and other thermodynamic map at 1200 UTC. Raw data was downloaded from these websites and customized maps for area of our interest have been prepared. Grid Analysis and Display system (GrADS) software has been used for preparing different maps. RS/RW data from University of Wyoming website (http://www.weather.uwyo.edu/) was used for getting different thermodynamic indices.

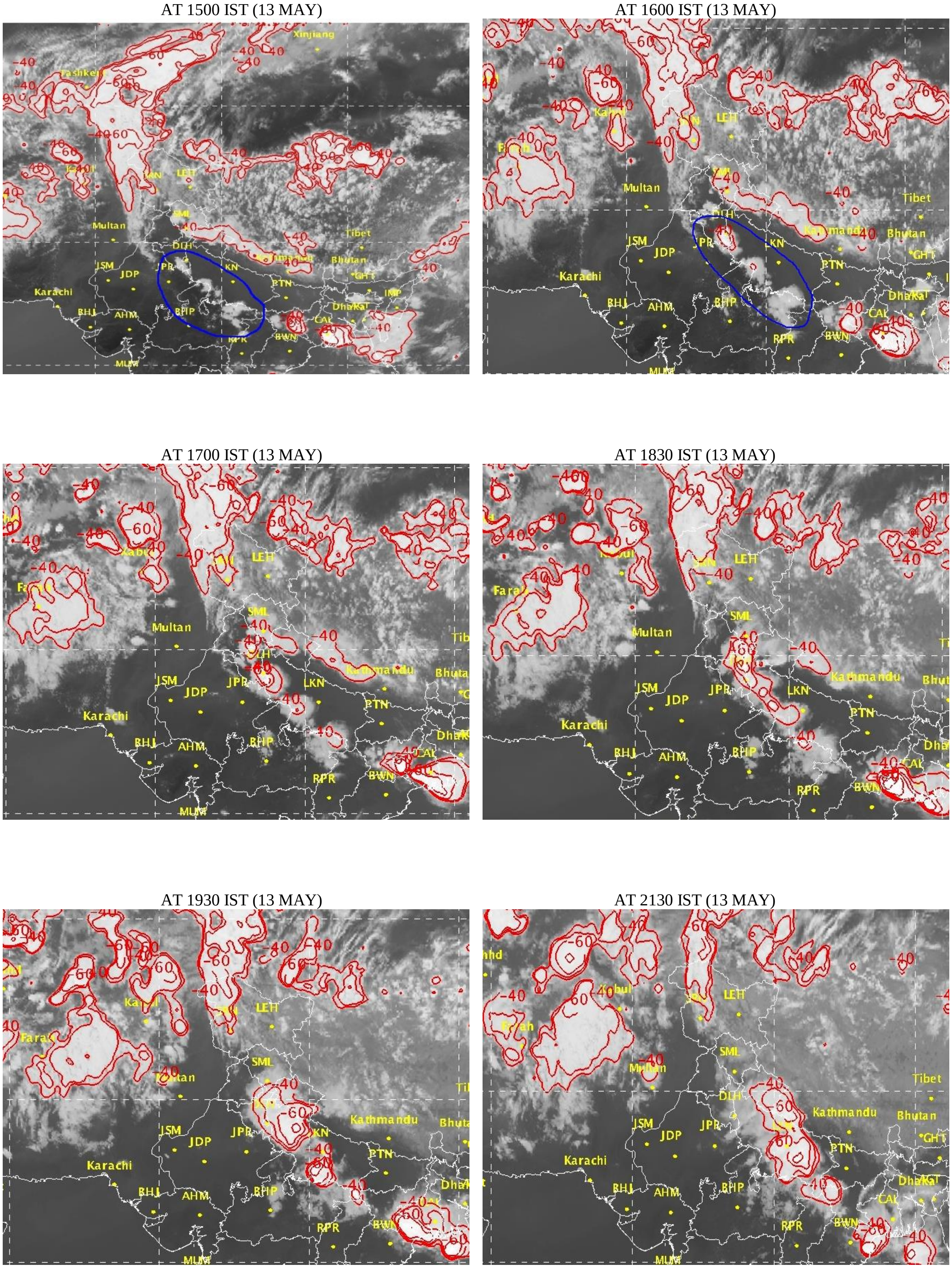
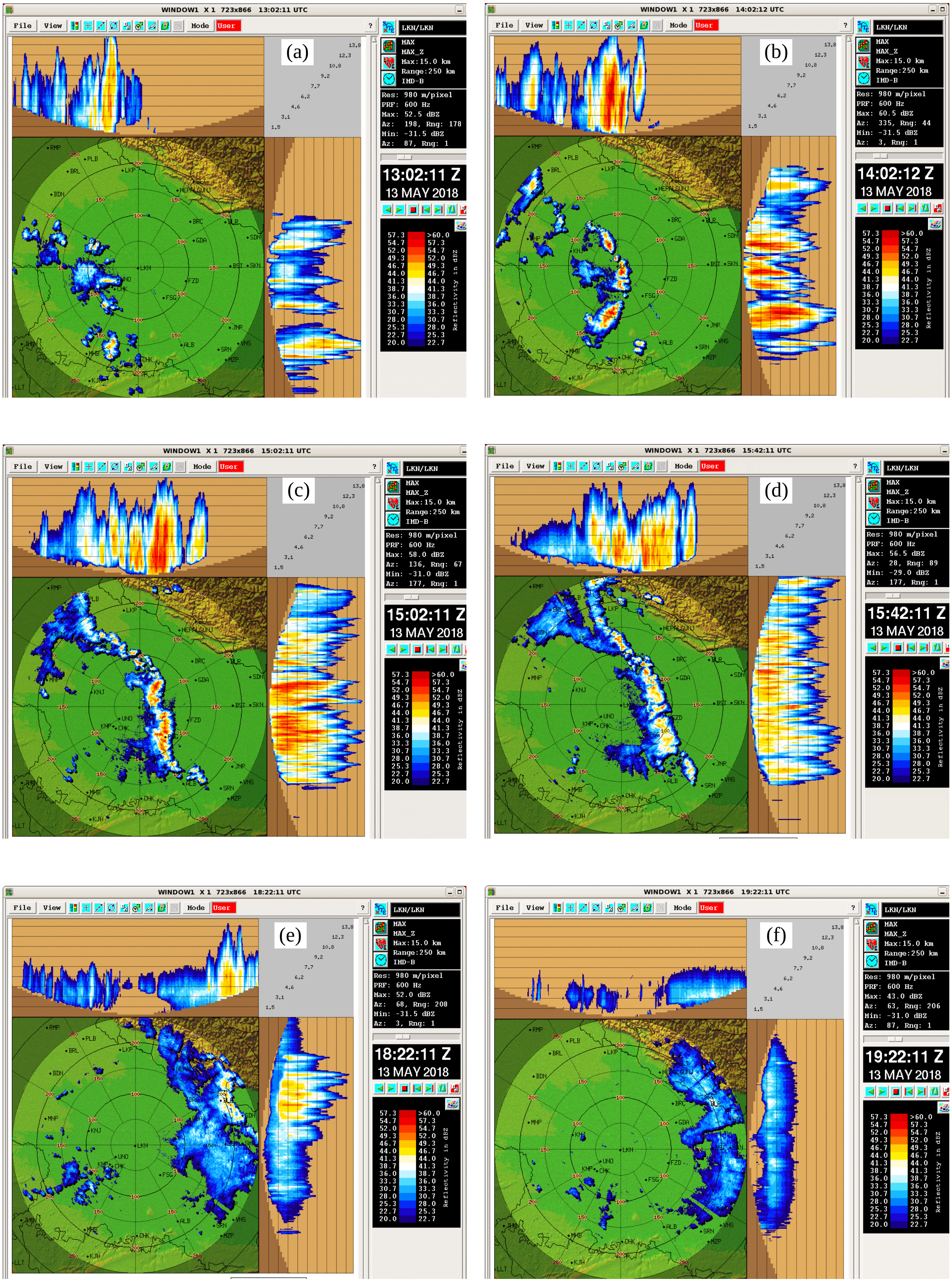
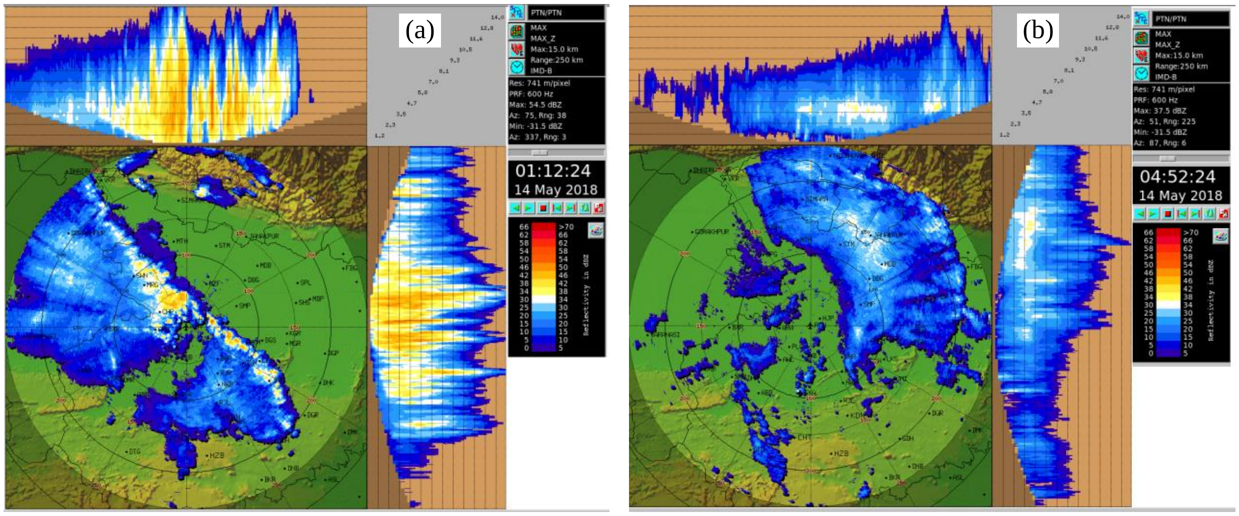


