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A study of extreme rainfall events and urban flooding over Hyderabad, October 2020

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सार – इस अध्ययन में, 13 अक्टूबर 2020 को हैदराबाद में अत्यधिक वर्षा की घटना के दौरान मध्य-मापक्रम संवहनी कॉम्प्लेक्स (एमसीसी) के विकास और इसकी वायुमंडलीय स्थितियों का विश्लेषण और वर्णन किया गया है। यह चरम मौसमी घटना एक सिनोप्टिक-माप प्रणाली में अंत:स्थापित एक मध्य-मापक्रम घटना थी। अक्टूबर 2020 के दूसरे सप्ताह के दौरान, पश्चिम-मध्य बंगाल की खाड़ी (बीओबी) पर एक अवदाब बना और प्रायद्वीपीय भारत के माध्यम से उत्तर-पश्चिम की ओर चला गया, जिससे 13-14 अक्टूबर को भारत के आंध्र प्रदेश और तेलंगाना राज्यों में भारी वर्षा हुई। 13 अक्टूबर को हैदराबाद और साइबराबाद के कई हिस्सों में 24 घंटे के भीतर 300 मिमी से अधिक वर्षा हुई। सैटेलाइट इमेजरी से पता चलता है कि इस मध्य-मापक्रम प्रणाली ने एमसीसी में रिपोर्ट किए गए संरचित संवहन का एक अनूठा समुच्चय बनाया है। इस एमसीसी में हैदराबाद में लगभग 9 घंटे के जीवन चक्र के साथ 100000 किमी^{2} से अधिक के क्षेत्र में -33 °C से कम के निरंतर कम आईआर तापमान के साथ एक क्लाउड शील्ड है और 50000 किमी^{2} से अधिक के क्षेत्र में -54 °C से कम के निरंतर कम आईआर तापमान के साथ एक क्लाउड शील्ड है। इस एमसीसी में बहुकोशिकीय विशेषताएँ थीं, जो दर्शाती हैं कि इसके वातावरण में महत्वपूर्ण निम्न-स्तर की नमी के साथ-साथ प्रबल उद्वाह का मिश्रण थाजो हैदराबाद में महत्वपूर्ण वर्षा दर को दर्शाता है। सिनोप्टिक विशेषताओं से पता चलता है कि उच्च वर्षणीय जल के साथ, 0850 एचपीए पर निम्न-स्तरीय नमी अभिसरण की लंबी धुरी और 0925 एचपीए पर बड़ी क्षैतिज भ्रमिलता के औसत पवन प्रवाह के समानांतर उन्मुख थे। इस मामले में, नमी अभिसरण के क्षेत्र में गर्ज के साथ तूफान के पुंज उत्पन्न हुए जिससे अत्यधिक भारी वर्षा की अवधि बढ़ गई। उच्च वर्षा दर, अपेक्षाकृत धीमी तूफान गति, और कई घंटों तक एक ही स्थान पर प्रेक्षित लंबे समय तक बैक-बिल्डिंग के भारी वर्षा संचय के लिए जिम्मेदार होने की संभावना है। जल विज्ञान संबंधी स्थितियों ने मूसलाधार वर्षा के प्रभावों को और बढ़ा दिया, जिसके परिणामस्वरूप प्राकृतिक खतरा पैदा हो गया।

ABSTRACT. The present study analyses and describes the evolution of the Mesoscale Convective Complex (MCC) and its atmospheric conditions during Extreme rainfall event in Hyderabad, on 13th October 2020. This extreme weather event was a mesoscale event embedded in a synoptic-scale system. During the second week of October 2020, a depression formed over the west-central Bay of Bengal (BoB) and travelled north-westwards through peninsular India, causing heavy rains in Andhra Pradesh and Telangana states of India on October 13-14. On October 13, many parts of Hyderabad and Cyberabad received more than 300 mm of rain within 24 hrs. Satellite imagery suggests that this mesoscale system constituted a unique set of structured convection those reported in MCC. This MCC has a cloud shield with a continuous low IR temperature of less than - 33 °C over an area of more than 100000 km^2 and a cloud shield with a continuous low IR temperature of less than -54 °C over an area of more than 50000 km^2 over Hyderabad with a life cycle of about 9 hours. This MCC featured multi cellular characteristics, showing that there was significant low-level moisture in its environment, as well as a mix of vigorous updrafts, implying significant rainfall rates over Hyderabad. The synoptic features suggest that with high precipitable water, the long axis of low-level moisture convergence at 0850 hPa and large horizontal vorticity at 0925 hPa were oriented parallel to the system's mean wind flow. In this case, a clusters of thunderstorms arose in the area of moisture convergence which prolonged the duration of extremely heavy rainfall. The high rain rate, relatively sluggish storm motion, and prolonged back-building over the same locations for several hours are likely to blame for the heavy rainfall accumulations that were observed. The hydrological conditions compounded the effects of the torrential rain, resulting in a natural hazard.

Key words – Mesoscale convective complexes, Urban floods, Depression, Thunderstorm.

1. Introduction

Researchers and policymakers have been paying close attention to the vulnerability of cities owing to urban floods due to climate change impacts. Extreme rainfall events have occurred in tropical regions in recent years, including India, over the megacities (Niyogi *et al*., 2018; De *et al*., 2013). The Mumbai floods of July 2005 (De *et al*., 2006), the Chennai floods of December 2015 (Balakrishnan 2016), and the Hyderabad floods of October 2020 (Rangari *et al*., 2021) are all examples of extreme urban floods. Due to anthropogenic climate change and India's growing urban population, the likelihood of large-scale extreme occurrences is increasing (IPCC 2007, IPCC 2012). Hyderabad and its surrounding regions were hit by an exceptionally heavy rainstorm (rainfall exceeding more than 30 cm a day in some locations) with high rain rates of 6 hours resulting in severe flash floods (Rangari *et al*., 2021). According to official estimates, 40 people died in Hyderabad as a result of the heavy rains and almost 40,000 families were impacted. Property losses totaled nearly Rs. 6.7 billion (Rs 670 crores) "Rain fury leaves capital battered, bruised". *The Hindu*. ISSN 0971-751X. Archived from the original on 15 October 2020.

Due to land scarcity and growing property prices in emerging cities, high-rise buildings have become the norm in new urban planning expansion (Oleksandr *et al*., 2011). The roughness parameter in the boundary layers increases in this new urban environment, resulting in lighter winds in the metropolis (Rajeswari *et al*., 2021). The tall towers may produce eddies that have an impact on the immediate area. According to one recent study (Boyaj *et al*., 2020), growing urbanization in Telangana and Tamil Nadu is predicted to increase rainfall by 20-25% during severe rain events. Higher surface temperatures and a deeper and moister boundary layer result from changes in land use and land cover. This results in a higher convective accessible potential energy and, as a result, heavier rainfall. Between 2000 and 2017, the amount of rain that fell during major rainstorms grew considerably. According to research on rainfall trends over Hyderabad (Singh *et al*., 2015), there is an increasing trend in heavy rainfall events during the Southwest monsoon season (June to September) and a large increase in the month of August. Hyderabad is one of the city that is urbanizing the fastest. The surface landscape of the city is dominated by population growth, growing urbanization and land use, land cover, and change (LULCC). According to Oke (1982), changes in surface properties affect local and regional energetics, which in turn interact to change the region's moisture, albedo and surface roughness as well as its weather and climate (National Research Council and Climate Research Committee, 2005; Pielke *et al*., 2011). Extreme rainfall events have occurred in tropical regions in recent years, including India, over the megacities (Niyogi *et al*., 2018). Research in the Indian subcontinent continue to show how unrestrained urbanization can result in unexpected and higher flood danger (Gupta and Nair, 2010). Moreover, studies have demonstrated that urbanization results in more frequent rainstorm events and extensive flooding (Kishtawal *et al*., 2010; Ghosh *et al*., 2012). The surface energy balance and fluctuations in the atmospheric boundary layer can be affected by the thermodynamic properties of the land surface (Niyogi *et al*., 2006). Urbanization-related anthropogenic changes are a factor in the variations in anthropogenic aerosols, boundary-layer heating, and surface heat fluxes. The surface's albedo, emissivity, and roughness could alter due to changes in Land Cover properties, which could also have an impact on mesoscale temperature patterns, humidity, convergence and CAPE values, according to a study by Douglas *et al*., (Pielke *et al*., 2007; Pielke *et al*., 2011; Osuri *et al*., 2017). Rapidly expanding cities in particular have a strong potential to alter mesoscale characteristics including the neighbourhood surface climate, circulation patterns, and urban hydrological cycle (Collier 2006; Niyogi 2019). Using a high-resolution mesoscale model over the rapidly urbanizing metropolis of Hyderabad, the study's primary goal is to evaluate the impact of urbanization on heavy rainfall in terms of timing of onset, peak activity, spatial distribution, and site of rain intensification. Hyderabad should be studied for two different reasons. In addition, recent observational analysis (Agilan and Umamahesh, 2015) has shown that the sub-daily (4-hourly) extreme rainfall during the non-monsoon months has increased between 1 and 4 am and 5-8 am by 4.5% and 1%, respectively.

It is a major problem to forecast the quantitative aspect of flash floods (Doswell *et al*., 1996). The goal is not only to predict the occurrence of an event, which is difficult enough in itself, but also to assess the magnitude of the event using cause and effect knowledge. It is the amount of rain that transforms a typical rainstorm into a life-threatening extreme event. This problem is exacerbated by the interaction between meteorology and hydrology. Precedent precipitation, the size of the drainage basin, the terrain of the basin and the degree of urban use within the basin influence the chance of a flash flood during a specific heavy rainfall event. As a result, a flash flood happens when a meteorological event occurs in conjunction with a specific hydrological scenario. Several studies have been conducted on urban floods in Hyderabad in regard to hydrology and other perspectives (Khole and De 2001, Naik 2017, Sharma *et al*., 2018, Mishra and Nagaraju 2021).

