JJEES

JJEES (2025) 16 (3): 276-283
ISSN 1995-6681

Jordan Journal of Earth and Environmental Sciences

Analysis of the Extremely Heavy Rainfall over Uttar Pradesh (India) during September 2022

Ruma[1], Shashi Kant[2*], Deepak Kumar[1]

[1] Department of Applied Sciences, School of Engineering and Technology, Manav Rachna International Institute of Research and Studies, Faridabad, India
[2] India Meteorological Department, Ministry of Earth Sciences, New Delhi, India

Received on December 7, 2024, Accepted on March 3, 2025

Abstract

Extremely heavy rainfall (>20cm/day) activities were recorded over some stations in different parts of India during the southwest monsoon (June to September) 2022. Furthermore, the persistence of extremely heavy rainfall events is unusual, particularly over Uttar Pradesh, where only one or two events occurred during the monsoon season. One extremely heavy rainfall episode was recorded over Uttar Pradesh from 15-17 September 2022. This paper analyzes the associated meteorological conditions.

The enhanced rainfall activity can be attributed to several key atmospheric processes working together over a geographical area. In this case, the synoptic analysis reveals that an active monsoon low-pressure area over the region provided favorable atmospheric conditions at the synoptic scale. Moisture transport from the Arabian Sea played a crucial role in fueling precipitation, with strong southwesterly winds bringing large amounts of moisture into the study area across central India. At lower tropospheric levels, the presence of a trough in the atmosphere contributes to the development of favorable conditions for rainfall. Positive relative vorticity was another key factor. Upper-level divergence supports the upward motion of air, aiding in removing air from the upper levels of the atmosphere. This divergence at higher altitudes allows more air from below to rise, creating a more favorable environment for convection and precipitation. In addition, high relative humidity at lower tropospheric levels of the atmosphere ensures that the air contains a significant amount of moisture. Lower-level convergence occurs when winds at the surface converge and force air upwards, further contributing to upward motion and cloud formation. In this case, the overall dynamics support upward air motion, amplifying rainfall activity. Together, these processes create an environment where rainfall is not only sustained but also intensified.

Keywords: *Southwest Monsoon; Heavy rainfall; Meteorological Analysis; Uttar Pradesh (India)*

1. Introduction

It is well known that the southwest monsoon (SWM) during June to September is the primary rainy season in India. Heavy rainfall occurrences are not a uncommon during the SWM; however, each heavy rainfall spell usually brings new experiences for operational forecasters, numerical weather prediction (NWP) modelers, disaster managers, decision-makers, and other stakeholders, including the public. For a summary of Monsoon 2022, readers can refer to salient features of Monsoon-22 issued by India Meteorological Department (IMD). The extremely heavy rainfall (>20cm/day) over a station in Uttar Pradesh for two or more days consecutively is a rare phenomenon and occurs only one or two such cases in the whole SWM season (June to September). The documentation of such cases is essential to understand the mechanism for further improvement in its management and their early warning for the safety of the public and livestock. Scientific experiences, the accuracy of early warnings, lead period and field experiences to reduce the impact of such events may be documented and published in the form of reports and articles.

Some studies have been reported in the scientific literature on heavy rainfall in various regions of India. Rao et al. (2021) investigated heavy rainfall events over Haryana in July 2016. Authors discussed observational aspects from different sources, synoptic conditions associated with the heavy rainfall, and thermo-dynamical situations for this severe weather event. Their analysis found that during Haryana's extreme rainfall episodes, an interaction between a trough in mid-tropospheric levels westerlies and strong monsoonal winds created a strong convergence zone. Kumar et al. (2017) studied the meteorological features associated with the unprecedented precipitation that occurred in different parts of the country in March 2015. The authors also discussed synoptic systems in this study. Viswanadhapalli et al. (2019) conducted a diagnostic analysis of extreme heavy rainfall over Kerala in August 2018. Kant (2023) examined synoptic systems associated with extreme heavy rainfall in July 2022. In this paper, synoptic systems were documented for extremely heavy rainfall. Nandargi & Dhar (2011) documented extreme heavy rainfall over the Himalayas between 1871 and 2007. Mehfoozali et al. (2013) discussed synoptic systems for heavy rainfall over the Lower Yamuna Catchment for the period 1998-2010. Several case studies of extremely heavy rainfall, mainly from Madhya Pradesh and

* Corresponding author e-mail: onlineskmishra@gmail.com

East Rajasthan, were discussed in terms of synoptic systems.

Gond et al. (2025) analyzed dry–wet events and their transitions using 48 years of data (1971–2018) from 18 synoptic locations in the state of Uttar Pradesh. Ankit et al. (2024) conducted a statistical analysis of extreme rainfall over the eastern parts of Uttar Pradesh, mainly in Ambedkar District, using data from 1985 to 2019 to investigate the trends in the region. Saha et al. (2020) discussed the spatial distribution of extreme rainfall events over India during the monsoon period from 2016 to 2018. They used the Global Forecast System (GFS) and National Centre for Medium-Range Weather Forecasting (NCMRWF) Unified Model (NCUM) models for verification. In these studies, no rigorous synoptic discussions were conducted.