Fig. 2. CT-BT image at different hours on 13[th] May, 2018



Figs. 3(a-f). Squall line movement captured by DWR Lucknow at different times in sequence (all times in UTC)



Figs. 4(a & b). Squall line movement captured by DWR Patna at different times in sequence (all times in UTC)

Uttar Pradesh is divided into two met sub-divisions, *viz*., East Uttar Pradesh and West Uttar Pradesh. As per WMO definition "One or more sudden electrical discharges, manifested by a flash of light (lightning) and a sharp or rumbling sound (thunder)" is known as Thunderstorm. A day on which at least one thunderstorm event is observed at any station is considered as a thunderstorm day. In East Uttar Pradesh respectively 7, 9 & 19 Thunderstorm days were reported in March, April and May where as in West Uttar Pradesh 2, 12 and 16 Thunderstorm days were reported respectively in March, April and May, in 2018.

3. Results and discussion

3.1. *Satellite data (CT-BT) Image analysis*

Northwest-Southeast oriented convective clouds (Fig. 2), passing though Uttar Pradesh, in association with Western Disturbance over North Pakistan and neighbourhood were seen at 1500 IST along the trough. Three cloud accumulation centers, which later on proven very disastrous, were observed. These were over (*i*) South Haryana & adjoining areas of northeast Rajasthan-southwest Uttar Pradesh, *i.e*., close to cyclonic circulation over south Haryana (*ii*) West Uttar Pradesh and adjoining areas of north Madhya Pradesh and (*iii*) northeast Madhya Pradesh and adjoining areas of southeast Uttar Pradesh. The later two were associated with trough extending from south Haryana to Chhattisgarh. First one intensified faster as compared to other two and at 1600 IST Cloud Top-Brightness Temperature (CT-BT) of first cluster was -40 °C or less. Thereafter rapid intensification of all three clusters was noticed. Moving northeastwards first two clusters merged with convective cloud clusters that moved from Himachal Pradesh and Uttarakhand resulting in a large area of intense convection over West and Central Uttar Pradesh at 1930 IST with lowest CT-BT of -60 °C. It continued to moves northeastward producing duststorms, lightening, squalls, light to moderate rain and hailstorms in the track of its movement. Heavy rainfall of 104.0 mm was recorded at Baheri Tehsil in Bareilly district and Hailstorm was reported at Varanasi (Airport) from 1720-1735 IST of the day.

It further moved northeastwards and disappeared completely from the state in the morning 0500 IST of 14th May, 2018.

3.2. *Doppler Weather Radar (DWR) data analysis*

Thunderstorm activity on 13-14 May, 2018 over the state was a synoptic scale activity which was directly associated with northeastward movement of Western Disturbance over north Pakistan and a trough from cyclonic circulation over south-Haryana to Chhattisgarh. The development of clouds were seen along these systems and were visible in CTBT satellite imageries as discussed above. Thunderstorms affected Uttar Pradesh in addition to many other states of India as discussed in para 3.1. DWR is an important tool for monitoring of thunderstorm formation, intensity and its expected movement. In present study DWR data of Lucknow and Patna have been utilized.