1.1. *Background and context : the city of Hyderabad, India*

Hyderabad (Lat. 17.37° N, Lon. 78.48° N) is the capital of Telangana state, which is located on the Deccan plateau in north-central India. Hyderabad city is divided into three districts: Hyderabad, Ranga Reddy and Medchal-Malkajgiri, with a total size of 625 square kilometers and a population of 6809,970 people, making it India's fourth most populated metropolis (https://hyderabad.telangana.gov.in). Over the previous two to three decades, it has emerged as India's cyber city, resulting in population growth and city expansion (Oleksandr *et al*., 2011). As a result, an increase of nearly 87 percent in the overall population from 3,637,483 in the 2001 census to 6,809,970 in the 2011 census is a cause for concern in terms of urban planning. Residential areas account for 44% of the Greater Hyderabad Municipal Corporation's (GHMC) census, with open land and agriculture accounting for the remaining 56%. Mixed usage accounts for about 6.2 percent of the population (http://www.ghmc.gov.in/cdp/chapters percent 202.pdf). Due to irresponsible land use to satisfy the needs of growing metropolitan areas and a lack of city planning, such regions have become more prone to severe weather damage (Naik 2017).

The river Musi runs through Hyderabad. During one of the most historic flood occurrences, which occurred in 1908 (Cohen, 2011), the city, which was spread over 55-60 square kilometers, suffered extensive damage due to the lack of appropriate drainage. For long-term flood prevention, the Nizam of Hyderabad enlisted the services of renowned engineer Sir Visweswarayya. As part of the city's drainage system, he developed two balancing reservoirs, Himayathsagar and Osmansagar, as well as a sewage treatment plant. However, as time passed, things began to shift dramatically. Rapid urbanization, along with a lack of effective urban planning, resulted in the development of a slew of colonies and housing complexes on property adjacent to riverbeds and other bodies of water. Priority was given to human requirements such as housing, rather than the drainage system and good urban planning. The Greater Hyderabad Municipal Corporation (GHMC) currently manages a population of almost 10 million people in the expanding city. The city's number of water bodies has decreased to just 190 from over 2500 in 1970, similar to other Megacities (De *et al*., 2013). All of these elements have exacerbated the situation and increased the city's vulnerability to catastrophic disasters. This is because the city is rapidly expanding and is representative of the growth throughout India. The postulation regarding potential urban and regional climate feedback producing this significant change in the time of the rainfall surrounding Hyderabad city was based on the observational analysis. This study uses a number of datasets to analyse the local meteorological conditions, examine the geographical and temporal aspects of the precipitation, and summarise the immediate effects in the city.

2. Datasets used

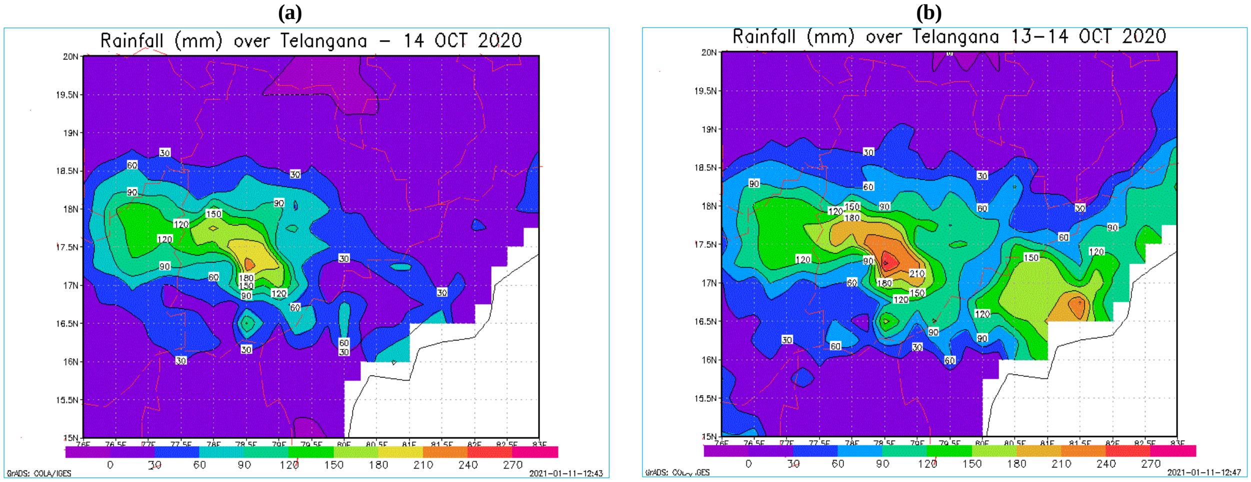
For this research, we analyzed a variety of datasets, including observed rainfall data for Hyderabad and adjoining stations, gridded reanalysis datasets, Doppler radar observed rainfall estimates, Radio-sonde radio-wind data, and outgoing Longwave radiation (OLR) data. We used daily rainfall data for Hyderabad district, Telangana, which includes 15 stations, to analyze extraordinarily heavy rainfall events over Hyderabad city and its surrounding districts (https://tsdps.telangana.gov.in/liveghmcrain.jsp). To understand the extreme one day rainfall events, long-term heavy rainfall records for Hyderabad station (1901-2020) were gathered from the National Data Centre, IMD, Pune (https://imdpune.gov.in/ClimPredLRFNew/GridedDataDownload.html). The atmospheric fields were obtained from ERA5's hourly pressure-level and surface-level meteorological data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). All of them had a horizontal resolution of 0.25° × 0.25° and a vertical resolution of 37 levels with a 0.1 hPa pressure. The latitude and longitude varied from the Equator to 30° N and from 65° E to 105° E. The OLR was acquired at 2.5° × 2.5° resolution from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis-1 (https://psl.noaa.gov/data/gridded/data.uninterpOLR.html) For atmospheric sounding, K-index from ERA-5 Reanalysis and Radio-sonde radio-wind data from the University of Wyoming were utilized. INSAT-3D, an Indian meteorological geostationary satellite, is positioned over the Indian Ocean at 82° East. For the study of thunderstorms over Hyderabad, the INSAT-3D satellite measured TIR-1 brightness temperature (BT) and IR1 at a resolution of 4 km are used (https://www.satmet.imd.gov.in/insat.htm). The Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) from the National Oceanic and Atmospheric Administration's Air Resources Laboratory is used for computing simple air parcel trajectories (http://journals.ametsoc.org/doi/abs/10.1175/ BAMS-D-14-00110.1).

3. Result and discussions

3.1. *Characteristics of the rainfall event*

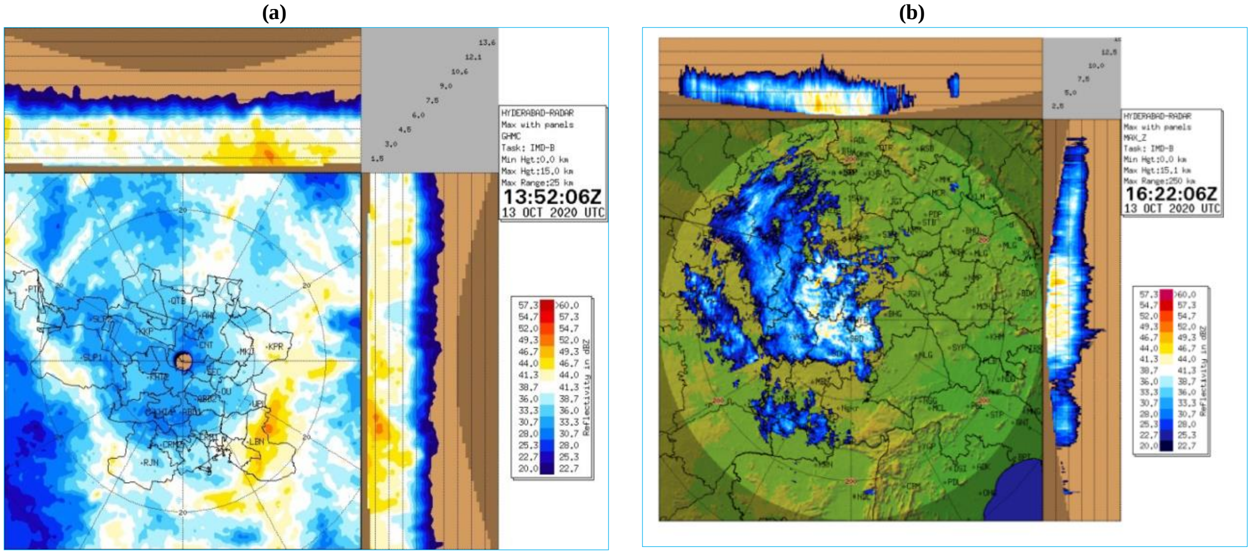
Daily rainfall data for 15 stations around Hyderabad city recorded heavy to extremely heavy rainfall at most places for the same period. According to the Greater

(a) **(b)**



Figs. 1(a&b). IMD high spatial resolution (0.25° × 0.25°) gridded daily rainfall (mm) maps showing areas affected by (a) 24 & (b) 48-hour rainfall totals over Telangana State

(a) **(b)**



Figs. 2(a&b). Doppler Radar observations (a) 25 km range & (b) 250 km range at 0600 UTC on 13th October, 2020 over Hyderabad

Hyderabad Municipal Corporation (GHMC) state rain-gauges report, the following are the realized rainfall (cm) amounts from 0830 hours on October 13th to 0830 hours on October 14th, with some of the exceptional rainfall amounts: Singapur Township (Medchalmalkajgiri District) has 32; Hayathnagar (District : Rangareddy) has 29; Verkatpalle (District : Bhongir) has 26, Mangalpalle (District : Rangareddy) has 25, Rajeevnagar, Osmania University (District : Hyderabad) has 22, Begumpet (District : Hyderabad) has 22, Begumpet (District : Hyderabad) has 22, Begum (District : Hyderabad). The most intense rainfall locations were evenly spread over the three districts of Rangareddy, Medchal-Malkajgiri and Hyderabad respectively.