Latheef and Mohamed (2023) investigated rainfall patterns across three agro-ecological regions of Sri Lanka using data from the period 1961–2005 and applying different statistical methods. Their study showed that climate change had impacted rainfall trends, although they were statistically insignificant. Dzarma et al. (2020) studied the trends, rainfall variability, and discharge in the River Kilange catchment in Adamawa State, Nigeria, using time-series data from 1987 to 2013 and Pearson's Product-Moment Correlation. They concluded that mean monthly rainfall and discharge were moderately and positively correlated and provided some recommendations. Mohammed et al. (2015) proposed an aridity classification based on rainfall data for the period 1961–2012 from 22 weather stations in Jordan.

The documentation and analysis of extreme or unprecedented heavy rainfall events are indeed crucial for scientific understanding and improving preparedness and response strategies. In general, some important points in connection with such weather events need rigorous scientific discussion. Hence, in general, the following points may be relevant in the studies of extremely heavy rainfall:

i. **Timing and duration of weather event:** Start and end timings of intense spells are important for the detection of persistence. The impact varies with the time of occurrence. For instance, during daytime, it may have a direct impact on day-to-day economic activities.

ii. **Spatial distribution of heavy rainfall:** During summer monsoon, rainfall is received in active and break spells. Active spells are usually related to some heavy rainfall events. These spells are not uniformly distributed, and more specifically, extremely heavy rainfall is usually not reported in wider areas. Hence, the investigation of extremely heavy rainfall regions that were most affected and whether these weather events were localized or had widespread impacts.

iii. **Intensity & comparison to Climatology:** As mentioned in point (i) above, it is a matter of concern to identify the peak rainfall recorded during the weather event and how this rainfall compares to climatological records.

iv. **Accumulated rainfall:** As per meteorological convention, 24-hour accumulated rainfall is classified into different intensities. IMD follows the well-specified classification of rainfall (See Table 1).

Table 1. Classification of the intensity of Rainfall (Source: IMD)

Category	24 hours cumulative rainfall (mm)
No Rain/dry	0.0
Very light Rain	0.1-2.4
Light Rain	2.5 - 15.5
Moderate Rain	15.6 - 64.4
Heavy Rain	64.5 – 115.5
Very Heavy Rain	115.6 – 204.4
Extremely Heavy Rain	>204.4

v. **Meteorological conditions and temporal evolution:** Scientific discussion is required on synoptic, dynamic, mesoscale & thermodynamic features during the event (e.g., Low Pressure Area (LPA), convergence zones, moisture influx, instability, etc.). How did the synoptic systems evolve leading up to and during the heavy rainfall event? Were there any significant changes in meteorological parameters before and after the event?

vi. **Impacts:** What were the impacts of the heavy rainfall event on infrastructure, agriculture, transportation, and communities? Were there any casualties or significant damage reported?

The literature review highlights several studies on heavy rainfall from different regions of India and other countries; some of them are highlighted here. However, very few, if any, specific case studies have been reported that focus on the synoptic analysis of heavy rainfall, particularly over Uttar Pradesh. Accordingly, the main objective of this study is to understand the major synoptic systems associated with heavy rainfall in Uttar Pradesh. The primary reason for selecting this case study is the occurrence of extremely heavy rainfall episodes in regions typically categorized as having deficient rainfall, particularly in the state of Uttar Pradesh. One such example is the persistent extreme heavy rainfall episode that occurred from 15–17 September 2022 over Uttar Pradesh, which is considered in this study.

2. Study area, the climatology, and observational aspects of weather events

The study area in this paper is the state of Uttar Pradesh in India. This state is surrounded by Uttarakhand in the northwest, Madhya Pradesh, Rajasthan in the south & southeast, Haryana in the west, Bihar in the east, and Nepal in the north. IMD issues the weather forecast and warnings for 36 meteorological subdivisions of India, including two meteorological subdivisions (West & East) of Uttar Pradesh. For districts and other details, refer to the official web page of Uttar Pradesh: https://up.gov.in/en.

The following generic questions are also selected for the sake of understanding the observational aspect of this weather event.

- Whether the heavy rainfall has occurred in particular districts/places of the state, or is it distributed in the whole state? This distribution will ensure the nonuniform distribution and discontinuous nature of rainfall occurrences.
- What was the actual amount of extreme rainfall, district-wise/station-wise ,in each day? This amount will confirm the intensity of rainfall and the spatial impact of the weather event.
- Whether such amount of rainfall per day occurred during the last 20 to 30 years? What is the actual rainfall map along with the anomaly for the study area, and what is the anomaly for climatological rainfall values during this period?