3.2.1. *Maximum Reflectivity (Max_Z)*

(*a*) *DWR Lucknow observation*

(*i*) Multiple thunderstorm cells of Max_Z more than 40 to 50 dBz and height up to 15 km were captured

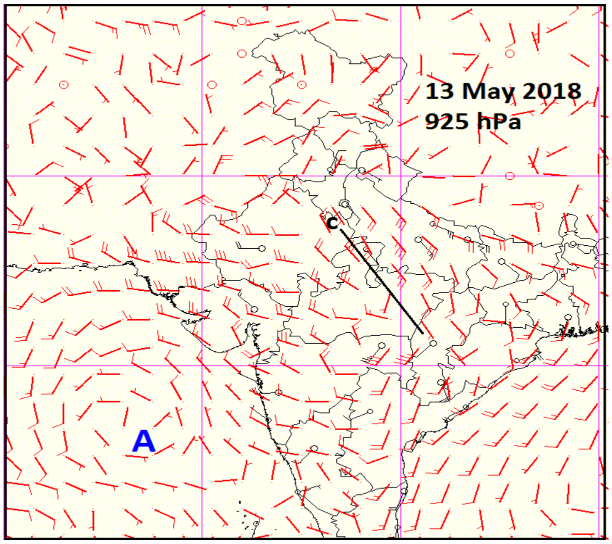


Fig. 5. 925 hPa GFS analysis wind at 0000 UTC of 13th May, 2018

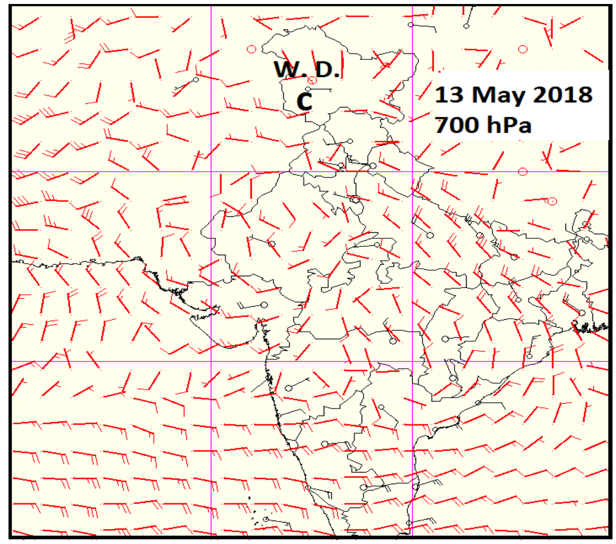


Fig. 7. 700 hPa GFS analysis wind at 0000 UTC of 13th May, 2018

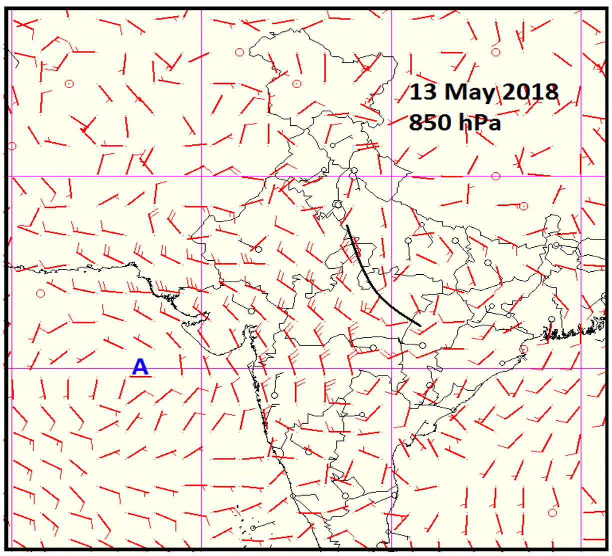


Fig. 6. 850 hPa GFS analysis wind at 0000 UTC of 13th May, 2018

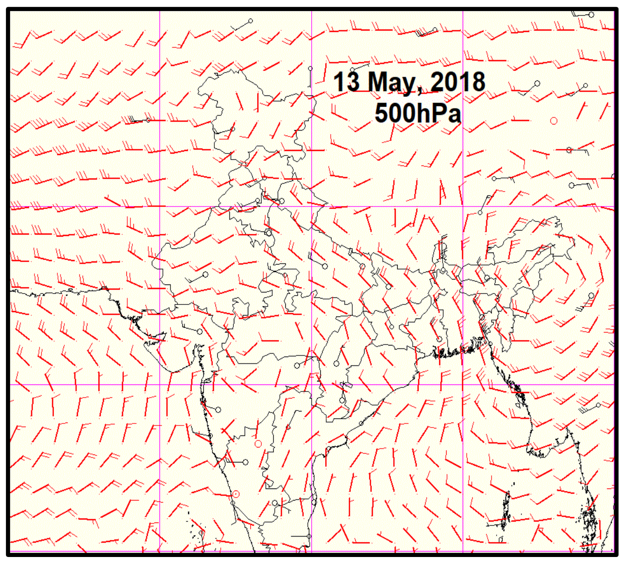


Fig. 8. 500 hPA GFS analysis wind at 0000 UTC of 13th May, 2018

in southwest to northwest sector of DWR Lucknow at 1302 UTC [Fig. 3(a)].

Hocker & Basara (2008) in their study of spatial climatology of squall line storms across Oklahoma suggested the following criteria of squall line:

(*i*) length of 50 km or greater

(*ii*) length to width ratio of at least 5:1

(*iii*) persist for 30 minute or more

(*iv*) squall line initiation based on first occurrence of necessary length and length to width ratio.

(*v*) squall line termination occurs when any criteria failed.

Moving in northeast direction these cells became organized and formed a bow shaped squall line fulfilling the above conditions at 1502 UTC when Max_Z was 55 dBZ or more and height was 15 km or more.

(*ii*) These thunderstorm cells disappeared from the range of DWR Lucknow by 1922 UTC [Figs. 3(b-f)].

