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Meteorological conditions associated with the unprecedented weather activity over eastern parts of Uttar Pradesh, India on 16 & 17 September, 2021

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सार – **यह शोधपत्र 16 और 17 सितंबर 2021 के दौरान भारत के उत्तर प्रदेश के पूर्वी भागों के कुछ स्थानों पर दर्ज की गई भारी वर्षा की घटना से संबंधित है, और संबंधित मौसम संबंधी स्थितियों की जांच की गई है। प्रत्येक भारी वर्षा की घटना संबंधित उपयोगकर्ताओं के मौजूदा ज्ञान में सुधार के लिए प्रमुख वैज्ञानिक दस्तावेजीकरण की हकदार है। भले ही इससे आम जनता को भी लाभ हो सकता है, क्योंकि भारी वर्षा इस क्षेत्र में सभी को चिंतित करती है। यह केस स्टडी उपरोक्त उद्देश्य की पूर्ति करेगी और नीति निर्माताओं, आपदा प्रबंधकों, आपदा प्रतिक्रिया और शमन के लिए उपयोगी हो सकती है।**

भारी वर्षा की घटना के लिए अनुकूल मौसम संबंधी स्थितियों के संबंध में, यह पाया गया है कि संक्षेप में इस क्षेत्र में एक सक्रिय वेल मार्क्ड लो-प्रेशर सिस्टम था। इसके अलावा, सकारात्मक सापेक्ष भंवर, ऊपरी-स्तरीय विचलन, उच्च सापेक्ष आर्द्रता, निचले-स्तरीय अभिसरण और ऊर्ध्वाधर वेग (ओमेगा) प्रोफाइल जैसी अन्य स्थितियों ने भी एक अनुकूल पर्यावरणीय तंत्र प्रदान किया। बंगाल की खाड़ी से पूर्वी/दक्षिण-पूर्वी हवाओं के माध्यम से निरंतर नमी की आपूर्ति मध्य क्षोभमंडल स्तर (500 hPa) तक फैली हुई थी, जो वर्षा की घटनाओं की घटना के लिए एक और महत्वपूर्ण कारक था। यह मामला एक उदाहरण के रूप में कार्य करता है कि भारत में 200 hPa पर एक सक्रिय जेट कोर की अनुपस्थिति में भी, पूर्वी उत्तर प्रदेश में बहुत भारी/अत्यधिक भारी वर्षा हो सकती है।

ABSTRACT. This paper is concerned with the heavy rainfall episode reported over some locations of the eastern parts of Uttar Pradesh, India during 16 & 17 September 2021 and the associated meteorological conditions are investigated. Each heavy rainfall episode deserves major scientific documentation for the improvement in the existing knowledge of the concerned users. Even though it may also benefit the general public, as heavy rainfall concerns everybody in the domain. This case study will serve the above purpose and may be useful for policymakers, disaster managers, disaster response, and mitigation.

Regarding the favourable meteorological conditions for heavy rainfall episode, it is found that synoptically there was an active Well Marked Low-Pressure system over the region. In addition, other conditions like positive relative vorticity, upper-level divergence, higher relative humidity, lower-level convergence, and vertical velocity (Omega) profiles also provided a favorable environmental mechanism. Continuous moisture supply from the Bay of Bengal through easterly/southeasterly winds extended up to middle tropospheric levels (500 hPa), which was another important factor for the occurrence of rainfall episodes. This case serves as an example that even in the absence of an active Jet core at 200 hPa over India, very heavy/extremely heavy rainfall may occur over east Uttar Pradesh.

Key words – Southwest monsoon, Heavy rainfall, Meteorological analysis, East Uttar Pradesh.

1. Introduction

The rainfall studies are done at different levels, for example at the levels of the country, the state, the district level, or location-specific. The rainfall analysis at the national level is done by (Sathiyamoorthy *et al.*, 2010; Kumar *et al.*, 1992; Guhathakurta *et al.*, 2011a and Guhathakurta *et al.*, 2011b). Trends of extreme rainfall events are another important fact and have been studied by (Subbaramayya and Naidu, 1992; Munot *et al*., 2000; Kumar *et al*., 2010; Das *et al*., 2014; Pai and Sridhar, 2015; Pattnaik and Rajeevan, 2010; Singh *et al*., 2019; Nikumbh *et al*., 2019; Paul *et al*., 2018; Satyanarayana and Kar, 2016) and a study on observed changes in southwest monsoon rainfall over India during 1901-2011 by Guhathakurta *et al*. (2015).

Rainfall Patterns and General Atmospheric Circulation have been documented in a very generic study by Winstanley (1973). Thermodynamic characteristics associated with localized torrential rainfall events in the southwest region of the Korean peninsula have been studied by Jung *et al*. (2015). Kumar *et al*. (2017) discussed the meteorological features at the national level that are related to the heavy rainfall observed during the first week of March 2015. Physical and dynamic factors associated with the heavy rainfall event over themiddle Korean Peninsula on 26-27 July 2011 were studied by Lee *et al*. (2017).

In a recent study, the meteorological features associated with the heavy rainfall event observed on 14th July 2016 at Yamuna Nagar (Haryana, India) were documented by Narasimha *et al*. (2021). This study was mainly focused on location-specific, as they investigated radar and satellite features for the movement of clouding and convection. In another recent study, Tomar (2022) investigated the meteorological features of a severe weather event that occurred on the 23rd of May 2016 over parts of northwest India. With the application of Radar data, the cloud burst event over Chennai was studied by Ray and Kannan (2022). Microphysical structures of location-specific extreme rainfall events over the coastal Metropolitan City of Guangzhou have been studied with the application of Polarimetric Radar by Wang *et al*. (2022).

The Indian summer monsoon rainfall (ISMR) is an important source of rainwater for different natural and manmade resources, including water resources, rivers and agriculture and overall, it is related to the economy of the country. Monsoon rainfall occurs in spells, and sometimes heavy to very heavy rainfall is reported over different parts of the country in just a couple of days, with some incidences of exceptionally heavy rainfall events recorded during the monsoon period. Heavy rainfall events have also been observed in September 2021. The related details and data sets are also available in the report, which can be accessed at the following link: https://www.imdpune.gov.in/cmpg/Product/Monthly_Climate_Summary/Monthly_Clim_Summary_9_2021.pdf.

The performance of southwest monsoon rainfall in 2021 was deficient during June and July but normal during August and September over eastern parts of Uttar Pradesh. Refer to the monsoon report available online at Weather in India MONSOON SEASON (June - September 2021) MAUSAM (imd.gov.in) for more information. This case study is concerned with the heavy rainfall spell reported during September 14-17, 2021 over the eastern parts of Uttar Pradesh. During this spell, Azamgarh and Furshatganj reported exceptionally heavy rainfall and broke the previous climatological records for September. The main objective of this study is to review the meteorological conditions associated with the heavy rainfall spell.

The remainder of the paper is structured as follows: Section 2 presents the case description, followed by Section 3 which outlines the data and methods used. Section 4 provides an analysis of Satellite Imagery, while Section 5 discusses the meteorological conditions. Finally, Section 6 offers a brief conclusion.

2. Case description

India Meteorological Department (IMD) has classified India into 36 meteorological sub-divisions. The state of Uttar Pradesh is classified into two meteorological sub-divisions namely west and east Uttar Pradesh. Accordingly, in this study, heavy rainfall spell reported over east Uttar Pradesh during the period of15-17 September 2021 has been investigated in terms of meteorological conditions. The heavy spell impacted parts of east Uttar Pradesh. Flood events were reported over the same region. (refer to IMD's statement on climate summary for the months of September 2021, the same is available at https://www.imdpune.gov.in/ cmpg/Product/ Monthly_Climate_Summary/Monthly_Clim_Summary_9_2021.pdf).

According to the India Meteorological Department (IMD)'s statement on the climate summary for the month of September 2021, districts in eastern parts of Uttar Pradesh (including Barabanki, Basti, Ballia, Chitrakoot, Ghazipur, Fatehpur, Kaushambi and Lucknow) reported deaths due to flood and heavy rain during 14-18 September 2021. Station locations experiencing heavy rainfall can be found in the same report, not only for Uttar Pradesh but also for other parts of the country.