Rainfall intensity shifted westward, resulting in a reported deluge between 1300 to 1900 UTC. Fig. 1 shows the above-mentioned areas, as well as 24 and 48-hour rainfall totals (a&b) in and around Hyderabad for the 13-14 October period. In Doppler radar measurements taken in Hyderabad on October 13th at 0600 UTC, high reflectivity (dbz) on radar panels where rain rate is observed is largely centred across Hyderabad, Rangareddy and Medchal-Malkajgiri districts (Fig. 2).

The frequency of very high rainfall occurrences in the categories (>115-204.5 mm)/day in Hyderabad is rather low. As a result, we limited our research to instances with rainfall higher than or equal to

TABLE 1

Intense heavy rainfall over Hyderabad (Begumpet Airport) and the respective date of occurrence (1901-2020)

Date (dd/mm/yyyy)	Rainfall recorded (mm day-1)
06/10/1903	117.1
27/09/1908	153.2
24/08/1910	111.5
26/06/1914	122.9
03/10/1915	105.9
08/09/1915	101.9
08/07/1916	109.2
30/10/1916	102.1
31/03/1928	103.1
26/08/1954	190.5
20/09/1965	116.0
15/07/1965	110.4
22/09/1970	119.0
25/09/1971	122.0
09/09/1975	148.9
15/08/1978	113.8
04/11/1987	112.5
24/07/1989	140.5
24/08/2000	241.5
12/06/2001	114.6
27/07/2006	106.8
09/08/2008	121.9
18/08/2009	133.7
21/07/2012	115.1
26/08/2017	113.7
14/10/2020	190.2

100 mm/day. Table 1 shows the rainfall records as well as the dates on which they occurred. Ten of the 26 cases occurred between the last two weeks of September and the first two weeks of October. According to daily rainfall data dating back over 120 years, the rainfall of 241.5 mm on August 24, 2000, was the highest ever recorded in Hyderabad, followed by 190.5 mm on August 26, 1954, and 190.2 mm on October 14, 2020. We found that rainfall on 24th August 2000 was also under the influence of depression passing over Hyderabad city, similar to the case study.

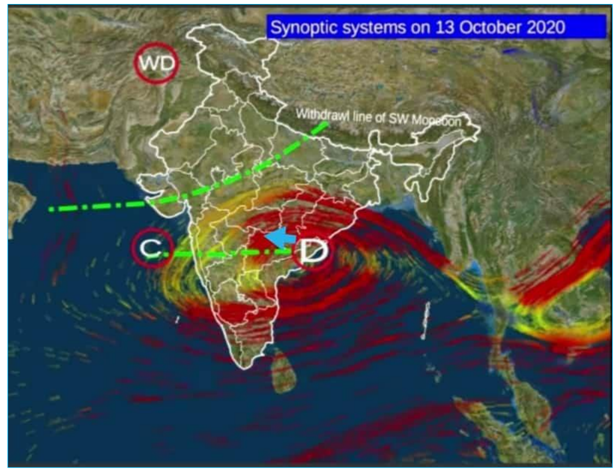


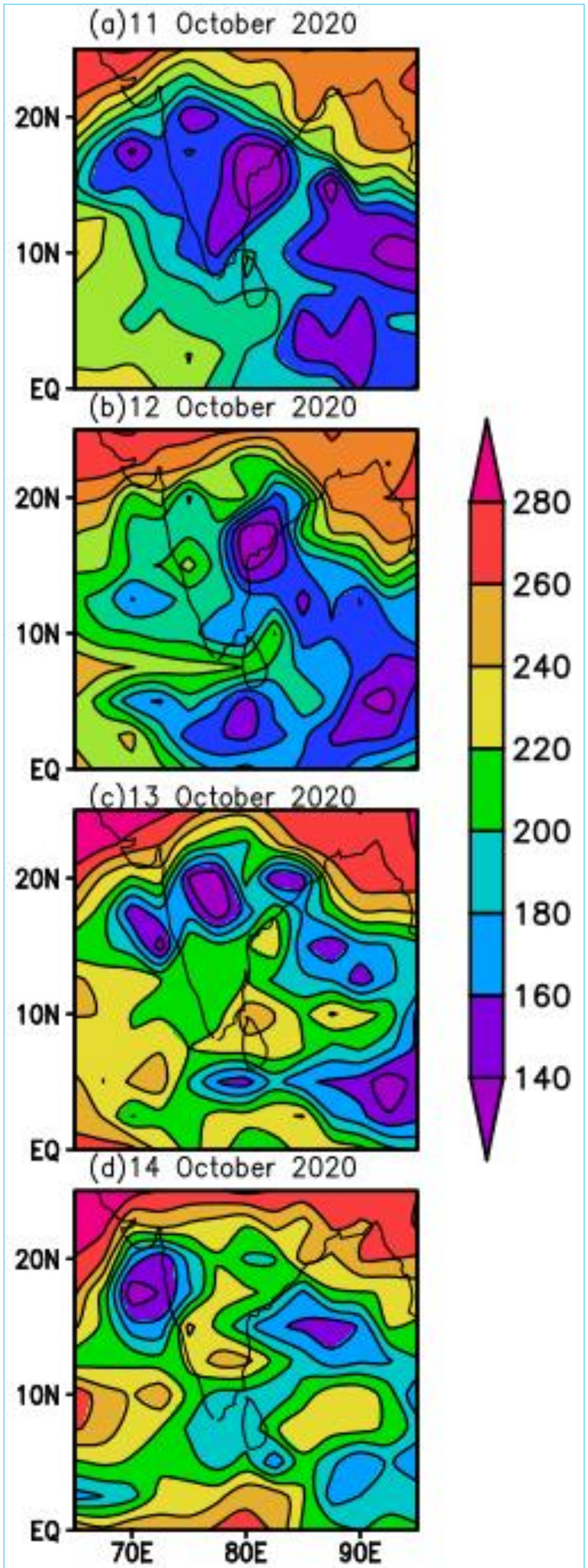
Fig. 3. Significant synoptic systems on 13 October, 2020 over Indian region

3.2. *Synoptic conditions associated with Hyderabad heavy rainfall event*

In order to understand the origin of the event, the synoptic conditions before, during and after this event have been studied. It is interesting to note that the Indian summer monsoon (ISM) was in the withdrawal phase. The withdrawal line of the Southwest Monsoon was passing through Lat. 28° N/Long. 83° E, Faizabad, Fatehpur, Nowgong, Rajgarh, Ratlam, Vallabh Vidyanagar, Porbandar, Lat. 21° N/Long. 65° E and Lat. 21° N/ Long. 60° E (Fig. 3).

In the receding monsoon phase, the formation of Low-Pressure Areas (LOPAR) over BoB is a common occurrence during the post-monsoon season (October to December). During their journey to the Arabian Sea, these LOPARs move west-northwestwards, bringing significant rainfall to the southwest sector (Rao 1976; Sikka 1977). Fig. 4 depicts the evolution of Outgoing Longwave Radiation (OLR) from October 11 to 14, 2020. Cold cloud tops emitting low OLR values are usually indicative of deep convective clouds. A deep convective cloud is represented by an OLR minimum. Convective clouds are defined as OLR <240 Wm^{-2}. As a result, negative OLR anomalies indicate the presence of convection/cloudiness in the area.

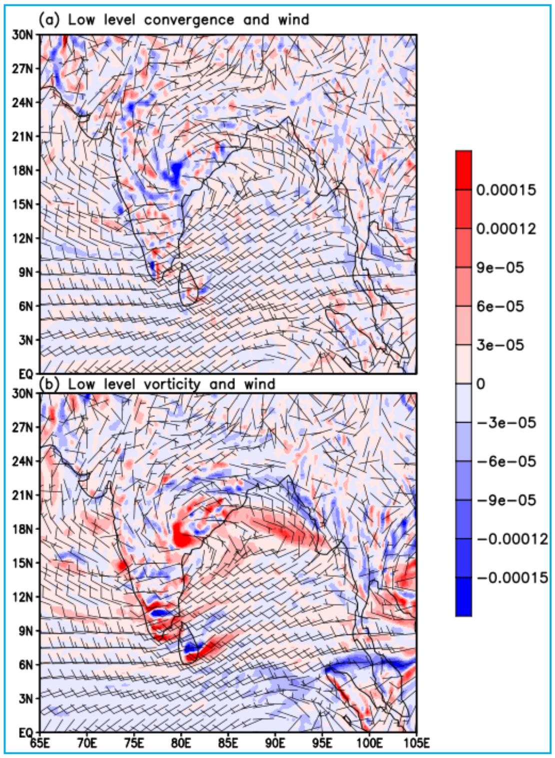
The formation of a low-pressure area (LOPAR) over west-central (BoB) and its subsequent northwestward movement may be seen in the figures. A Depression formed at latitude 15.3° N and longitude 86.5° E as a well-defined low-pressure depression across east-central and adjoining the southeast Bay of Bengal. A cyclonic circulation forms across north interior Karnataka and its vicinity, while other forms over Andhra Pradesh and its