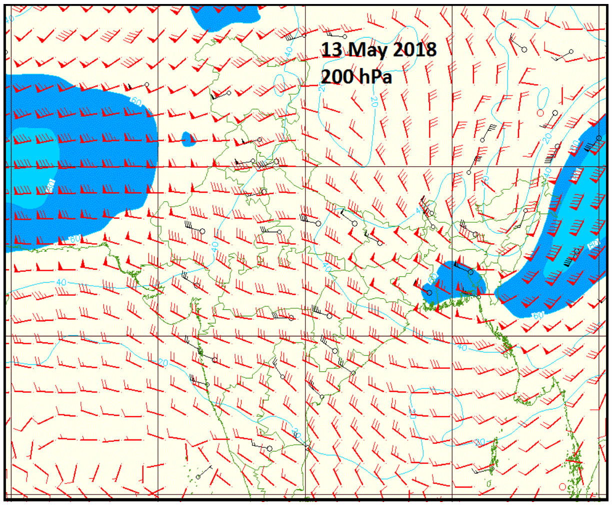


Fig. 9. 200 hPa GFS analysis wind at 0000 UTC of 13th May, 2018

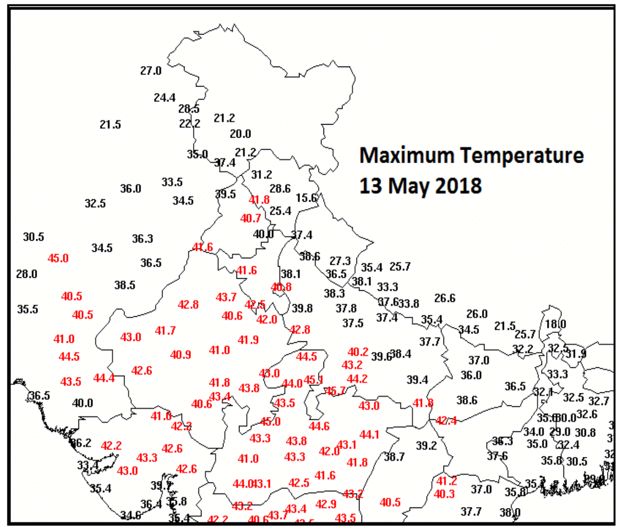


Fig. 11. Maximum temperature on 13th May, 2018

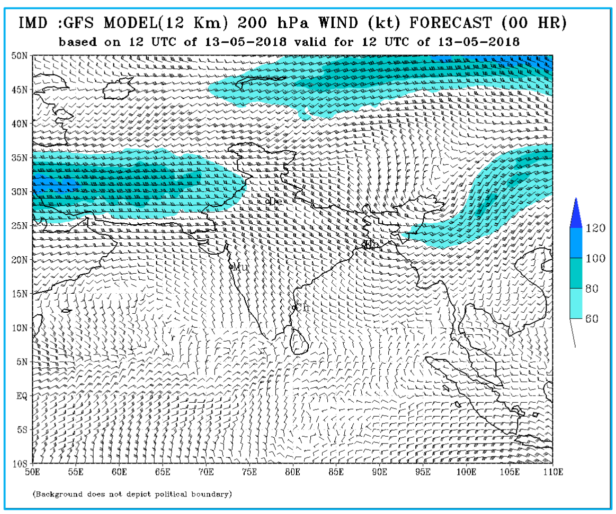


Fig. 10. 200 hPa GFS analysis wind at 1200 UTC of 13th May, 2018

(*iii*) The same were captured by DWR Patna as squall line [Fig. 4(a)] at 0112 UTC of 14th May, 2018 which continued to move northeastwards close to foothills of Himalayas with decreasing intensity as is evident from Fig. 4(b).

Duststorms/Squalls/Thunderstorms with rain were observed over most parts of south Uttar Pradesh. Rainfall recorded was up to 5 cm. Due to the movement of these devastating severe thunderstorms though the state more than forty nine people and large number of animals and birds lost their lives and properties worth millions of Rupees were damaged.

3.3. *Thermodynamic and Dynamic Conditions*

Before discussing the various thermodynamic and dynamic aspects associated with the severe thunderstorm activity over the state on the day, it is better to have a look on the synoptic conditions prevailing over north India on that day. Fig. 5 to Fig. 9 show actual wind over laid on GFS model analysis wind at 0000 UTC of 13th May. 2018 at different atmospheric levels, *viz*., 925, 850, 700, 500 and 200 hPa and Fig. 10 shows 12UTC GFS analysis wind at 200 hPa. Following synoptic systems were identified;

(*i*) The Western Disturbance as a cyclonic circulation over Jammu & Kashmir and neighbourhood at 3.1 km above mean sea level with a trough aloft along Long. 74° E to the north of Lat. 34° N.

(*ii*) A cyclonic circulation over south Haryana and neighbourhood and extending upto 0.9 km above mean sea level.

(*iii*) A trough from above cyclonic circulation over south Haryana to Chhattisgarh through East Rajasthan, Southwest Uttar Pradesh and East Madhya Pradesh extending upto 1.5 km above mean sea level.

(*iv*) An anticyclone over Arabian Sea extending upto 1.5 km above mean sea level. Sub-Tropical Westerly Jet (STWJ) stream with jet core centered around 30° N and 62° E is seen at 200 hPa, *i.e.*, west of Indian region. Another branch of jet stream is noticed over South Bangladesh adjoining Gangetic West Bengal with increasing wind speed eastwards.

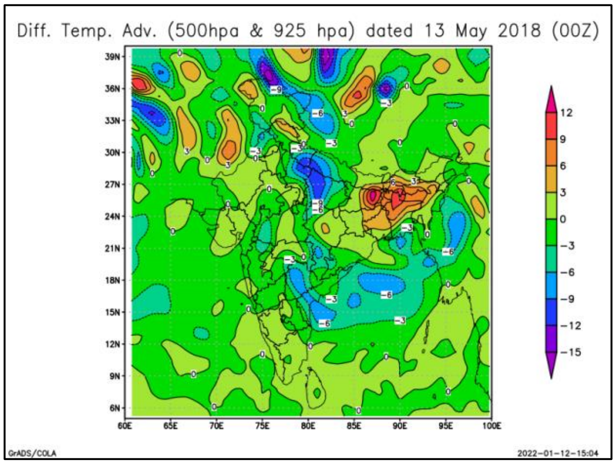


Fig. 12. Differential Temperature Advection between 500 & 925 hPa at 0000 UTC on 13th May, 2018 using ERA Interim daily data