IMD follows the standard criteria for heavy rainfall classification (Table 1). In this study, the same criteria are applied. To explain RR24 (24 hours cumulative recorded rainfall) for a non-meteorologist or a common man, let us take a practical example. If we consider the 24-hour accumulated realized (reported) rainfall over a station such as 'Azamgarh' on 17th September to be 370.0 mm, this means that this rainfall occurred during the period from 0300 UTC of 16th September to 0300 UTC of 17th

TABLE 1

IMD classification of Heavy Rainfall. RR_{24} stands for 24-hour cumulative rainfall during 0300 UTC of previous day to 0300 UTC of current day (*Source* : IMD's forecasting Circular 2015)

Category	RR_{24} (cm) (0300 UTC of previous day to 0300 UTC of present day24-hour cumulative rainfall)
Heavy rainfall	$7 \le RR_{24} \le 11$
Very Heavy Rainfall	$12 \le RR_{24} \le 20$
Extremely Heavy Rainfall	$RR_{24} \ge 21$
Exceptionally Heavy Rainfall	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm

TABLE 2

Record Breaking rainfall reported during September 2021 (*Source* : IMD's statement on climate summary for the month of September, 2021)

Station	RR_{24} (mm)	Date	Previous Record
Azamgarh	370.0	17-09-2021	225 mm on 14-09-1976
Furshatganj	186.3	16-09-2021	137.8 mm on 27-09-2019

TABLE 3

Stations reported extremely heavy rainfall (*Source* : IMD)

Station	RR_{24} (cm)	Date
Azamgarh	37	17-09-2021
Ayodhya	37	17-09-2021
Laharpur	28	17-09-2021
Ramnagar	24	17-09-2021
Tirwa	23	17-09-2021
Tanda	21	17-09-2021
Sirauli Gauspur Tehsil	21	17-09-2021

September. Sometimes popularly it is called 24 hours accumulated rainfall on 0300 UTC of 17th September. Accordingly, the same pattern is followed in this paper. In similar fashion, the data in Tables 2 or 3 may be explained by the readers.

To illustrate the impact of the heavy rainfall spell, record-breaking rainfall was reported at several stations in Uttar Pradesh. Specifically, exceptionally heavy rainfall was recorded at two stations in east Uttar Pradesh: Azamgarh and Furshatganj (Table 2). During the period from 0300 UTC of 16th September, 2021 to 0300 UTC of 17th September, 2021, seven stations reported extremely

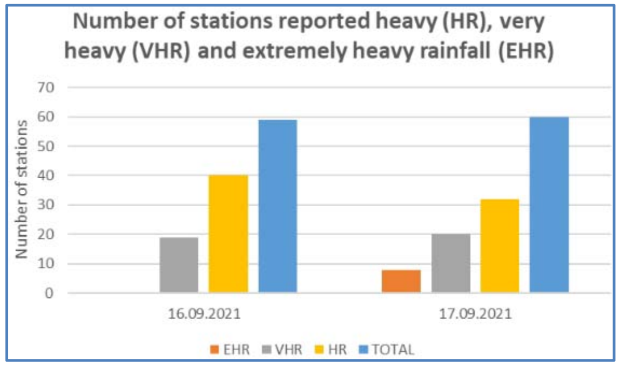
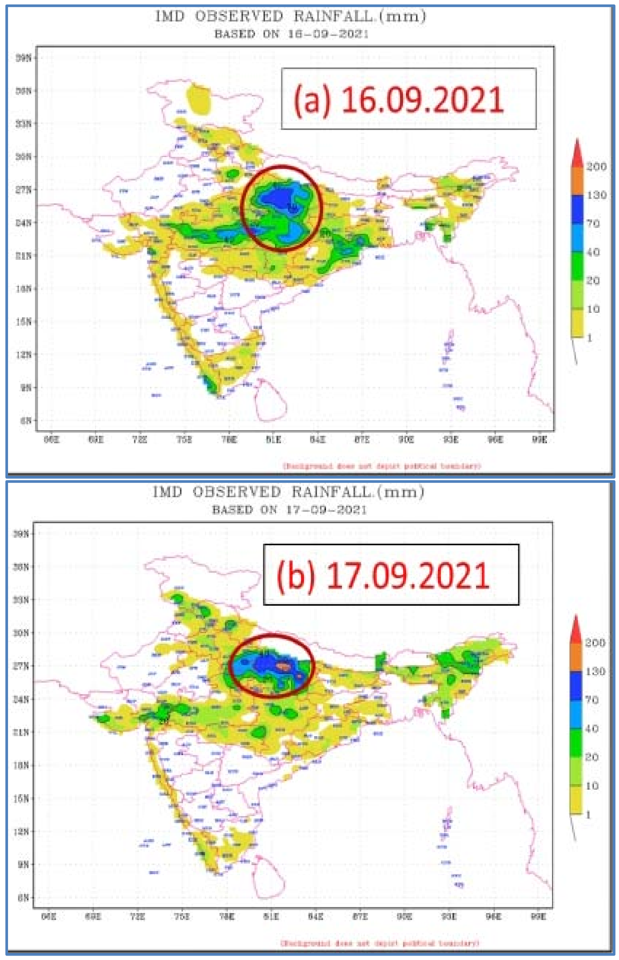
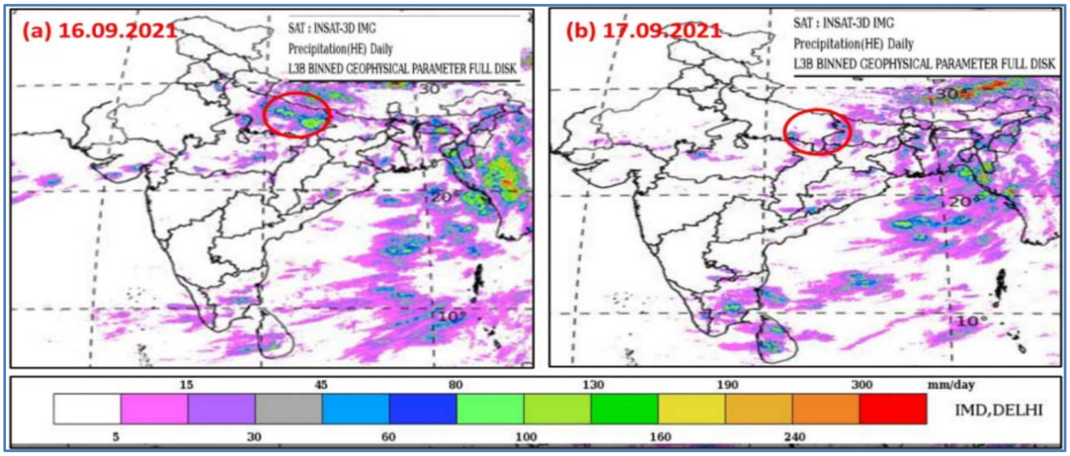


Fig. 1. No. of Stations reported heavy rainfall (≥7 cm) over East Uttar Pradesh on 16th & 17th September, 2021 (*Source* : IMD)