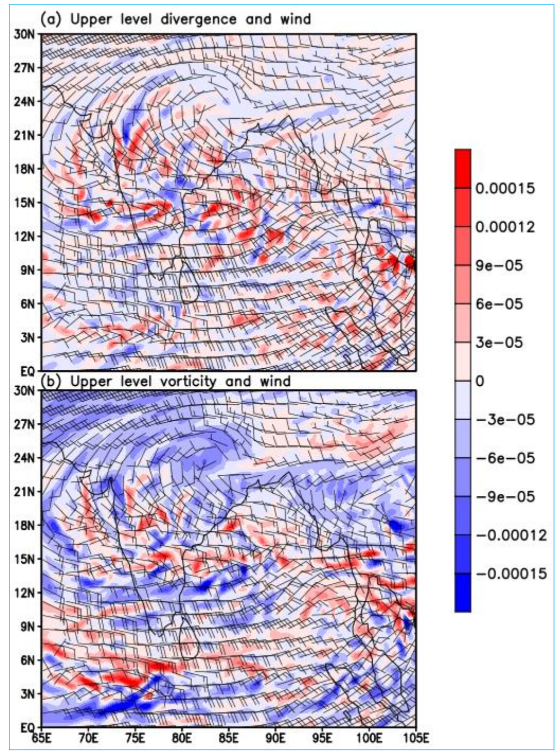
Figs. 4(a-d). Evolution of Longwave outgoing radiation (Wm^{-2}) for the period 11-14 October 2020

adjacent areas [Fig. 4(a)]. On October 12th, 2020, depression over the west-central Bay of Bengal deepened into a Deep Depression at latitude 15.9° N and longitude 84.8° E, about 250 km south-southeast of Vishakhapatnam (Andhra Pradesh) and 290 km east-southeast of Kakinada (Andhra Pradesh) [Fig. 4(b)]. It crossed the north Andhra Pradesh coast near Kakinada (around Lat. 17.0° N and Long. 82.4° E) as a Deep Depression between 0630 and 0730-hours IST on October 13th [Fig. 4(c)], with maximum, sustained wind speeds of 55-65 kmph gusting to 75 kmph. In the next 06 hours, it travelled west-northwestward and weakened into a Depression. From the last two days, the trough extended between 3.1 and 5.8 km above mean sea level from the cyclonic circulation associated with the aforesaid system to the east-central Arabian Sea roughly along Lat. 15° N across coastal Andhra Pradesh, Rayalaseema, coastal and north interior Karnataka. On the 14th of October, 2020, it continued to move west-northwestward through north interior Karnataka and the territories of Maharashtra and Telangana, near Lat. 17.7° N / Long. 77.5° E, and emerged into the east-central Arabian Sea off the coast of Maharashtra [Fig. 4(d)].

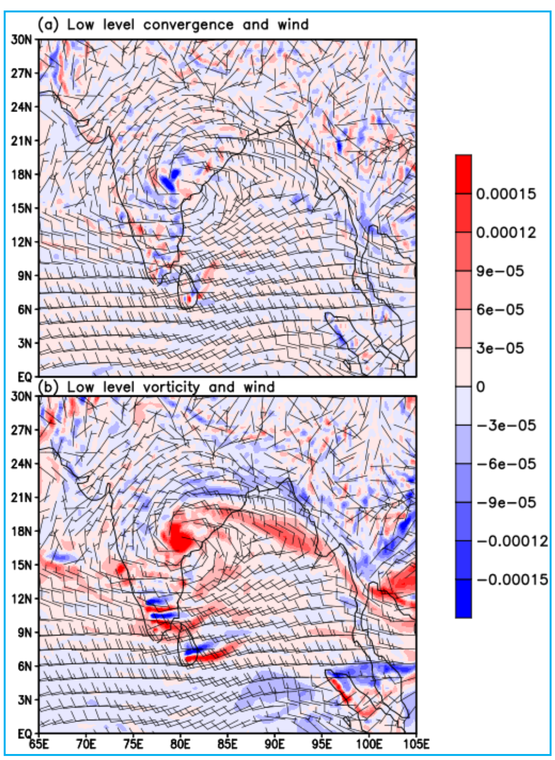
The LOPAR/depressions are synoptic-scale cyclonic circulations that occur over the northern BoB. Climatologically, MDs that originate in or around the Bay of Bengal propagate northwestward (Sikka 1977). This unusual movement of depressions embedded in strong lower-tropospheric westerlies has been attributed to a quasi-geostrophic vortex stretching west-southwest (Rao and Rajamani 1978), the convergence maximum being southwest of the centre (Krishnamurti *et al*., 1975), or anomalous circulation being supported by latent heat release above the precipitation maximum in the same place (Chen *et al*., 2005). Several investigations have been conducted to determine what causes low-pressure systems to intensify into depressions. The combination of lower tropospheric convergence and high tropospheric divergence is a key synoptic phenomenon that contributes to extremely heavy rainfall occurrences. These characteristics are also linked to upper-level positive vorticity and advection, which help in the northern BoB's upward motion and lower-level convergence. However, in some situations, the development of depression occurs without adequate modifications in the upper tropospheric circulation prior to the time of intensification. One of the reasons for LOPAR formation over the region is the presence of strong monsoon westerlies to the south of the genesis area, as well as the strengthening of the lower tropospheric westerlies over peninsular India (Daggupaty and Sikka 1977). Most of the depressions that emerge near the head of the BoB are related to pressure disturbances arriving from the east as remnants of typhoons from the Eastern Pacific Ocean (Saha and Chang, 1983). LOPAR



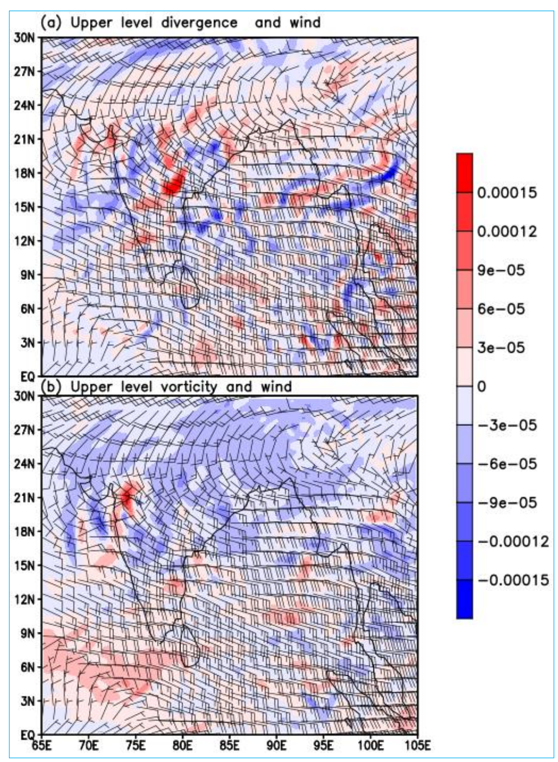
Figs. 5(a&b). (a) Low-level convergence and wind (b) Low-level vorticity and wind at 925 hPa on 13th October, 2020 (1200 UTC)



Figs. 7(a&b). (a) Upper-level divergence and wind (b) Upper-level vorticity and wind at 200 hPa on 13th October 2020 (1200 UTC)



Figs. 6(a&b). (a) Low-level convergence and wind (b) Low-level vorticity and wind at 850 hPa on 13th October, 2020 (1200 UTC)



Figs. 8(a&b). (a) Upper-level divergence and wind (b) Upper-level vorticity and wind at 100 hPa on 13th October 2020 (1200 UTC)

TABLE 2

Current weather reported half-hourly at Rajiv Gandhi International Airport and Begumpet Airport on 13th October 2020 during 1030 to 1730 UTC

Time of Observation (UTC)	Rajiv Gandhi International Airport (VOHS)			Begumpet Airport (VOHY)			Remark
	Weather	Visibility (Meters)	Wind Direction/Wind Speed	Weather	Visibility (Meters)	Wind Direction/Wind Speed	
1030	-RA	2000	300/09KT	+RA	1000	300/14KT	Cb
1100	RA	2000	300/12KT	+RA	1000	320/18KT	Cb
1130	RA	2000	310/10KT	+RA	2000	320/18KT	Cb
1200	RA	2000	300/12KT	TSRA	1500	320/10KT	Cb
1230	TSRA	2000	320/12KT	TSRA	1500	310/09KT	Cb
1300	TSRA	2000	330/12KT	TSRA	1500	310/08KT	Cb
1330	TSRA	2000	340/14KT	TSRA	1500	320/10KT	Cb
1400	+TSRA	2000	340/15KT	TSRA	1500	320/13KT	Cb
1430	+TSRA	2000	310/15KT	TSRA	800	330/10KT	Cb
1500	+TSRA	2000	310/15G25KT	TSRA	800	340/11KT	Cb
1530	+TSRA	2000	310/15G25KT	TSRA	800	340/05KT	Cb
1600	+TSRA	2000	320/15G25KT	TSRA	800	330/06KT	Cb
1630	TSRA	2000	320/09KT				Cb
1700	TSRA	2000	330/09KT				Cb
1730	TSRA	2000	340/08KT				Cb

RA= Rain, TSRA= Thunderstorm with rain, Cb= Cumulonimbus cloud, G= Gusting, and KT= Knots. If any precipitation begins with a minus or plus (-/+), it is either light or heavy

development and intensification are attributed to vertical wind shear and convective instability of the second kind (CISK). Cumulus convection is principally responsible for maintaining the monsoon depression. By releasing heat at appropriate levels above the cold-core of the depression, where a slight warm-core exists, cumulus convective heating provides eddy available potential energy. The rising of relatively warm air here contributes greatly to the depression's generation of eddy (Krishnamurti *et al.*, 1976). Various mechanisms for the occurrence of a Depression over the northern BoB during the SW monsoon season have been discussed. The northwestward migration of these disturbances causes extensive rainfall along the course, with particularly heavy rainfall in the southwest.