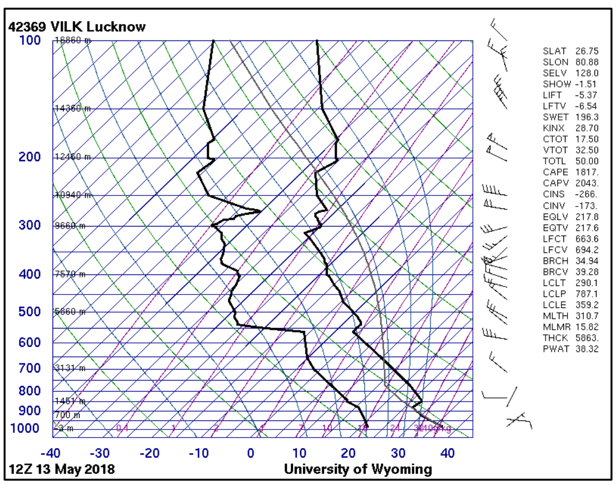


Fig. 13. Skew-T gram of Lucknow for 1200 UTC of 13th May, 2018

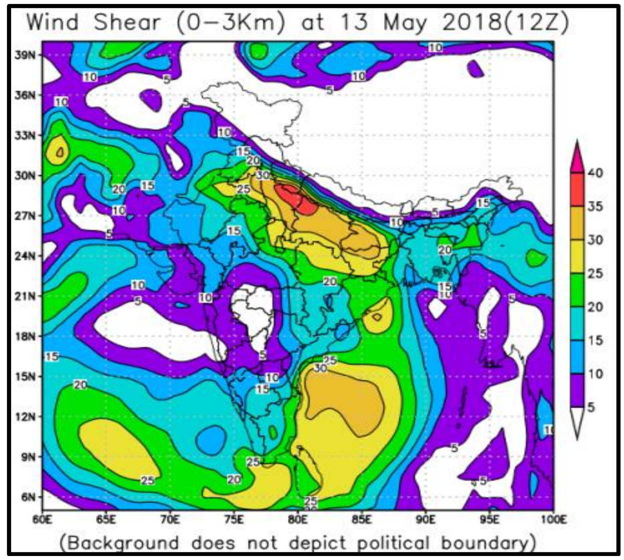


Fig. 14. Low level (0-3km) wind shear of the day at 1200 UTC using ERA Interim daily data

(*v*) In 1200 UTC GFS analysis at 200 hPa the 1st branch of STWJ is noticed more or less at the same area while the 2nd branch over south Bangladesh disappeared.

Development of clouds were directly associated with Western disturbance and extending along trough running from Cyclonic circulation over south Haryana to Chhattisgarh.

Maximum temperatures over Rajasthan, Madhya Pradesh and neighbouring area of Uttar Pradesh were more than 40 degree Celsius (Fig. 11) and these were persisting from last few days prior to intense convection episode over the region. These high surface temperatures resulted in heating of adjacent layers of the atmosphere leading to high lapse rate in the lower levels and produced significant lifting of air in association with prevailing synoptic systems over the region. Fig. 12 represents differential temperature advection between 925 & 500 hPa at 0000 UTC using ERA Interim daily data of ECMWF.

It can be seen that the value are highly negative over Uttar Pradesh indicating cold air advection in middle levels leading to high lapse rate. Also, the 925 hPa GFS analysis wind at 0000 UTC of the day indicated strong southeasterly over Uttar Pradesh which led to high moisture feeding in the lower levels from Bay of Bengal.

Moderate to strong southeasterlies of the order of 20-25 kts at 925 with speed decreasing to 5-10 kts at 850 hPa and moderate to strong northwesterlies of 15-35 kts at 700 hPa & above as shown in GFS wind analysis at 0000 UTC resulted in strong wind shear both with respect to direction as well as speed in lower to mid-levels, one of the favourable conditions for severe thunderstorm activity. This is also evident from (*i*) Skew-T gram (Fig. 13) of Lucknow for 1200 UTC of the day taken from Wyoming site which shows a wind shear of about 25 kt between 850 hPa and 600 hPa and (*ii*) 1200 UTC low level (0-3 km) [Fig. 14)] wind shear analysis using ERA daily Interim reanalysis data of ECMWF at 1200 UTC on 13 May, 2018, which indicated high (>30 kt) low to mid-level wind shear over Uttar Pradesh. Squall line formation and movement over Delhi has been found to be aided by the high unidirectional shear in the lower to middle troposphere (Sen Roy *et al*., 2019).

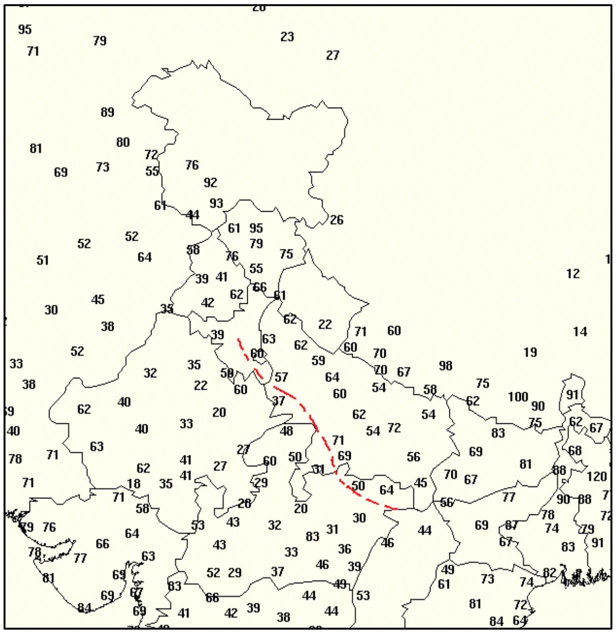


Fig. 15. Surface relative humidity at 0300 UTC of the day showing moisture discontinuity over south Uttar Pradesh

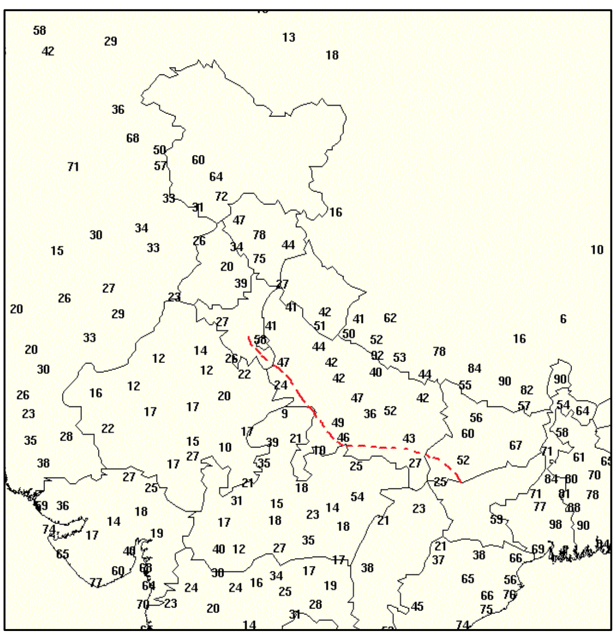


Fig. 16. Surface relative humidity at 1200 UTC of the day showing moisture discontinuity over south Uttar Pradesh

The GFS analysis wind at 0000 UTC and 1200 UTC indicated that there is no jet core over Uttar Pradesh at 200 hPa. However, the radiosonde data of Lucknow at 1200 UTC of the day taken from Wyoming site shows a layer of more than 60 kt wind from 273 hPa to 271 hPa only with maximum wind of 62 kt at 272 hPa and while that of Bhopal at 0000 UTC shows a single level at 193 hPa with wind speed 60 kt. The available 0000 UTC data of Gorakhpur, Gwalior, Bhopal, Patiala and Delhi does not show any wind of 60 kt or more.