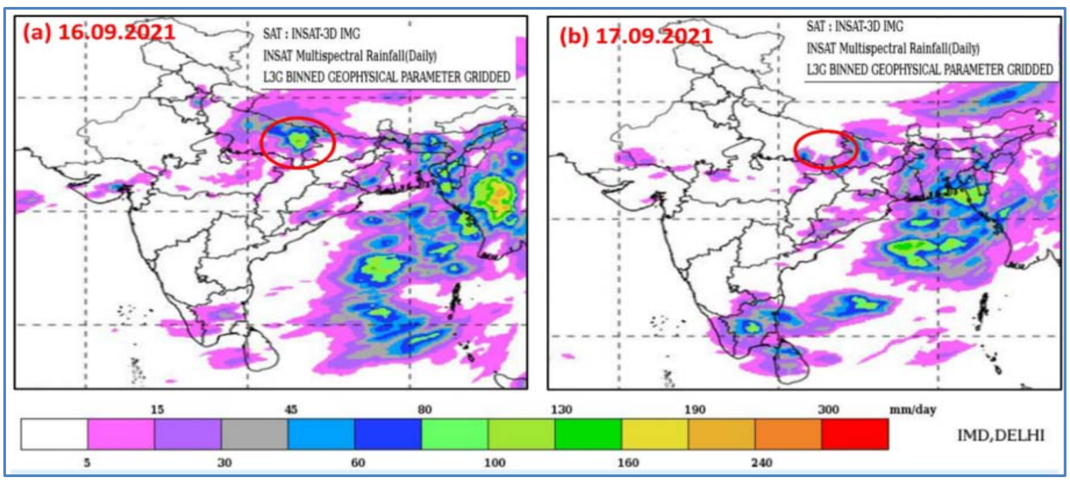


Figs. 2(a&b). IMD Observed Rainfall over East Uttar Pradesh on 16th & 17th September 2021 (*Source* : IMD)

heavy rainfall (Table 3). The number of stations reporting heavy rainfall (≥7 cm) over East Uttar Pradesh on 16th & 17th September, 2021 is depicted in Fig. 1, while the realized rainfall is illustrated in Fig. 2. It is evident from Fig. 1 that extremely heavy rainfall was reported on 17th



Figs. 3(a&b). Precipitation (HE) [HEM] daily from INSAT-3D during 15-17 September, 2021



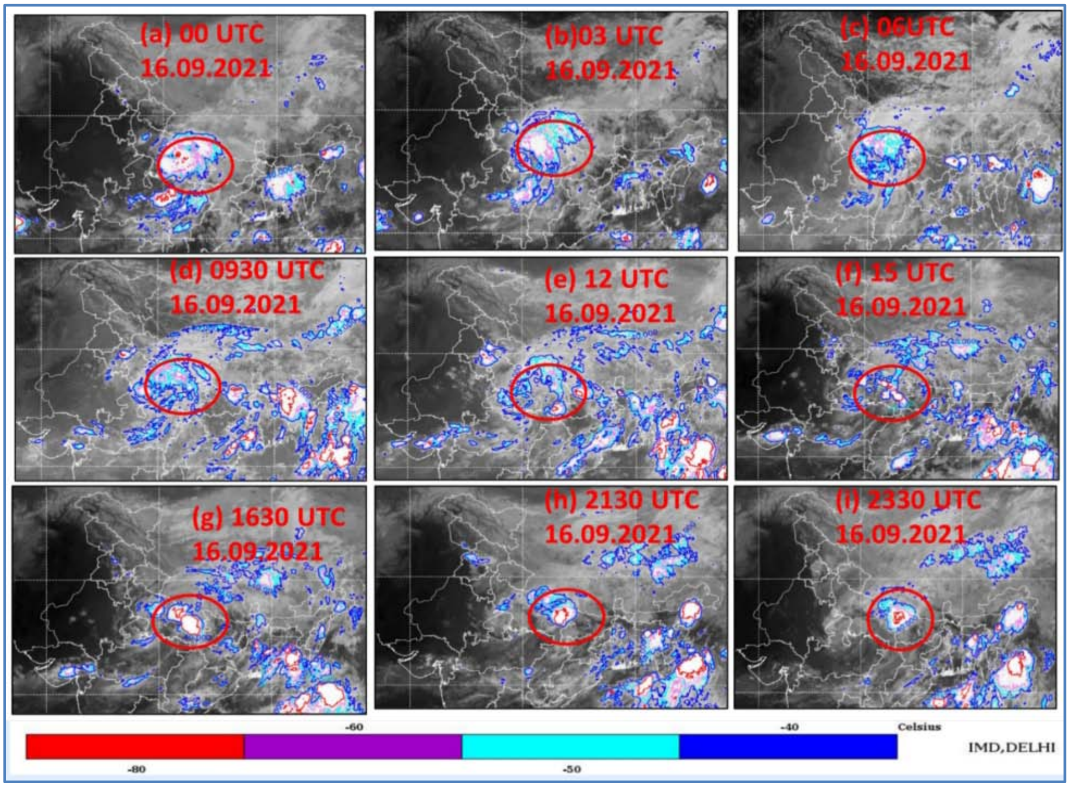
Figs. 4(a&b). Multispectral Rainfall (daily) [IMR] from INSAT-3D during 15-17 September, 2021

September, 2021. Furthermore, Fig. 2 indicates that rainfall of 7-13 cm was reported over east Uttar Pradesh on 16th September, followed by 13-20 cm over the same sub-division on 17th September, 2021.

3. Data sources and methods

This study primarily relies on the analysis of meteorological data to investigate severe weather events reported over east Uttar Pradesh. The identification of heavy rainfall cases involves the use of both manual observations and remote sensing tools, such as satellites. Rainfall data from rain gauges and observatories is obtained from the India Meteorological Department (IMD). Additionally, rainfall estimation products, such as Rainfall using Hydro Estimator (HEM) from Satellite INSAT 3D (HEM, per pixel) and INSAT Multi-Spectral Rainfall Algorithm (IMSRA) generated IMR (0.1 deg. × 0.1 deg.) product, are collected from IMD to estimate realized rainfall. Gridded format data for realized rainfall is obtained from the Numerical Weather Prediction (NWP) Division of IMD. Dynamical parameters, including relative vorticity, convergence, divergence, *etc*., are sourced from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) (https://tropic.ssec.wisc.edu).

To identify prevailing synoptic systems, data analysis includes wind at different levels, surface pressure and other parameters obtained from the Numerical Weather Prediction (NWP) division of the India Meteorological Department (IMD). Daily and anomaly data for mean air temperature, vertical velocity (Omega), relative humidity, *etc*., are downloaded from the reanalysis of the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) Reanalysis, available at https://psl.noaa.gov/data/composites/day/.



Figs. 5(a-i). CT-BT imageries from 0000 UTC-2330 UTC of 16th September, 2021

The synoptic analysis is conducted under four different categories to better understand the vertical extension (depth) of the associated synoptic systems, facilitating the identification of possible meteorologically favorable weather systems.

(*i*) *Analysis at Surface level* : This involves isobaric analysis for mean sea level pressure and wind analysis at 10 meters above the surface.

(*ii*) *Analysis at lower tropospheric levels* : Tropospheric levels up to 600 hPa (4.5 km above mean sea level) are considered. This paper utilizes data from 925 hPa, 850 hPa, and 700 hPa for lower-level analysis. Relative vorticity profiles at 850 hPa and 700 hPa and lower-level convergence (LLC) are also examined.

(*iii*) *Analysis at middle tropospheric level* : Analysis at the 500 hPa level is conducted to assess synoptic systems prevailing at middle levels. Relative vorticity profiles at 500 hPa are also analyzed.

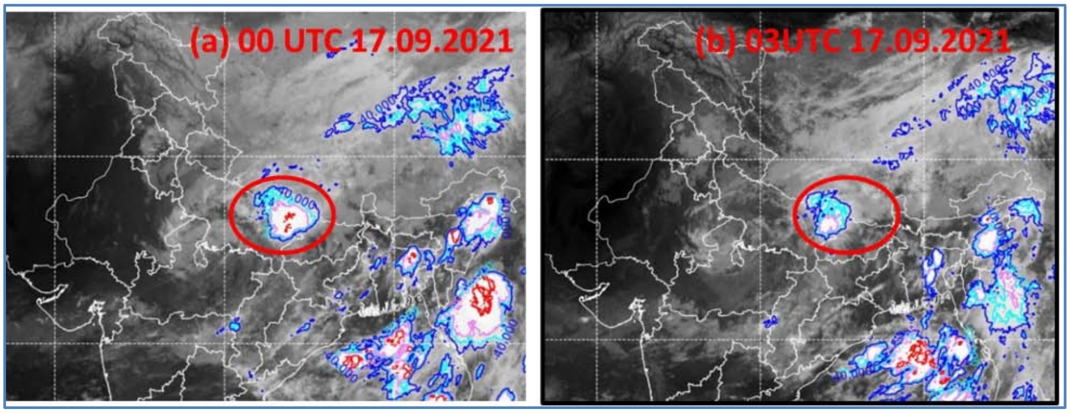
(*iv*) *Analysis at upper tropospheric levels* : Tropospheric levels beyond 500 hPa are considered upper tropospheric levels. Wind analysis at 200 hPa is performed, along with the examination of relative vorticity profiles and upper-level divergence (ULD) at the 200 hPa level.