3.3. *Mesoscale system embedded in favourable synoptic-scale flow pattern*

It is clear that large-scale features alone cannot explain such a massive rainfall event. We tried to dig further into both synoptic and mesoscale aspects to see whether there was any scale interaction that might have resulted in such a catastrophic rainfall event over Hyderabad. Figs. 5-8 and 11 depict a large-scale flow pattern over the Indian subcontinent seen at 1200 UTC on October 13th, 2020 at various standard levels of the atmosphere. It indicates a strong cyclonic circulation reaching up to mid-tropospheric levels with height above Hyderabad, as well as a well-defined low-pressure area on the surface. We have shown wind speed and direction alongwith low level convergence and vorticity for 925 hPa (Fig. 5) and 850 hPa levels (Fig. 6) as well as upper air divergence and vorticity at 200 (Fig. 7) and 100 hPa levels to support this (Fig. 8). We also measured relative humidity and vertical velocity at 500 hPa (Fig. 11) to better understand the rising wind's high moisture content and vertical motion around 1200 UTC on October 13th, 2020. First, we will look at wind: Fig. 7 depicts the depression's 850 hPa wind speed and direction. The maximum wind intensity may be found in the relative northeast, around 2 degrees from the centre, while a local minimum can be found over Hyderabad. We observed northwesterly winds with a speed of 10 knots seen in the lower level at 925 hPa over Hyderabad (Fig. 6), which turn northerly at 850 hPa (Fig. 6), northeasterly at 500 hPa

(Fig. 11), and easterly at 200 hPa (Fig. 7), indicating that winds veered with height during the current rainstorm. Veering is defined as the turning of the wind direction clockwise as we travel higher in the atmosphere, which is always accompanied by warm air advection (Holton 1979). As a result, wind conditions at the lower tropospheric level were ideal for moisture intrusion from the bordering BoB before and during the current heavy downpour. Analysis of the data for the lower tropospheric level shows that convergence is more pronounced at 925 hPa (Fig. 5) and the horizontal vorticity at 850 hPa level. We observed that the long axis of low-level moisture convergence at 0850 hPa and large values of horizontal vorticity at 0925 hPa were oriented parallel to the direction of the mean wind with high precipitable water. In this situation, supercells thunderstorms form in the area of moisture convergence. This synoptic feature indicates that heavy rain will likely last longer and result in higher total rainfall quantities. The depression contributes a weak anticyclone at 200 hPa to the much stronger monsoonal jets at this height at 100 hPa (Fig. 7).

As a result, we noticed that deep, moist convection reached up to 200 hPa over Hyderabad. Above the core, there is a minimum wind speed, just as there is above tropical cyclones (DeMaria 1996). The background flow provides the vertical shear that prevents depressions from developing into cyclones in mid-summer, resulting in a bimodal distribution of tropical cyclones in the Northern Indian Ocean, with maximum in May and November and minima in February and August (Ramage 1959; DeMaria 1996; Kikuchi and Wang 2010). As a result, we noticed that deep, moist convection reached up to 200 hPa over Hyderabad.

Between 1030 and 1730 UTC on October 13th, 2020, the half-hourly current weather reports of Rajiv Gandhi International Airport (RGIA) and Begumpet Airport (BA) were investigated to determine the Thunderstorm activity over Hyderabad city (Table 2).

Cumulonimbus (Cb) was identified as the main observable cloud responsible for thunderstorms with heavy rain at 1030 UTC. For an hour, severe rain was reported at Begumpet Airport, decreasing visibility to roughly 1000 metres. Then, in the late afternoon, around 1200 UTC, this Cb cell expanded over a large area. Around 1400 UTC, the rainfall intensity grew even more as a strong thunderstorm with rain and lightning was reported over both airports simultaneously. The intense spell of rain lasted for one hour between 1500 to 1600 UTC with gusting of wind of 25 Knots at RGIA and visibility of 800 meters at BA. Recorded 3 hourly rainfalls for Begumpet Airport show that around 14.7 cm rain reported between 1200 to 1800 UTC (Fig. 9). The

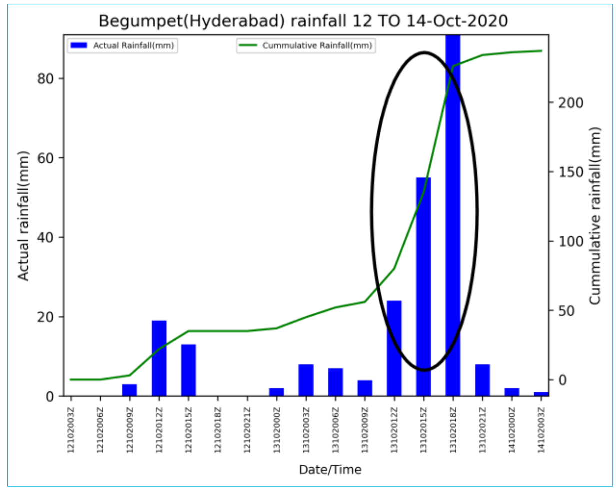


Fig. 9. Recorded 3 hourly and cumulative rainfall for Begumpet Airport from 12 October, 0300 UTC to 14 October, 0300 UTC

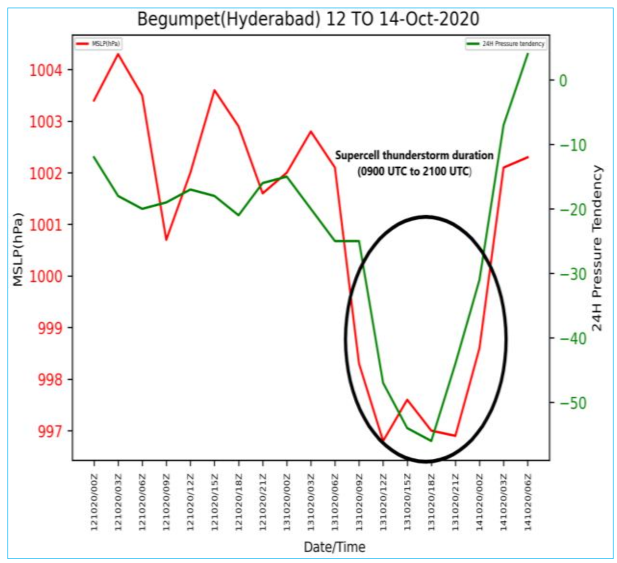
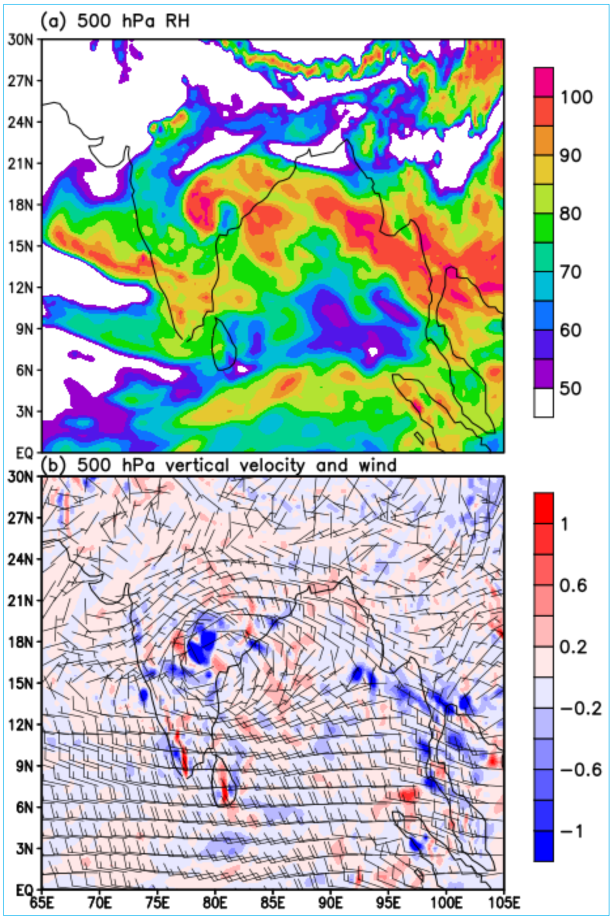


Fig. 10. Recorded 3 hourly Mean Sea level pressure (hPa) and 24 hrs Pressure change for Begumpet Airport from 12th October 0000 UTC to 14th October, 0600 UTC

previous all-time heaviest rainfall in 24 hours recorded (available in the National Data Archives of the India Meteorological Department) was reported by Begumpet Airport over Hyderabad only on three occasions: (24.2 cm in August 2000, 190.5 cm in August 1954 and 19.2 cm in October 2020). The passage of the Depression was observed over the city caused by changes in surface pressure and the duration of time it lasted (Fig. 10). The mean sea level pressure (MSLP) declined from 1002.1 hPa at 0600 UTC to 996.8 hPa at 1200 UTC on the following day. MSLP was below 1000 hPa up to 0000 UTC on 14 October. It was also observed that



Figs. 11(a&b). (a) Relative humidity and wind (b) Vertical velocity and wind at 500 hPa on 13th October, 2020 (1200 UTC)

24-hour negative pressure departure persisted for more than 9 hours, with the lowest pressure change at 1800 UTC (-6.0 hPa). With the slower westward translation of the depression's, increased low-level moisture convergence lasted longer over an area, probably leading to multiple-cell regeneration.