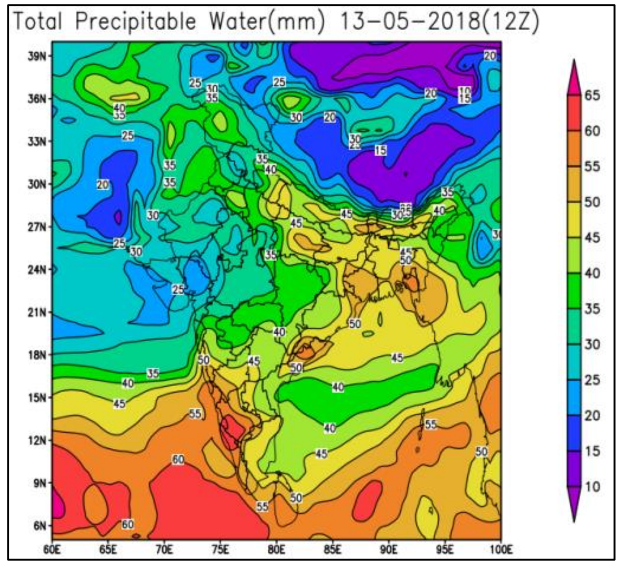


Fig. 17. Total Precipitable Water (mm) at 1200 UTC of 13th May, 2018 using ERA Interim daily data

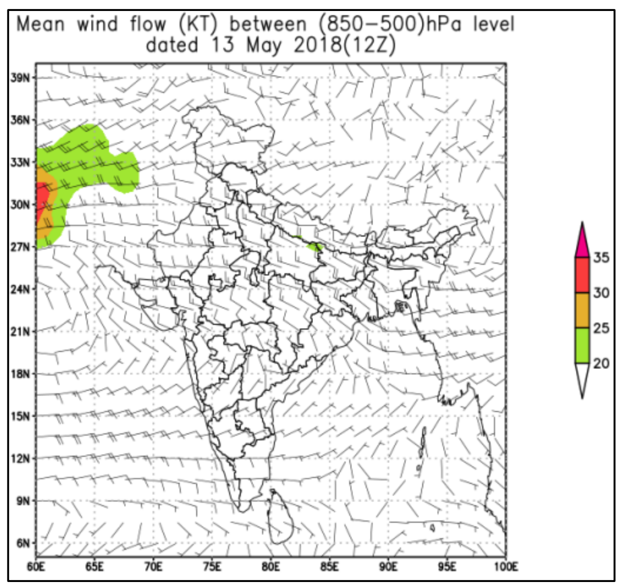


Fig. 18. Mean wind (kt) 850-500 hPa level dated 13th May, 2018 at 1200 UTC

The 0300 and 1200 UTC surface relative humidity (RH) data of the day clearly indicated moisture discontinuity line [Figs. 15 & 16-red dashed lines] passing through south Uttar Pradesh with high values on its north

TABLE 1

Thermodynamic Parameters of various stations at 0000 UTC on 13th May, 2018

Indices	Delhi	Lucknow	Gorakhpur	Gwalior
Convective Available Potential Energy (CAPE) (J/KG)	2660.51	1268.67	437.40	1302.69
Total Total Index (°C)	55.00	52.40	47.10	52.00
Lifted index (°C)	-7.98	-4.66	-0.28	-4.99
SWEAT index	258.41	241.40	228.00	164.20
K index (°C)	32.70	31.90	32.60	25.10
Perceptible water [mm] for entire sounding	35.58	38.20	45.35	28.02

and low values towards south leading to severe convection towards more moist regions along this line. Further, the RH values over East Bihar and adjoining Sub-Himalayan West Bengal & Sikkim were very high as compared to other regions both at 0300 & 1200 UTC. Also, 1200 UTC total precipitable water imagery prepared using ERA daily Interim reanalysis data of ECMWF (Fig. 17) indicated more moisture availability over East Uttar Pradesh, Bihar, West Bengal and Sikkim.

The direction and speed of propagation of the system is determined by the prevailing wind flow in the lower to mid-levels and upto upper levels for more deep convective systems generally termed as steering flow. In earlier studies on Tropical Cyclones (TC) (George and Gray, 1976; Chan and Gray, 1982) averaged winds within 7° of the TC centre at a height between 700 and 500 hPa were well correlated with the motion of the TC. In another study over Germany (Hagen *et al*., 1998) it was found that the direction of moving thunderstorms is mainly controlled by the flow in heights around 3 or 6 km above msl. However, in the present study we have taken mean winds between 850 to 500 hPa to find out the steering flow of squall line (Fig. 18). The fig clearly indicates nearly westerly steering flow of 15-20 kts over entire north Indian belt extending from Haryana through Uttar Pradesh to Bihar with highest speed towards northeast Uttar Pradesh.

The high moisture content region together with westerly steering flow of 15-20 kts over the activity area determined the movement of the system towards more moist-easterly direction. This was more evident from the shape and orientation of the squall line as indicated by DWR imageries discussed earlier. The initially bow shaped squall line transformed into northwest-southeast oriented squall line as the southern end of the squall line had more stronger northerly component than the northern end showing a tendency to move towards more moist regions of East Bihar & adjoining Sub-Himalayan West Bengal.

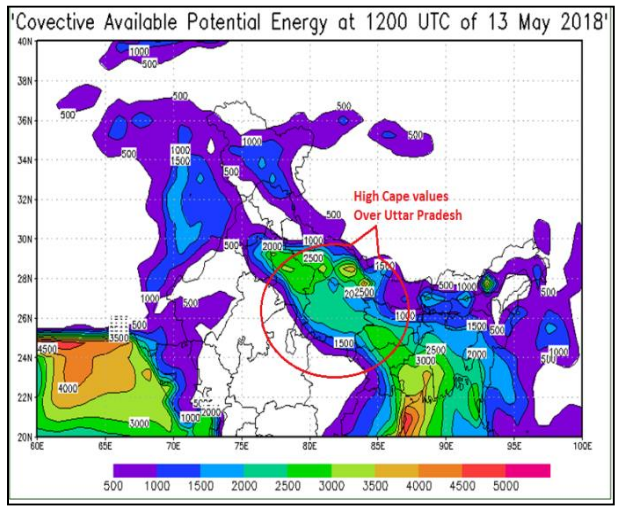


Fig. 19. Convective Available Potential Energy at 1200 UTC on 13th May, 2018 using ERA Interim daily data

Thermodynamic indices are also an important tool for forecasting of thunderstorm. Tyagi *et al*. (2011) have calculated threshold values of many thermodynamic indices over Kolkata for the occurrence of thunderstorm in pre-monsoon season. Yamane and Hayashi (2006) demonstrated that CAPE represents the atmospheric instability required for the evaluation of environmental conditions for the formation of severe local storms over the Indian subcontinent. Sahu *et al*. (2019) showed that K-index ≥20 is indicative of an increasing frequency in air mass thunderstorm activity over Chhattisgarh.