4. Analysis of Satellite Imageries

In this case study, we monitored cloud movement and intensity using remote sensing tools, specifically satellite imagery. We investigated products from the Indian satellite INSAT 3D.

We first analyzed satellite imagery to estimate observed rainfall. For this purpose, we used satellite products (HEM & IMR) from INSAT 3D (Figs. 3 & 4). Rainfall (>80 mm) was reported over East Uttar Pradesh on 15th and 16th September, 2021 [Fig. 3(a)]. There was a spatial reduction in observed rainfall reported on 17th September, 2021 [Fig. 3(b)], although isolated patches of heavy rainfall (>80 mm) were reported over east UP adjoining Bihar and southeast UP [Fig. 3(b)]. The same rainfall pattern is consistent in the IMR (0.1 deg. × 0.1 deg.) product [Figs. 4(a&b)].

We analyze the Cloud Top-Brightness Temperature (CT-BT) images of INSAT 3D from 0000 UTC on 14th March to 2330 UTC on 17th September, 2021 (images from 16th & 17th September are provided for reference). A small convective cloud mass (-40°C) over the border of eastern Uttar Pradesh and Bihar persisted from 0000 UTC to 0500 UTC on 14th September, with slight intensification to around -50-60 °C occasionally during



Figs. 6(a&b). CT-BT imageries from 0000 UTC-0300 UTC of 17th September, 2021

the period over southeast UP. At 0800 UTC of the same day, further intensification was reported over southeast UP of the order of (-80 °C) and -50-60 °C over eastern UP & adjoining areas of Bihar and northeastern UP & adjoining areas of Nepal. The central parts of eastern UP remained free of convection. The same cloud conditions continued to prevail until 0930 UTC. Convection over northeastern UP and adjoining Nepal intensified, reaching the intensity of the order of (-80 °C) at 1000 UTC of the same day. Hence, the major cloud convection was observed over southeast UP and northeast UP, with weak convection of the order of -40 °C in isolated pockets over the remaining parts of eastern UP. The same conditions persisted until 1130 UTC. Consequently, until 1330 UTC, the major convection was observed over northeastern UP and adjoining Nepal, with isolated patches of the order of -50 °C to -60 °C over the remaining parts of eastern Uttar Pradesh. At 1330 UTC, convection weakened to -50 °C to -60 °C over northeastern UP and adjoining Nepal, with isolated patches of the order of -50 °C over the remaining parts of eastern UP, and the same conditions persisted until 1500 UTC. Thereafter, convection weakened further with isolated patches of the order of -50 °C until 2330 UTC of the same day.

At 0000 UTC on 15th September, no significant convection was observed over eastern UP. Thirty minutes later, at 0030 UTC, convective clouds were observed over border areas of Bihar and eastern UP. These clouds persisted over the same region until 0600 UTC with no reported movement. At 0630 UTC, fresh convective clouds entered southeast UP from Madhya Pradesh and persisted until 0730 UTC. By 0800 UTC, clouds with temperatures of around -50 °C were reported over eastern UP. At 0830 UTC, major convective clouds of the order of -80 °C were observed over southeast UP, with temperatures of -50 °C to -60 °C over isolated parts of the remaining areas of eastern UP. By 0900 UTC, convective

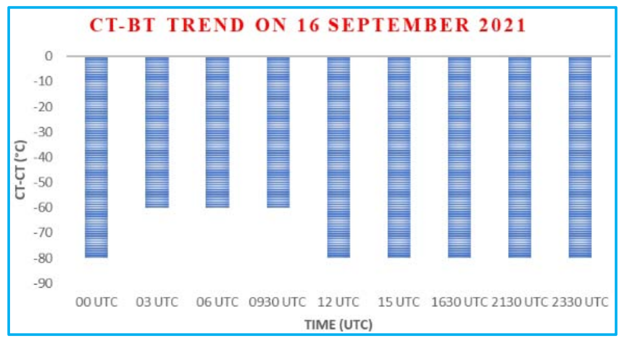


Fig. 7. CT-BT trend on 16th September, 2021

clouds with temperatures of -80 °C over southeast UP began moving north-northeastwards, covering most parts of eastern UP until 1100 UTC. Clouds continued to grow and intensify over many parts of eastern UP until 2330 UTC on 15th September, 2021.

The convective clouds maintained their intensity until 0300 UTC on 16th September [Figs. 5(a&b)]. Convection began weakening after 0300 UTC; however, spatially, clouds persisted over eastern UP until 0930 UTC, further reducing spatially after 0930 UTC and remaining weak until 1200 UTC. They then regained strength from 1500 UTC and reached an intensity of around -80 °C at 1500 UTC over eastern UP [Figs. 5(c-i)]. This patch persisted over northeastern UP until 0300 UTC on 17th September [Figs. 6(a&b)].

5. The meteorological conditions

Before delving into the detailed discussion on the associated meteorological conditions, we will briefly examine the meteorological conditions from September 12th to 15th. Following that, we will continue the meteorological discussion covering the period from