In order for a multi-cellular thunderstorm to form, three variables were present: instability, an uplifting mechanism, and moisture in the lower and mid-levels of the atmosphere in this case. Near the ground, an unstable air mass was warm and moist, but relatively cold and dry in the high atmosphere. Air that was pushed upward has continue to climb as the air mass was unstable. Synoptic-scale low-level convergence and differential heating were used to push the air higher. Moisture condensed as air rises in a thunderstorm updraft, forming convective clouds as enough moisture was present. When moisture condensed, it releases heat into the air, making it warmer and less dense than its surroundings, allowing the updraft to continue. On the 13th of October, the presence of a

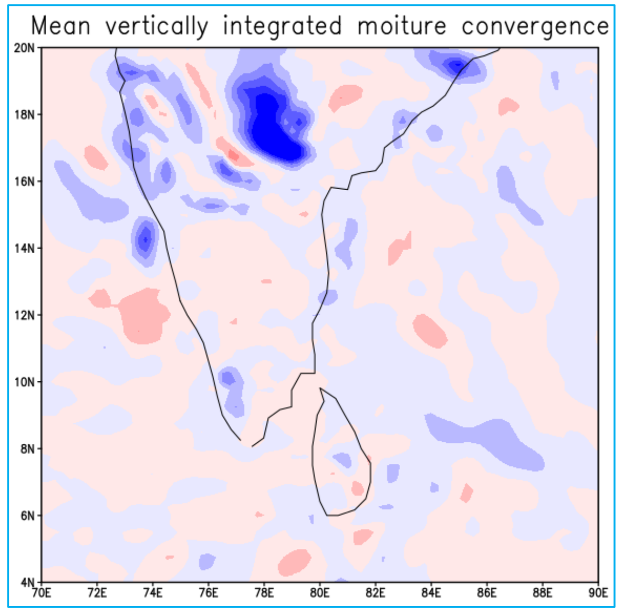


Fig. 12. The Mean vertical integrated moisture convergence on 13th October at 1200 UTC

highly moist air mass at large depth from the BoB in the lower levels, along with the instantaneous presence of strong low-level convergence (Figs. 5&6), leads to severe convection and the development of a thunderstorm cell over Hyderabad. Multi-cellular storms with short-lived updrafts will be preferred if the vertical wind shear is weak (McNulty 1995). Extreme instability, strong vertical wind shear, and an intrusion of dry air at mid-level are the three decisive elements in such circumstances (Johns and Doswell's 1992; McNulty 1995) research. In the instance of Hyderabad, the vertical wind shear was quite strong at 500 hPa, resulting in storms with long-lasting updrafts (Fig. 11). Fig. 12 depicts the Mean vertical integrated moisture convergence (MVIMC) for Hyderabad city on October 13, 2020 at 1200 UTC (from 1000 to 500 hPa). During this incident, a high negative anomaly of MVIMC was seen over Hyderabad and the surrounding areas. This means that ascended air contains a lot of water vapor and a fast ascent rate, which allowed for the formation of severe thunderstorms and a lot of precipitation. The ascent rate and mixing ratio of the ascending air, which was very high in this case, are supposed to be proportional to the instantaneous rainfall rate at a specific place. The condensation rate, which is the ultimate source of precipitation, can be related to the vertical moisture flux (Fig. 12).

$$\text{VIMFC} = \frac{-1}{g}\int_{P1000}^{P500}\left(\frac{\partial uq}{\partial x}+\frac{\partial vq}{\partial y}\right)dp \tag{1}$$

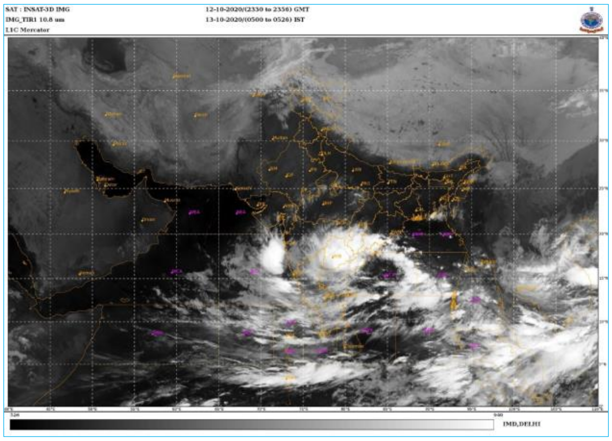


Fig. 13. Enhanced infrared satellite image over the Indian region at 2330 UTC, 12 October, 2020

As a result, this system's moist convection and the rapid ascent of air over the region was favorable for the development of supercell thunderstorms, resulting in extremely heavy rainfall.

Fig. 11 shows that relative humidity was approximately 90% at 500 hPa level at 1200 UTC on the 13th of October. An updraft in the low level caused by convergence (Figs. 5&6), along with relatively severe ambient vertical wind shear, may have prompted the development of the additional lifting mechanism required for the occurrence of this type of supercell thunderstorm above Hyderabad. The size and intensity of rainfall associated with convective systems appear to be influenced by relative humidity at 500 hPa, which in this case was above 90%. However, on a smaller scale, with high precipitable water and relative humidity exceeding 70%, less extreme episodes occurred, demonstrating that other elements regulate the scale of a system. But, the core of the strongest rains, on the other hand, frequently fell inside the 500 hPa axis of maximum relative humidity (Fig. 11).

3.4. *Satellite observed convective supercell development*

We noted that processes outside of the convective storm also influenced the propagation of convective development. These features that existed independently previous to the emergence of convection on the 13th of October at 0000 UTC (Fig. 13).

Fig. 13 depicts the development of convective cells prior to this event on the morning of October 13th. Low-level convergence at 0850 hPa and vorticity at 0925 hPa characterize this convective cell development. The generation of new convective cells may be impaired as a

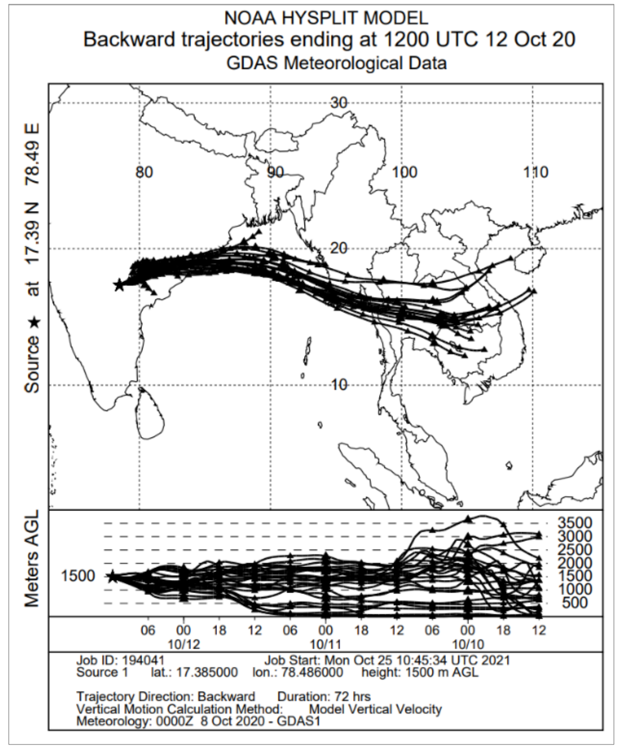
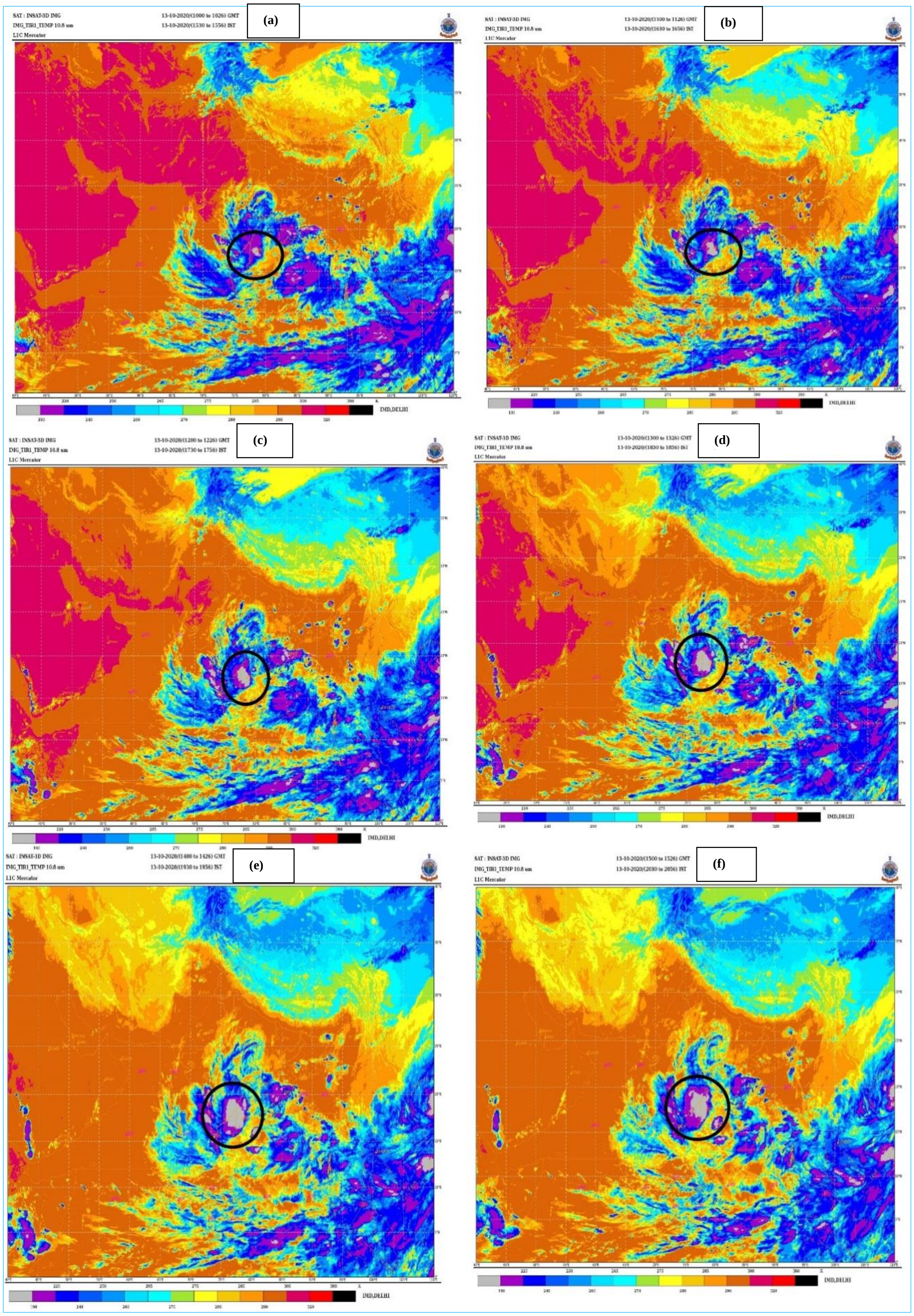