Uttar Pradesh have two RS/RW stations at Lucknow and Gorakhpur whose data have been taken into account. In addition, data of two nearby RS/RW stations namely Delhi and Gwalior have also been used to examine thunderstorm probability over and around Uttar Pradesh.

Table 1 shows Convective Available Potential Energy (CAPE) values at 0000 UTC over Delhi,

TABLE 2

Nowcast warnings issued by M. C. Lucknow and their realization

S. No.	Date and Time of issue of Nowcast	District for which Nowcast warning was issued	Weather realized (Based on Tehsil rainfall & observatory data)
1.	13.05.2018, 1530 IST	Etawah, Auraiya, Firozabad, Mathura, Jalaun	Dust Storm/Thunderstorm with rain occurred at Auraiya, Firozabad, Mathura & Jalaun
2.	13.05.2018, 1645 IST	Aligarh, Ghaziabad, Gautam Buddh Nagar, Baghpat, Bulandshahar, Hapur, Etah, Kannauj, Mainpuri	Dust Storm/Thunderstorm with rain occurred at Aligarh, Ghaziabad, Gautam Buddh Nagar, Baghpat, Bulandshahar, Hapur & Etah
3.	13.05.2018, 1725 IST	Kanpur (Urban), Kanpur (Dehat), Hardoi, Farrukhabad, Unnao	Dust Storm/Thunderstorm with rain occurred at Kanpur (Urban), Kanpur (Dehat) & Unnao
4.	13.05.2018, 1820 IST	Banda, Chitrakoot, Fatehpur, Kaushambi, Muzaffarnagar, Meerut, Bijnor, Amroha, Sambhal, Shamli, Kasganj, Hathras	Dust Storm/Thunderstorm with rain occurred at Banda, Fatehpur, Kaushambi, Muzaffarnagar, Meerut, Bijnor, Sambhal & Kasganj
5.	13.05.2018, 1930 IST	Badaun, Bareilly, Pilibhit, Lakhimpur, Shahjhanpur, Sitpur, Hardoi, Lucknow, Barabanki, Raebareili, Sultanpur, Faizabad, Jaunpur, Azamgarh, Allahabad, Mirzapur, Sant Ravidasnagar	Dust Storm/Thunderstorm with rain occurred at Badaun, Bareilly, Pilibhit, Lakhimpur, Shahjhanpur, Sitpur, Lucknow, Barabanki, Raebareili, Sultanpur, Faizabad, Jaunpur, Azamgarh & Allahabad
6.	13.05.2018, 2200 IST	Badaun, Bahraich, Gonda, Shravasti, Balrampur, Basti, Gorakhpur, Mahrajganj, Ballia, Deoria, Azamgarh, Ghazipur, Mau, Varanasi	Dust Storm/Thunderstorm with rain occurred at Badaun, Bahraich, Gonda, Shravasti, Balrampur, Basti, Gorakhpur, Mahrajganj, Ballia, Deoria, Azamgarh, Ghazipur, Mau, Varanasi

TABLE 3

No. of Casualties recorded on 13th May, 2018 (*Source* : Office of Relief Commissioner, Government of Uttar Pradesh)

S. No.	Name of District	No. of causalities
1.	Amethi	1
2.	Bulandshahar	4
3.	Bijnore	2
4.	Ballia	1
5.	Kannauj	1
6.	Jaunpur	3
7.	Ghaziabad	1
8.	Ghazipur	1
9.	Unnao	1
10.	Mathura	1
11.	Muzaffarnagar	2
12.	Aligarh	1
13.	Barabanki	8
14.	Pratapgarh	3
15.	Raebareilly	1
16.	Saharanpur	2
17.	Bareilly	8
18.	Kasganj	6
19.	Sitapur	1
20.	Mirzapur	1