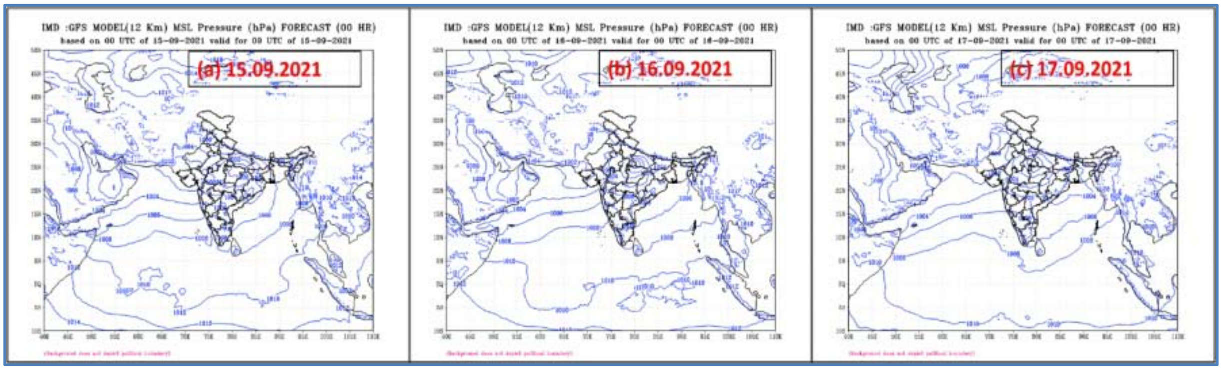


Fig. 8. IMD-GFS (12 km) Analysis of MSLP during 15-17 September, 2021

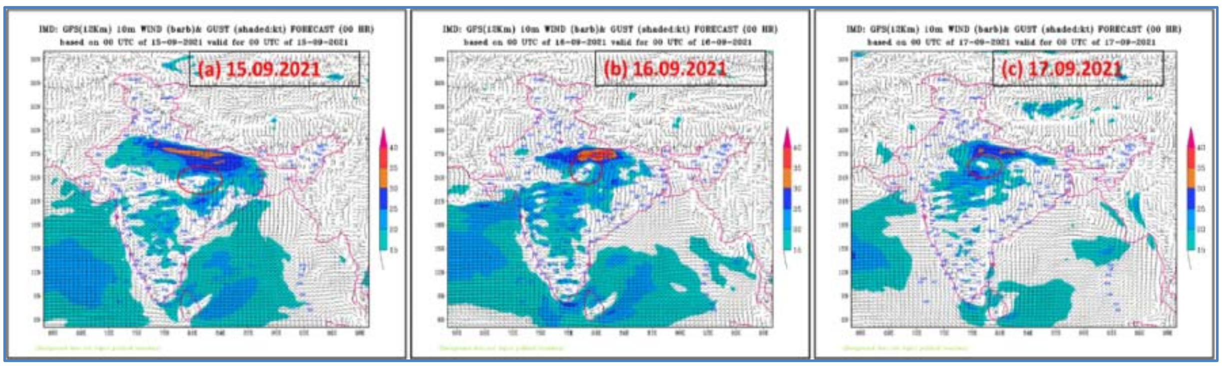


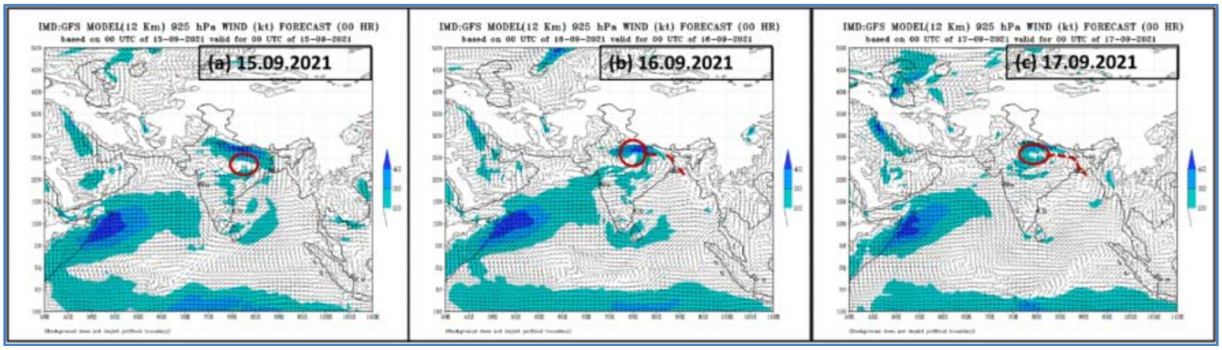
Fig. 9. IMD-GFS (12 km) Analysis of 10 m winds during 15-17 September, 2021

September 15th to 17th, 2021 in the subsequent part of this section.

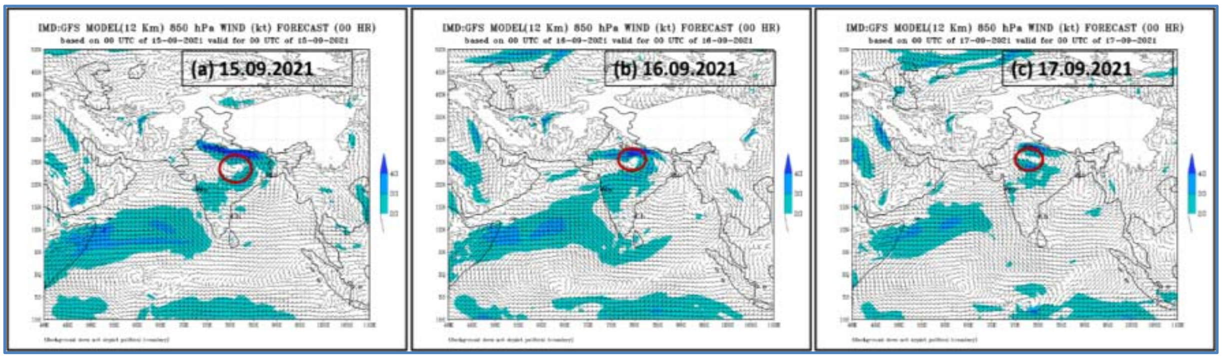
The Deep Depression : Under the influence of a pre-existing cyclonic circulation over east-central Bay of Bengal, a low-pressure area had formed over east-central and adjoining areas of northeast (NE) Bay of Bengal (BoB) at 0000 UTC on 11th September, 2021. It intensified into a well-marked low-pressure area (WML) over the northwest and adjoining west-central Bay of Bengal at 0000 UTC on 12th September, 2021. Further intensification occurred, turning it into a depression over northwest BoB and adjoining Odisha coast at 1200 UTC on 12th September, 2021. It intensified further into a deep depression (DD) over northwest BoB very close to the Odisha coast at 0000 UTC on 13th September, 2021 and crossed the north Odisha coast, close to south of Chandbali between 0000 UTC and 0100 UTC as a DD with maximum sustained wind speeds of 30 knots. Thereafter, after crossing, it weakened into a depression over the areas of north Chhattisgarh and adjoining north interior Odisha at 0300 UTC on 14th September, 2021 and into a WML over NE Madhya Pradesh and its neighborhood at 0000 UTC on 15th September, 2021. Details of this DD are available at [https://rsmcnewdelhi. imd.gov.in/]. Preliminary reports and all bulletins are available for historical and other details. The best track for DD is available at the RSMC New Delhi webpage [https://rsmcnewdelhi.imd.gov.in/uploads/report/33/33_7240f7_Best%20track%20Final%202021.pdf] and we skip those details. With this history of the previous DD, we now discuss the meteorological conditions during 15th-17th September 2021.

5.1. *Analysis at Surface level*

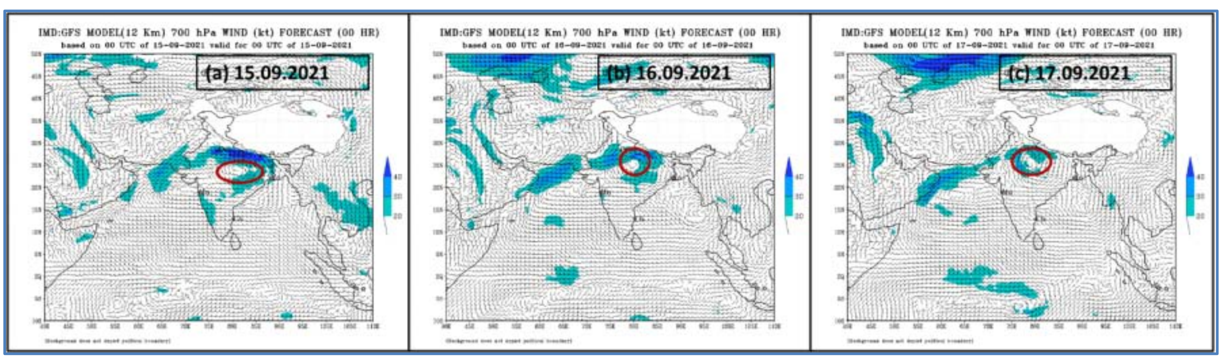
At the surface level, analysis mainly comprises isobaric analysis for mean sea level pressure and wind (10 m). At 0000 UTC on 15th September, 2021, the WML was situated over NE Madhya Pradesh & its neighbourhood [Fig. 8(a)]; over southeast Uttar Pradesh and adjoining areas during the morning hours of 16th September (0000 UTC) [Fig. 8(b)], persisting over the same region until the morning of 17th September (0000 UTC) [Fig. 8(c)]. The associated cyclonic circulation was observed over the same regions at 10 m [Figs. 9(a-c)]. Strong easterlies were also reported over the eastern parts of Uttar Pradesh, indicating continued moisture incursion from the Bay of Bengal during 15th-17th September, 2021. Therefore, meteorological conditions remained favorable at the surface level for heavy rainfall activity over eastern Uttar Pradesh during the same period.



Figs. 10(a-c). IMD-GFS (12 km) Analysis of 925 hPa winds during 15-17 September, 2021



Figs. 11(a-c). IMD-GFS (12 km) Analysis of 850 hPa winds during 15-17 September, 2021