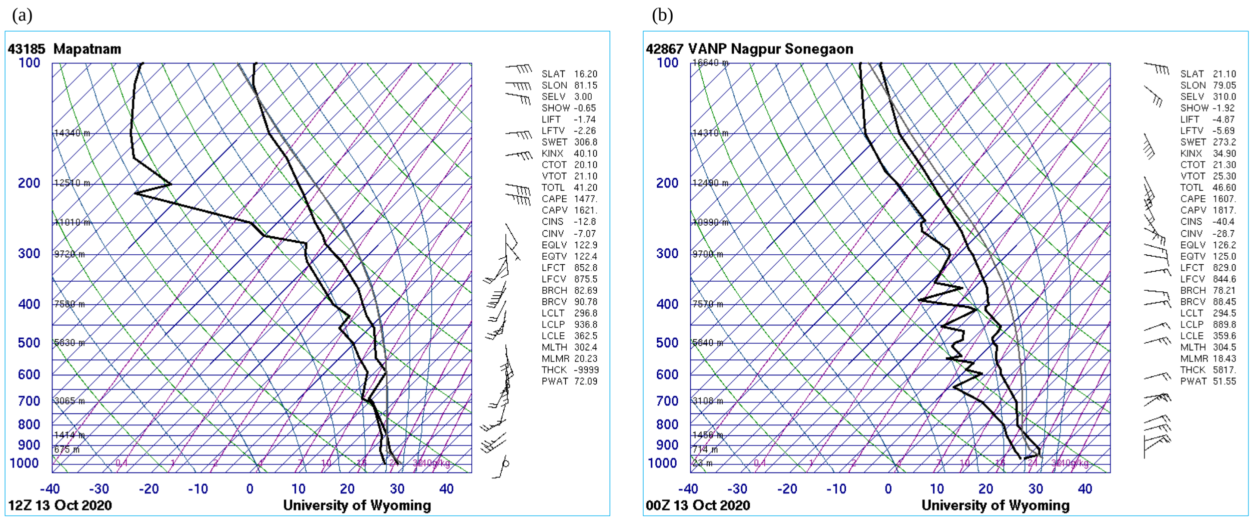
Fig. 14. Three-day back air parcel trajectories for Hyderabad, 12th October, 2020

result of this. When anticipating a system movement, these external factors must be considered. This is an ideal situation for a long-duration convective rainfall event when cells move roughly parallel to a slow-moving outflow boundary, leaving a quasi-stationary segment of the boundary behind into which a substantial moist boundary-relative flow is impairing, creating new cells that repeat the motion of their predecessors. The additional cells strengthen the boundary, keeping it in place against the inflow. As long as the moist unstable inflow is maintained, such a system can last for many hours.

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler and Hess, 1998) from the National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory is a complete system for computing simple air parcel trajectories as well as complex transport, dispersion, chemical transformation, and deposition simulations. In the atmospheric sciences community, HYSPLIT is still one of the most widely used air transport and dispersion models. We used the NOAA HYSPLIT model to undertake a 72-hour back trajectory analysis to better understand the origins of the air masses that arrived in the study region (Draxler and Rolph, 2003). The GDAS (Global Data Assimilation) dataset (reprocessed from



Figs. 15(a-f). Enhanced infrared satellite image over the Indian region at (a) 1000 UTC, (b) 1100 UTC, (c) 1200 UTC, (d) 1300 UTC, (e) 1400 and (f) 1500 UTC, 13th October, 2020. Enhancement corresponds to cloud-top temperatures of -64 °C



Figs. 16 (a&b). Vertical profile of (a) Machilipatnam and (b) Nagpur, at 1200m UTC on 13th October, 2020 (*Source* : University of Wyoming)

National Centres for Environmental Prediction (NCEP) by Air Resources Laboratory) was used as the meteorological input for the trajectory model. These trajectories were calculated for 12 October, 2020 at an altitude of 1500 meters (0850 hPa). Air mass arrived in Hyderabad from the Eastern Bay of Bengal, Equatorial Indian Ocean, South China Sea, and Western Pacific Ocean, and then travelled over the Bay of Bengal (Fig. 14). Fig. 14 shows the trajectories on the 12th of October. From 10 to 12 October, we noticed that the ITCZ was active over the western Pacific and into the Bay of Bengal around 10 °N. We discovered that all paths pass *via* an area of low-level convergence, which appears to be the primary source of moisture transport over Hyderabad. The moisture transport method for the precipitable water, which has been proven from the figure, is critical for intense rainstorm events to occur.

3.4.1. *Mesoscale Convective Complexes (MCCs)*

Maddox (1980) was the first to describe the large, persistent mesoscale convective structures that can arise called mesoscale convective complexes (MCCs). This categorization of convection is based solely on satellite-observable characteristics. Since persistent convection is inevitably multicellular in character. Almost every persistent convective system will develop a substantial anvil, thus, making is appears as an MCC on satellite, with the anvil size depending on updraft strength and the number of convective cells. It has been demonstrated in many studies of MCCs (Houze *et al*., 1989, Smull and Weisman 1993, Loehrer and Johnson 1995) that systems meeting MCCs criteria have their convection arranged in a more or less linear fashion as seen on radar. Such MCCs have a trailing stratiform precipitation region that can contribute to storm precipitation totals and exacerbate the flash flood threat by a prolonged period of moderate rainfall that follows the initial, shorter duration period of the most intense precipitation. Mesoscale Convective Complex (MCC) is a combination of Cumulonimbus clouds with low shear and high Convective Available Potential Energy (CAPE), with a duration of more than 6 hours (heavy rain 3 hours) and a vast region with an index CAPE stability of 1750 J/kg (Laing and Fritsch, 1993). MCCs can contribute to a special sort of evolution that can produce flash floods, as in the case of Hyderabad on 13th October 2020. Satellite imagery of the Indian Subcontinent and its surroundings reveals the presence of a mesoscale convective system with characteristics that are very comparable to those observed in MCCs. The evolution of the convective cell over Hyderabad between 1000 and 1500 UTC is observed in Fig. 15. This system was primarily nocturnal in nature and tended to form over or in close proximity to land. This MCC has a cloud shield with a continuous low IR temperature of less than -33 °C over an area of more than 100000 km^2 and a cloud shield with a continuous low IR temperature of less than -54 °C over an area of more than 50000 km^2 [Fig. 15(f)], fully satisfying the MCC definition over Hyderabad. This MCC has a life cycle of about 9 hours.