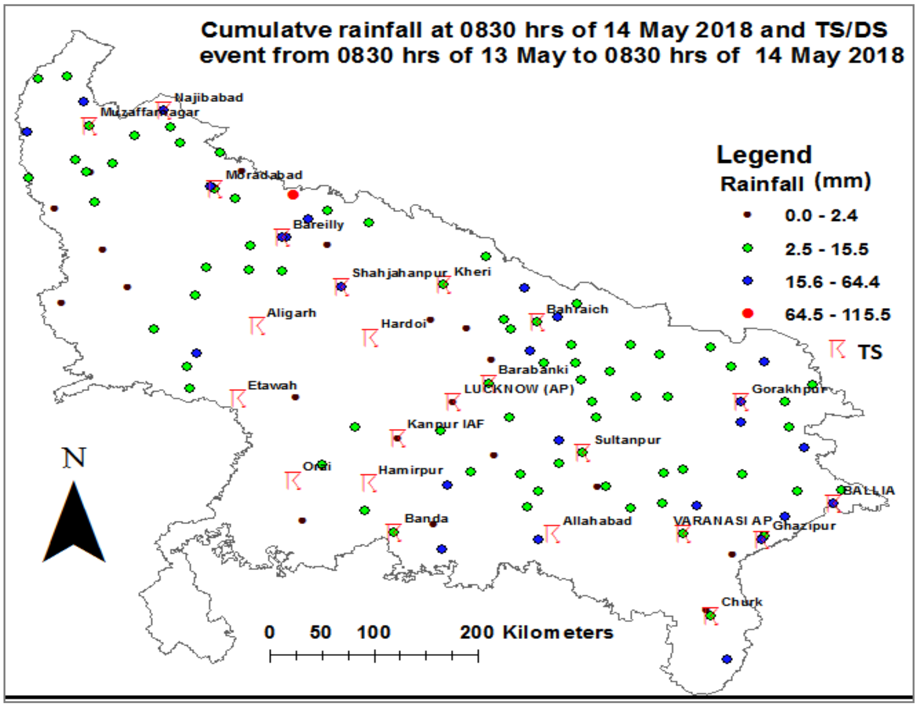


Fig. 20. Actual cumulative rainfall and Thunderstorm

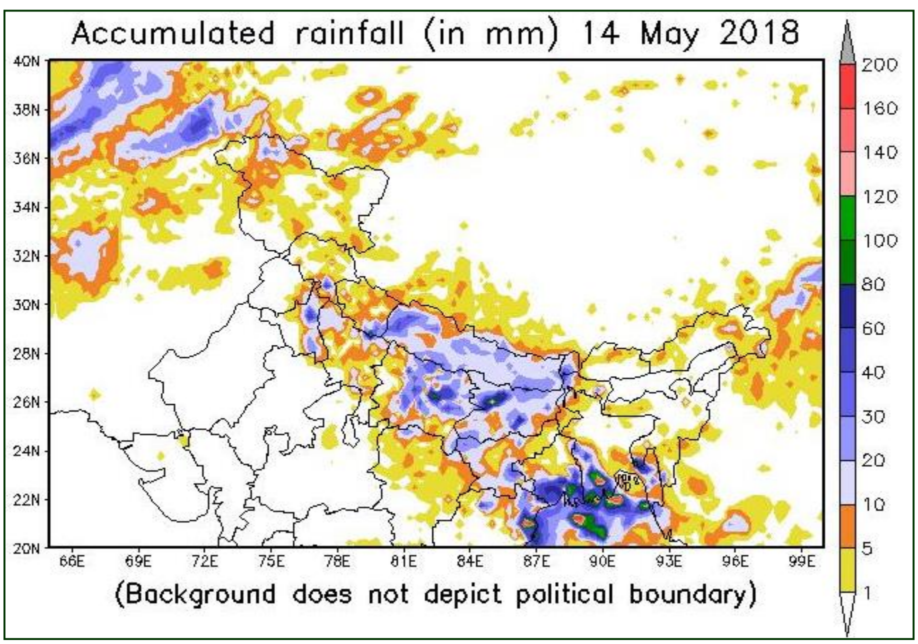


Fig. 21. Past 24 hours accumulated Gridded rainfall at resolution of 0.25° × 0.25° Lat./Long at 0300 UTC of 14 May 2018.

Lucknow, Gwalior and Gorakhpur. It was noticed that the CAPE values were high (>1000J/kg) over all these stations except Gorakhpur. CAPE map prepared at 1200 UTC using ERA Interim, daily data of ECMWF (Fig. 19) shows that CAPE values were > 2000 J/kg over most parts of the state with further higher values of more than 2500J/kg over West Uttar Pradesh.

Total Total Index (TTI) was more than 50 over all mentioned stations except at Gorakhpur where it was 47.1.

Lifted index was less than -4 over all the listed places except at Gorakhpur where it was -0.28. K-index was>28 over all the four stations. SWEAT index was more than 200 over all places except at Gwalior where it was 164.20. If other indices are favourable but sufficient moisture is not available in the sounding then either no or dry thunderstorm will take place. In the morning of 13th May, 2018 (at 0000 UTC) precipitate water for entire sounding was more than 35 mm over all places except at Gwalior where it was very low, *i.e*., 28.02 mm. Thunderstorm activity was not observed over and around Gwalior on that day. Thus all the thermodynamic indices were highly favourable for initiation of severe thunderstorm activity over the area. Tyagi *et al*. (2011) have found that CAPE ≥ 1000J/kg, Total Total Index ≥ 46, Lifted Index ≤ -3, SWEAT index ≥180, K index ≥24 are favourable for pre-monsoon thunderstorms over Kolkata. Here we find that the results exhibits the same relevance for thunderstorms in pre-monsoon season over Uttar Pradesh too.

4. Realised weather and damage occurred

Early detection and forecasting of thunderstorms is important in safeguarding and prevention of damages resulting from these violent thunderstorms (Dhawan *et al*., 2008). The 13th May 2018 wide spread convective activity over the state, as discussed above, claimed 49 human lives and many livestock in Uttar Pradesh (Table 3) as per the data released by Office of relief Commissioner, Government of Uttar Pradesh. These causalities occurred due to uprooting of trees, falling of electric poles and hoardings, lightening, hailstorm, duststorm, Squally winds etc. associated with this severe thunderstorm episode. Agricultural and horticultural losses worth millions of rupees were estimated due to rain, strong winds and hailstorms. Fig. 20 shows the actual cumulative rainfall and thunderstorms for past 24 hours reported at 0830 UTC of 14th May and Fig. 21 gives past 24 hours gridded accumulated rainfall.

On 13th May 2018, M. C. Lucknow had issued nowcast warnings for severe weather for specific districts & specific period of time (Table 2) on the basis of DWR observations and most of them were realized. The location specific nowcast warnings minimized the causalities otherwise this number could be higher.

4. Conclusion

Isolated thunderstorms over the state of Uttar Pradesh in pre-monsoon season is a very common phenomenon. But it is found that when synoptic conditions like WD, induced lows, troughs, wind discontinuities are present along with favourable thermodynamic conditions, then thunderstorm activity becomes very destructive. Development of dense convective clouds are generally seen over north Pakistan in these types of cases. If northwest-southeast oriented tough is observed at the western border of the Uttar Pradesh state then thunderstorm cells developed over north Pakistan in the afternoon moves eastwards into the interior of the state by evening or night. In large scale thunderstorm activities that occurred over the state on 30th & 31st May, 2014 (Ray et al, 2017) and 2nd & 3rd May, 2018 (Gupta *et al*., 2019), similar conditions, *i.e*., initial development of thunderstorm clouds over Pakistan were seen which moved over to Uttar Pradesh state after sufficient lead time.

The study shows that the environment was highly favourable thermodynamically for severe thunderstorm activity with high maximum temperatures (>40 °C), high CAPE (>1000J/kg), high Total Total Index (>50) and high negative Lifted Index values (<-5) over most parts of the northwest Indian plains. The moisture discontinuity line was clearly noticed over south Uttar Pradesh with high moisture contents towards its north. Also 0000 UTC GFS wind analysis of the day at 925 hPa indicated strong southeasterlies of the order of 30-35 kts over Uttar Pradesh resulting high moisture incursion in the lower levels over this region. The Low level wind shear was also high and was about 25-30 kt as evident from Skew-T gram of Lucknow for 1200 UTC of the day taken from Wyoming site as well as 1200 UTC low level (0-3 km) wind shear analysis using ERA Interim daily data of ECMWF on 13th May, 2018. These features together with synoptic conditions, *viz*.; WD in mid and upper levels and a cycir over south Haryana & neighbourhood as well as an east-west trough extending from this cycir in the lower levels made the environment highly favourable for severe thunderstorm activity over the region. The satellite CTBT imageries showing intense convection over West and Central Uttar Pradesh at 2030 IST with lowest CTBT of -60 °C and the Lucknow Radar imageries indicating the deep convection having reflectivity more than 50dbZ and height 10-15 km as well as the bow shape structure of squall lines are clear evidences of intensity and structure of the convection associated with severe thunderstorm episode.

Thunderstorms lead to significant loss of life and property. Hence, their early detection and warnings are very essential for minimizing the damages. Though Synoptic Charts, NWP Models and thermodynamic conditions of the atmosphere give indications for large scale thunderstorm activity over the state but their accurate detection with estimation of hazard potential is possible only through Doppler Weather Radar (DWR). Human activities can’t be suspended in anticipation of large scale thunderstorm activity over the entire state for long time. So location and time specific nowcast warnings for severe weather using DWR plays an important role in minimizing its devastating impact by timely dissemination of these warnings to disaster managers and the general public as well.

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Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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