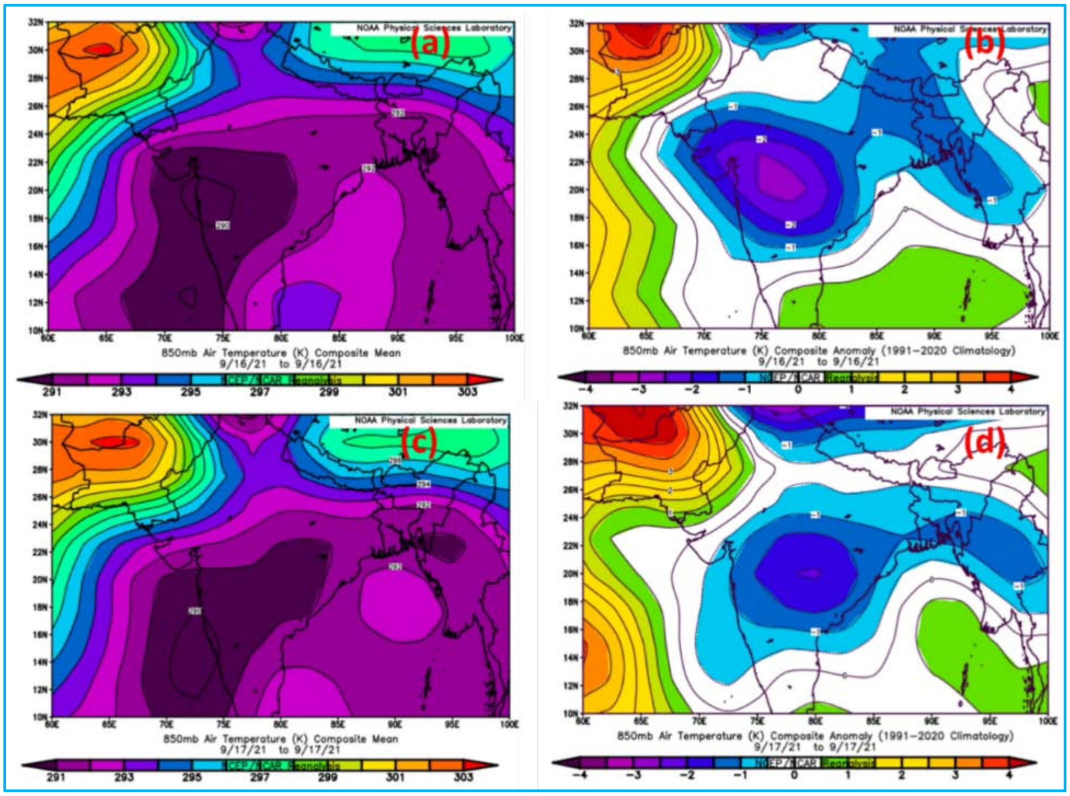


Figs. 12(a-c). IMD-GFS (12 km) Analysis of 700 hPa winds during 15-17 September, 2021

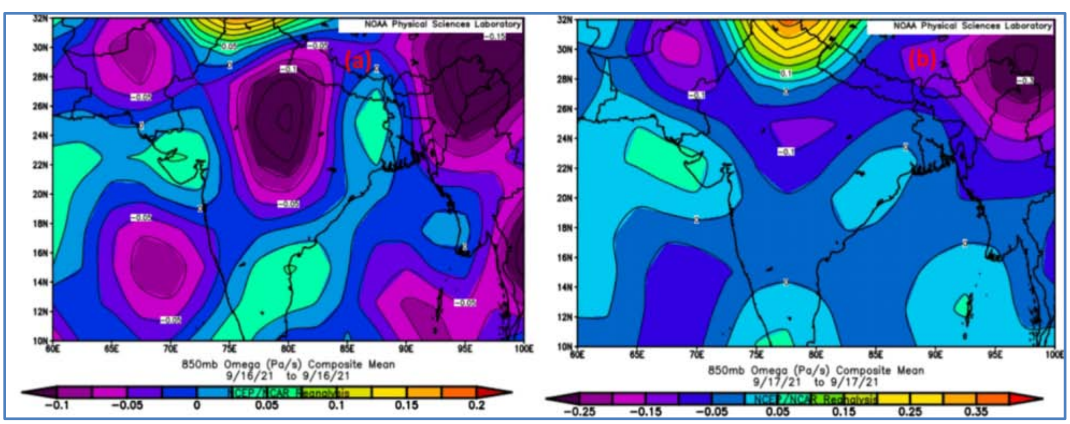
5.2. *Analysis at lower tropospheric levels*

First, we will discuss wind analysis at 925, 850 and 700 hPa levels. A cyclonic circulation associated with the well-marked low-pressure area was observed over NE Madhya Pradesh & its neighbourhood at lower tropospheric levels (925, 850 and 700 hPa) at 0000 UTC on 15th September [Figs. 10(a), 11(a), 12(a)]. Additionally, easterlies of the order of (≥40 kts) prevailed over parts of Uttar Pradesh & Bihar, while southeasterlies over Gangetic West Bengal maintained moisture supply from the Bay of Bengal to eastern Uttar Pradesh. On 0000 UTC on 16th and 17th September, associated cyclonic circulations were observed over southeast UP [Figs. 10-12 (b-c)]. Wind speeds reduced on 17th compared to 15th & 16th September, 2021. This reduction indicated a decrease in rainfall after 17th September due to reduced moisture supply from the Bay of Bengal. Overall, the moisture supply from the Bay of Bengal and an active cyclonic circulation in association with WML were favorable meteorological conditions at lower tropospheric levels.

The Mean Air Temperature (K) at 850 hPa on 16th and 17th September, along with the Air Temperature (K)



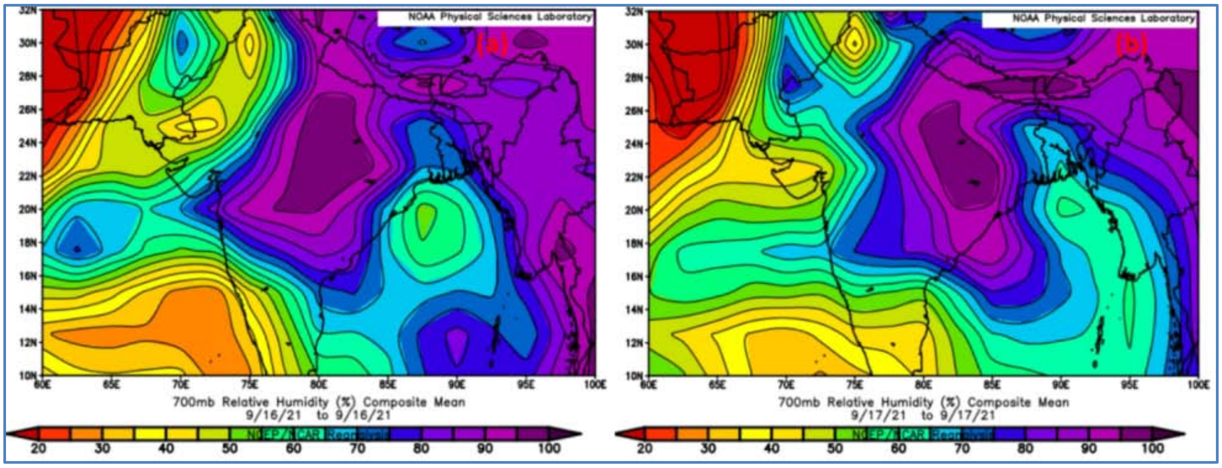
Figs. 13(a-d). (a, c) Mean Air Temperature (°K) at 850 hPa on 16th& 17th September (b, d) Air Temperature (K) Anomaly at 850 hPa on 16th& 17th September based on Climatology 1991-2020



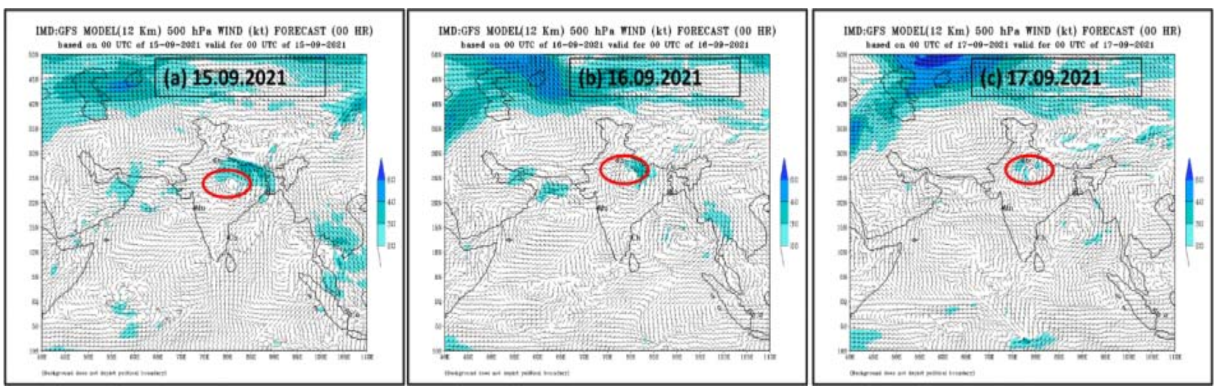
Figs. 14(a&b). Mean Vertical Velocity (Omega) at 850 hPa (a) 16.09.2021 (b) 17.09.2021

Anomaly (based on Climatology 1991-2020), is depicted in Fig. 13. Mean Air Temperature (K) at 850 hPa of the order of (≥291K) was observed over east Uttar Pradesh on 16th and 17th September, 2021, with a negative anomaly (0 to -1°C) [Figs. 13(a-d)]. As negative vertical velocity is known to be favorable for heavy rainfall over a location, the vertical velocity (Omega) collected from NCEP reanalysis is presented in Fig. 14. Negative Omega of the order of (-0.1 Pa/s) was observed over east Uttar Pradesh and adjoining areas on 16th September [Fig. 14(a)] and increased to the order of -0.05 Pa/s over the same region on 17th September [Fig. 14(b)]. This agreement suggests reduction in rainfall from 17th September, 2021. Accordingly, it is concluded that the air temperature and Omega were favorable for heavy rainfall.