When the observational resolution is high enough, supercells often exhibit multicellular traits, thus, we do not consider a supercell to be a single-cell event (Doswell and Burgess 1993). In the case of flash floods, supercells' proclivity for heavy updrafts is critical. Due to their interaction with the environment, such storms can contribute significantly to their updraft through dynamic

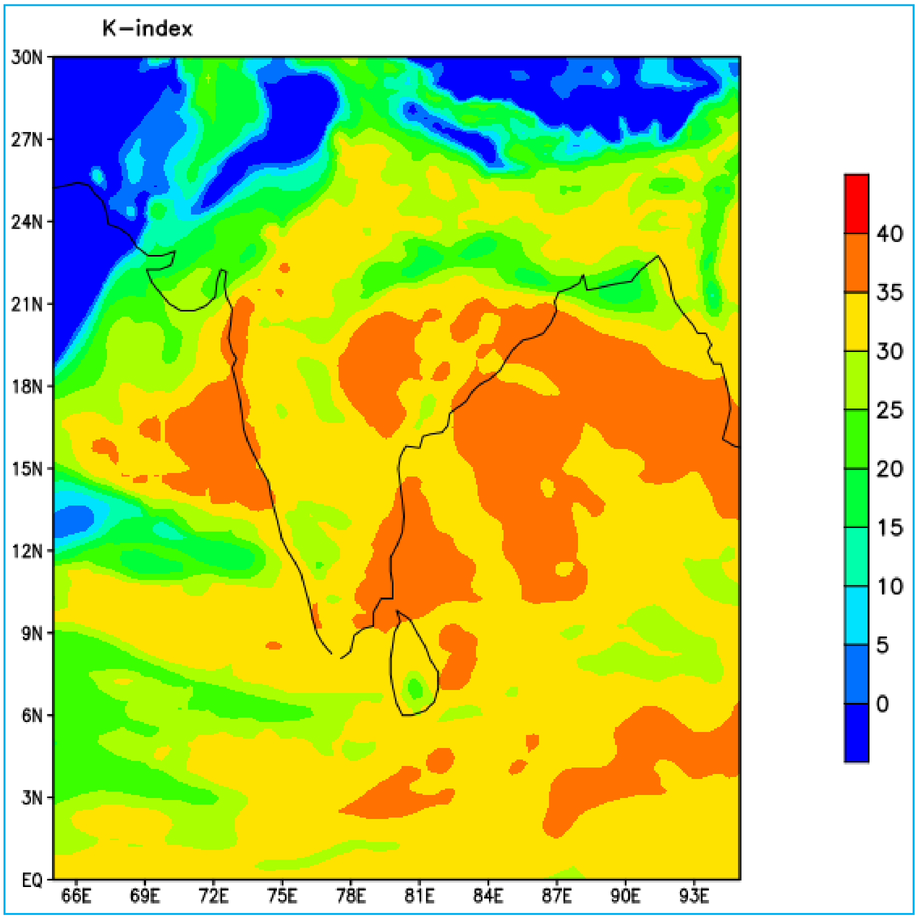


Fig. 17. The K-index from ERA -5 Reanalysis on 13th October at 1200 UTC

vertical acceleration (Rotunno 1993). Because supercells are known for having a lot of low-level moisture in their environment, the combination of strong updrafts and a lot of low-level moisture increases the chance of heavy rainfall.

3.5. *Analysis of thermodynamic conditions*

We studied atmospheric sounding data to see if the atmospheric thermodynamic conditions above Hyderabad favored the formation of such localized violent thunderstorms nested in large-scale favourable monsoon circulation. The moist airstream was continually elevated over peninsular India in the presence of a very strong low-pressure system in this scenario. Since there was no Radio-sonde Radio-wind ascent on the 13th and 14th of October in Hyderabad, the most representative ascents from Machilipatnam on the coast of Andhra Pradesh, where the depression crossed over land, and Nagpur in central India, which is north of Hyderabad, was used for the vertical profile (Fig. 16). The ascent from Machilipatnam indicated that the wet-bulb's potential temperature (*w*) was around 20 °C at 1200 UTC on October 13th, with roughly neutral stability up to 700 hPa. It is described as a deep, moist, conditionally unstable layer with a relative humidity greater than 70% from the surface to 300 hPa [Fig. 16(a)]. The convective available potential energy (CAPE) was 1477 J/kg, which is more than 1000 J/kg, indicating that the atmosphere is moderately unstable. Looking at the 1200 UTC ascent of Nagpur [Fig. 16(b)], we can see that the CAPE value, as well as the lower Convective Inhibition (CIN) values, indicates a more conditionally unstable atmosphere over inland areas than over Machilipatnam's coastline station. Due to the withdrawal phase of the monsoon, there was no capping of the stable layer, resulting in the aforementioned usual extensive convection.

Variation in atmospheric convection over the tropics is influenced by both dynamic and thermodynamic instability indices. The K index (KI) was created to determine the likelihood of severe thunderstorms (Tyagi 2011). The moist layer depth is determined by a combination of the lapse rate, lower-level moisture content, and lapse rate. The K index was determined to be in the range of 35 to 40. (Fig. 17). The existence of highly unstable atmospheric conditions over Telangana is indicated by the value of this index. Extremely heavy rains in and around Hyderabad were caused by adequate moisture supplied by the DD and a high order of convective instability over the area indicated by the index. The K index began to demonstrate atmospheric instability over Telangana well before the Deep Depression, and it was indicative of the moist flow advected from the Bay of Bengal.

4. Summary and conclusions

The Hyderabad City in Telangana state (India) experienced clusters of thunderstorms in the evening of Tuesday, October 13, 2020, resulting in high rainfall totals. In just a few hours, more than 150 mm of rain was measured in the area by a number of rain gauges, and locally as much as 320 mm. Impacts were surprisingly maximum, particularly because the majority of the rain fell over an urban area. We found that these severe rainfall occurrences were caused by a mesoscale system embedded in a favorable synoptic-scale flow pattern. The synoptic features suggest that with high precipitable water, the long axis of low-level moisture convergence at 0850 hPa and large horizontal vorticity at 0925 hPa providing ideal moisture, low-level convergence, and vorticity for convective cell development. In this case, a cluster of thunderstorms arose in the area of moisture convergence which prolongs the duration of extremely heavy rainfall. Because of the depression's slower westward translation (Fig. 10), increased low-level moisture convergence lasted longer over an area (Fig. 6), probably leading to cell regeneration and training over a common location, and hence higher system rainfall amounts. To summarise, we propose that, a number of reasons led to these thunderstorms' high precipitation efficiency (PE) as a result of the storm cell's movement and constant structural change are

(*i*) High tropospheric specific humidity.

(*ii*) High relative humidity (RH) in the medium to low levels (mean RH of 70% between the surface and 500 hPa in Fig. 11), which reduces the amount of rain that evaporates before hitting the ground.

(*iii*) Likely effective warm rain processes, such as collision-coalescence, given that a significant depth of convection was located between the parcel LCL and the freezing level.

(*iv*) High vertical velocities due to high CAPE.

According to Clark (2011), high rain rates can sometimes result from forced ascent from low-level convergence, which can increase an air parcel's vertical velocity. This may be a contributing factor to the high rain rates seen over Hyderabad. The high PE, relatively sluggish storm motion, and prolonged back-building over the same locations for several hours are likely to blame for the heavy rainfall accumulations that were observed. We have already mentioned that one of the main functions of the mesoscale process is to generate the lift required for convective initiation. Furthermore, MCC-related mesoscale processes have been implicated in a variety of heavy precipitation occurrences (Tyagi *et al*., 2012). This MCC has a cloud shield with a continuous low IR temperature of less than -33 °C over an area of more than 100000 km^2 and a cloud shield with a continuous low IR temperature of less than -54 °C over an area of more than 50000 km^2 over Hyderabad with a life cycle of about 9 hours. We found that system propagation was in two ways: first, through their usual organizational structure, which includes both a deep convective and a so-called stratiform component. As a result, heavy precipitation over Hyderabad, the deep convective component of MCC, supplied a very high rate of precipitation throughout the system's passage, whereas moderate rainfall in the trailing region contributed to the overall precipitation event's long duration. Third, this MCC frequently produces vast pools of outflow that continue for many hours after the rain-producing convection has subsided, and which play a critical role in the initiation of subsequent convection, resulting in a slow-moving MCC.

In metropolitan areas of Hyderabad, artificial surfaces with various thermal qualities are used to replace natural land surfaces (*e.g.*, heat capacity and thermal inertia). These surfaces are frequently better at absorbing solar energy and transforming it into usable heat. When sensible heat is transmitted to the air, metropolitan areas often have air temperatures that are 2° to 10 °C greater than those of the nearby non-urban areas (Shepherd *et al*., 2001). As a result, urban areas alter boundary layer processes by producing an Urban Heat Island (UHI), which can significantly affect mesoscale circulations and the subsequent convection (Shepherd *et al*., 2001). The question of how the process of urbanisation affected the distribution of precipitation was raised in the early 19th century (XiQuan *et al*., 2009). The initial study by Changnon *et al*. (1971) revealed that urbanisation caused summertime precipitation to increase. Burian & Shepherd (2005) Zhang *et al.* (2014) and Yang *et al*. (2015) have recently examined potential changes in urban area rainfall due to urbanisation. Urbanization may have a bearing on how much rain falls during the day, according to a 2005 theory by Burian and Shepherd. According to Kishtawal *et al*. (2009), urbanisation has caused changes in intense rainfall over India. In order to avert such calamities, the civic administration must decide whether the city's city plan requires quick readjustment. The need for long-term urban planning has been underscored once again in the aftermath of this natural disaster. As a result, urban flood control in developing countries involves consideration of socioeconomic concerns related to land use and urban development (Tucci, 2004). To determine the causes of heavy rainfall and urban floods in Indian cities, as well as the chances of such events occurring, more research is needed.

5. Statements and declarations

Competing interest

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript. The authors have no relevant financial or non-financial interest to disclose. The contents and views expressed here are those of the contributors and do not necessarily reflect the views of the organization to which they belong.

Data availability statement

The interested reader can obtain the datasets underlying the findings of the article by contacting Gauravendra P. Singh (gauravendra.singh@gmail.com). The data set used in the study is as follows rainfall (https://imdpune.gov.in/ClimPredLRFNew/GridedDataDownload.html), atmospheric wind field (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5), OLR field (https://psl.noaa.gov/data/gridded/data.uninterpOLR.html), Satellite-derived brightness Temp. (https://www.satmet.imd.gov.in/insat.htm) and Airback trajectory data (http://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-14-00110.1).

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

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