The mean relative humidity at 700 hPa was more than (80%) over east Uttar Pradesh and adjoining areas



Figs. 15(a&b). Mean Relative Humidity at 700 hPa (a) 16.09.2021 (b) 17.09.2021



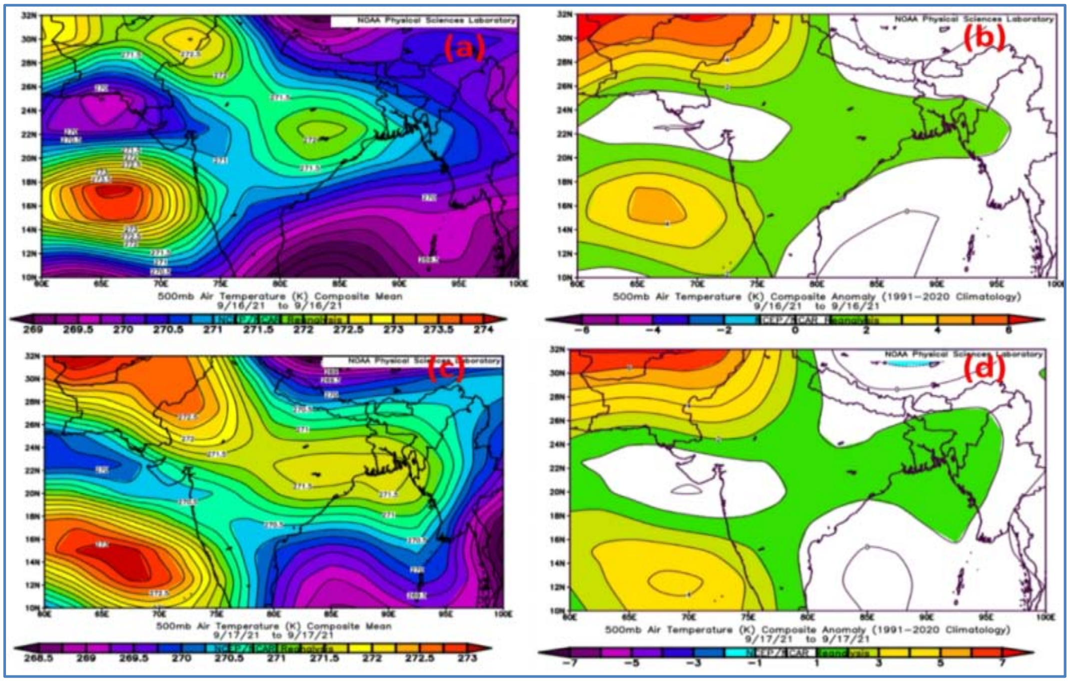
Figs. 16(a-c). IMD-GFS (12 km) Analysis of 500 hPa winds during 15-17 September, 2021

[Figs. 15(a&b)]. Lower-level convergence (LLC) was observed at the order of 10-20 units over north Chhattisgarh and adjoining areas (Lat. 23-25°N/Long. 83-86°E) at 0000 UTC on 16th September. The LLC further shifted westwards at 1200 UTC on 16th September, with LLC observed at the order of 10-20 units around (Lat. 23-26°N/Long. 80-82°E). By 0000 UTC, the main LLC zone had shifted northeastwards and was observed at the order of 10-20 over Bihar and east Uttar Pradesh. This LLC zone moved away from the Indian region by 1200 UTC on 17th September, 2021. The relative vorticity at lower levels, of the order of ≥(50 units), persisted until 1200 UTC over the area of east Uttar Pradesh and its neighbourhood, remaining conducive to heavy rainfall over east Uttar Pradesh.

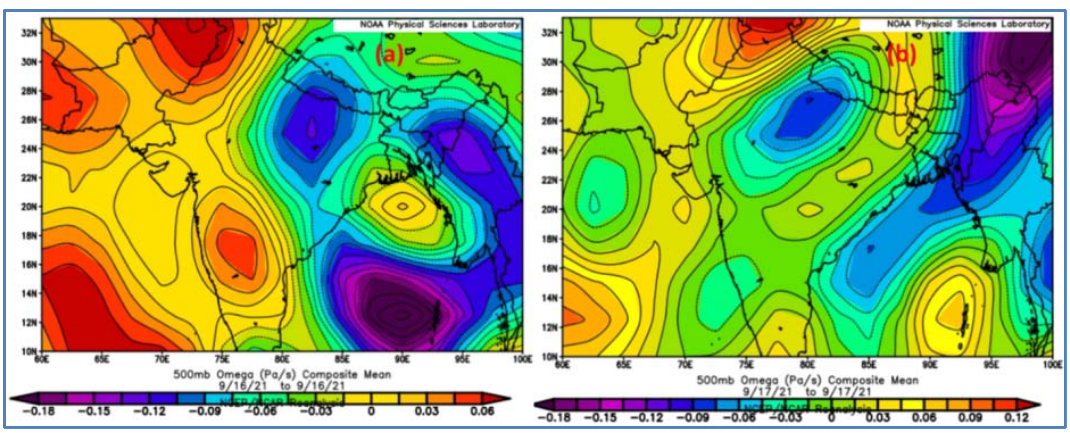
5.3. *Analysis at middle tropospheric levels:*

Now, we will discuss the wind pattern at middle tropospheric levels (500 hPa level). On 15th September, one important synoptic system was the cyclonic circulation (CC) associated with the well-marked low-pressure area over north Chhattisgarh and adjoining areas of northeast Madhya Pradesh (roughly along Long. 82°E and Lat. 24°N). The second important meteorological feature was the strong easterly winds over Uttar Pradesh and southwesterly winds over eastern parts of the country [Fig. 16(a)]. Therefore, moisture inclusion was observed at 500 hPa also. On 16th September, one CC was roughly around Long. 81°E and Lat. 21°N observed and easterly winds continued to prevail [Fig. 16(b)] and on 17th September, CC was seen over roughly around Long. 80°E and Lat. 25°N observed and easterly winds continued to prevail over east Uttar Pradesh with the reduction in wind speed, and also southerly winds were observed over east India, including Bihar **[**Fig. 16(c**)]**. This showed the reduction in moisture supply over the region. Therefore, winds were favorable during the period and reduction in rainfall occurred after 17th September with peak activity on 16th September.

It must be noted that for the rainfall of 16th September, winds and synoptic systems of 15th September



Figs. 17(a-d). (a, c) Mean Air Temperature (K) at 500 hPa on 16th & 17th September (b, d) Air Temperature (K) Anomaly at 500 hPa on 16th & 17th September based on Climatology 1991-2020

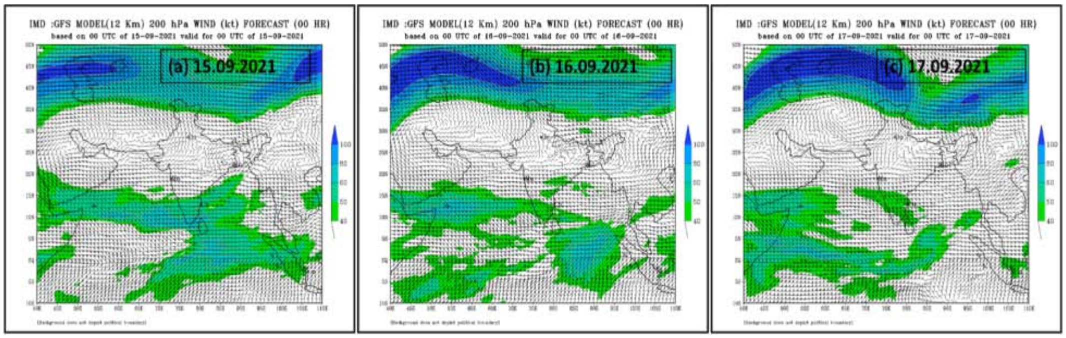


Figs. 18(a&b). Mean Vertical Velocity (Omega) at 500 hPa (a) 16.09.2021 (b) 17.09.2021

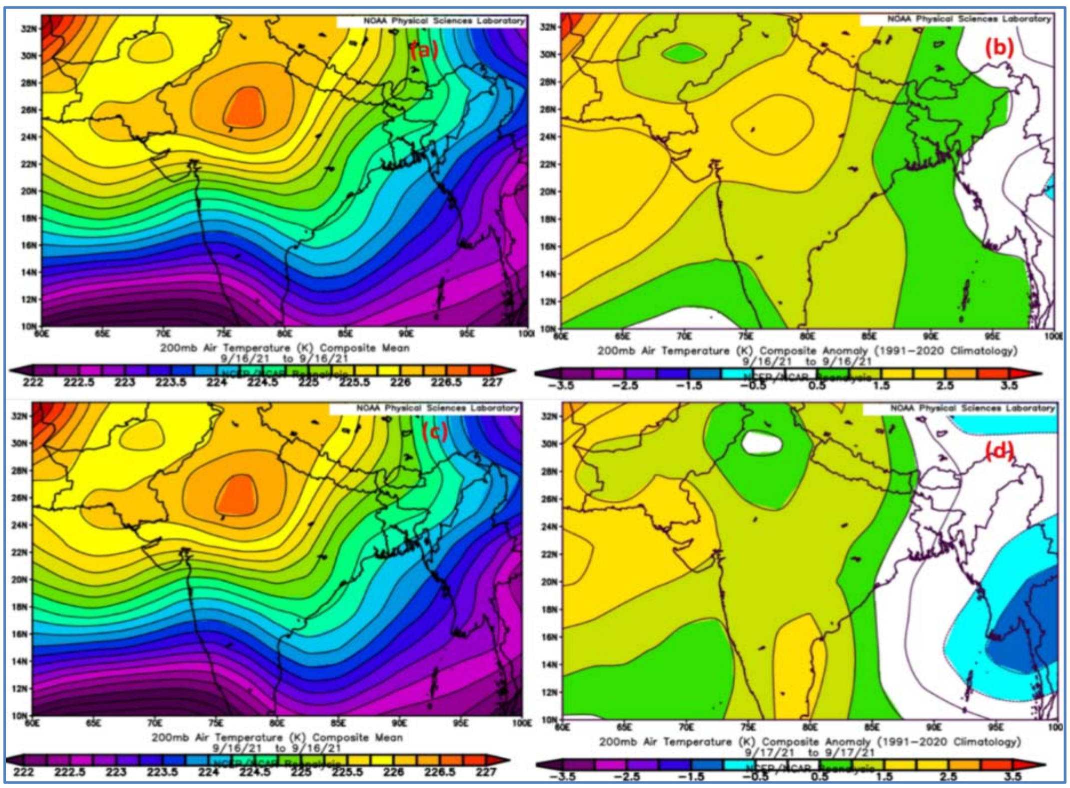
play a role, and for the rainfall of 17th September, the wind pattern of 16th does the same. Accordingly, the wind pattern of 15th to 17th September is discussed here. Mean air temperature on 16th & 17th September was seen over east UP of the order of 271K and anomaly of the order of 1K **[**Figs. 17(a-d)]. The negative vertical velocity (Omega) of the order of (-0.09 Pa/s to -0.015 Pa/s) was seen over east UP on 16th & 17th September, 2021 [Figs. 18 (a&b)]. The same was favorable for heavy rainfall.

5.4. *Analysis at upper tropospheric levels*

At 200 hPa, no specific wind feature was observed that could be associated with the heavy rainfall episode over east UP during 15-17 September, 2021. The Westerly Jet stream was reported north of the country (40-45°N) **[**Figs. 19(a&c)**]**. At 200 hPa, a warm core high zone (with maximum temperature of 227K) was reported over northwest India, including east Uttar Pradesh [Figs. 20(a &c)], with positive anomalies of 2.5K and 1.5K on 16th and 17th September, 2021, respectively [Figs. 20(b&d)]. The relative vorticity at 200 hPa was reported to be of the order of 0 units over northwest India during the period. As for upper-level divergence, it was highest, of the order of 30-40, around the system center of the well-marked low-pressure area (around Lat. 25°N and Long. 81°E) at 0000 UTC on 16th September and reduced to 10-20 at 1200 UTC over the same region. It was further



Figs. 19(a-c). IMD-GFS (12 km) Analysis of 200 hPa winds during 15-17 September, 2021



Figs. 20(a-d). (a, c) Mean Air Temperature (K) at 200 hPa on 16th & 17th September (b, d) Air Temperature (K) Anomaly at 500 hPa on 16th & 17th September based on Climatology 1991-2020

reduced to 05-10 at 0000 UTC on 17th September with northeast movement, and moved east-northeastwards toward the northeast Indian region at 1200 UTC on the same day.

6. Conclusion

As operational forecasters, we understand that each heavy rainfall episode is a learning experience, contributing to the enhancement of our monitoring, evaluation and dissemination of forecasts to various users. Therefore, every heavy rainfall event warrants comprehensive scientific documentation to advance the understanding of concerned stakeholders, including the general public. This case study serves the aforementioned purpose and holds potential utility for policymakers, disaster managers, and those involved in disaster response and mitigation efforts. This paper is concerned with the heavy rainfall episode reported in the eastern parts of Uttar Pradesh, India, on the 16th and 17th of September 2021 and investigates the associated meteorological conditions.

We observed that due to a pre-existing cyclonic circulation over the east-central Bay of Bengal, a low-pressure area formed over the east-central and adjoining areas of the northeast (NE) Bay of Bengal at 00 UTC on September 11th, 2021. This system intensified into a deep depression (DD) over the northwest Bay of Bengal, very close to the Odisha coast, at 0000 UTC on September 13th, 2021. An active Well Marked Low-Pressure (WML) system over the region (the remnant WML system of DD) proved to be a favorable synoptic system for the heavy rainfall activity over eastern Uttar Pradesh on September 16th and 17th, 2021. Thus, we can conclude that a low-pressure system/well-marked low-pressure system may be a suitable synoptic system for extremely or very heavy rainfall over the eastern parts of Uttar Pradesh during the latter parts of the monsoon season.

Dynamical features play a crucial role in the occurrence and persistence of severe weather. The relative vorticity, upper-level divergence, relative humidity, lower-level convergence and vertical velocity (Omega) profiles have been studied to explain the heavy rainfall episode over the region. It was found that relative vorticity up to the middle tropospheric levels, upper-level divergence, Omega, and relative humidity at lower levels were favorable conditions. In addition to the well-marked low-pressure area over the region, these dynamical features are equally important, as discussed in this study, for forecasters and require regular monitoring.

This case serves as an example that even in the absence of an active Jet core at 200 hPa over India, very heavy or extremely heavy rainfall may occur over East Uttar Pradesh. We observed that the wind speed over India was weak at the 200 hPa level, and the Jet stream was located north of the Indian region. This study may set a precedent for future heavy rainfall events.

We can infer that the strong easterly winds up to the middle tropospheric levels over East Uttar Pradesh induced a continuous moisture supply from the Bay of Bengal through southeasterly winds over East India, extending up to the middle tropospheric level (500 hPa), which was important for the occurrence of rainfall episodes over East Uttar Pradesh."

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