Therefore, before delving into the details of the case, it is important to understand the climatology (Hazard Atlas IMD Pune). The maximum probable frequency of very heavy rainfall and extremely heavy rainfall events (for September) for the period 1901-2019 is studied. It included the maximum probable frequency in the category more (>3-4 days) over Uttar Pradesh. Data showed that the regions of northwest Uttar Pradesh, southeast & southwest Uttar Pradesh (Bundelkhnad region) had the highest probable frequency (5-8) in the class of very heavy rainfall & extremely heavy rainfall. The districts of Bareilly, Barabanki, Lalitpur, Muzaffarnagar, Pilibhit, Saharanpur, Shahjahanpur, Sitapur, Varanasi, and Hamirpur were in the same frequency with the highest frequency of 8 in Muzafarnagar. The month-wise rainfall progress during monsoon 2022 showed that Uttar Pradesh reported deficient rainfall from June to August (specific figures are not attached). September was the only month when the state reported normal to above-normal rainfall (Figure 1).

The persistent very heavy to extremely heavy rainfall episodes during the period of 15-17 September contributed to above-normal rainfall. On the 15th of September, heavy rainfall activity commenced, and large excess rainfall was reported over the stations of east and adjoining west & northwest Uttar Pradesh (Figure 1a). On the 16th, the peak activity was reported with excess/large excess rainfall over most parts of Uttar Pradesh (Figure 1b). On the 17th of September, activity concentrated mainly over north Uttar Pradesh(Figure 1c).

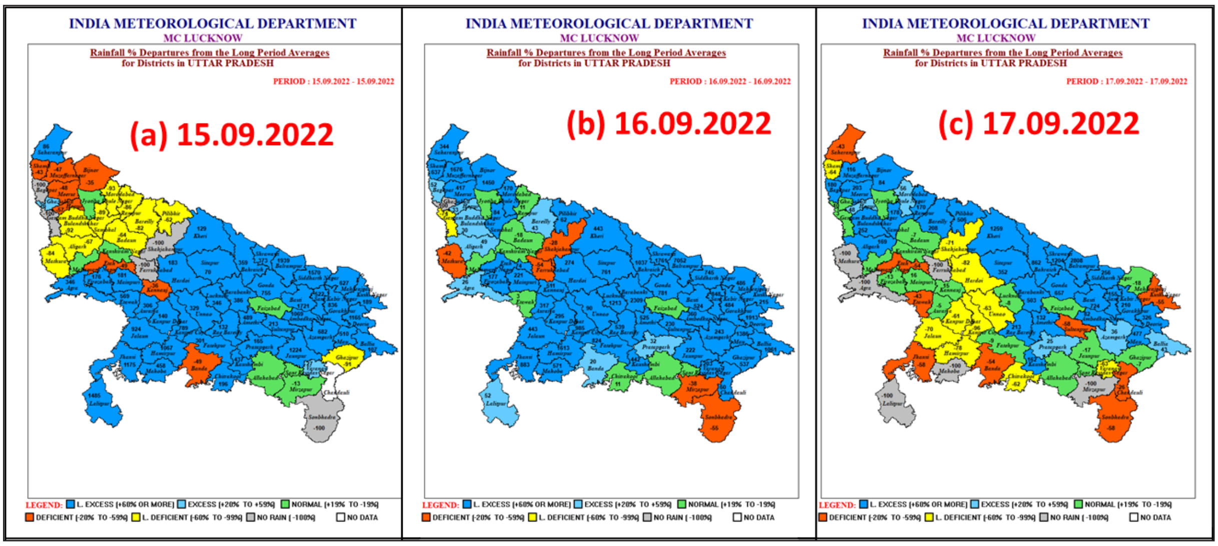

Figure 1. Rainfall percentage departure from the long period average over UP during 15-17 September 2022 (Source: IMD).

In this study, we collected rainfall data from 190 stations in east Uttar Pradesh and 135 stations in west Uttar Pradesh. The cumulative 24-hour rainfall (RR24) data from recording stations shows that East Uttar Pradesh reported very heavy rainfall (RR24 > 12cm) to extremely heavy rainfall (RR24>20cm) each day (Figure 2). The highest number of stations with heavy rainfall was recorded over East Uttar Pradesh on the 15th of September and West Uttar Pradesh on the 16th of September. East Uttar Pradesh reported the highest number of instances of extremely heavy rainfall on 16th September, followed by the 17th September, and isolated on the 15th of September. The very heavy rainfall was observed in West Uttar Pradesh on 15th with no instances of extremely heavy rainfall (Figure 2). On 15th September, Jaunpur; on 16th September, Barabanki and Kheri; and on the 17th of September, Gorakhpur and Kheri reported extremely heavy rainfall.

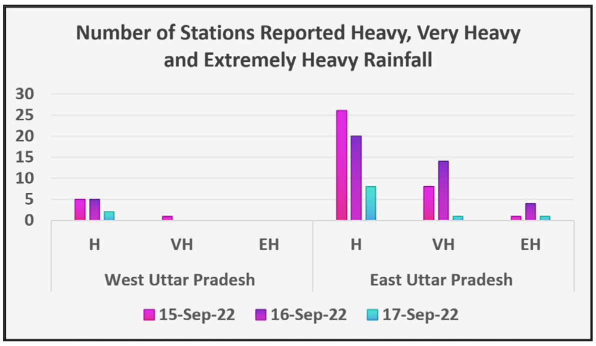

Figure 2. The number of stations reported heavy, very heavy, and extremely heavy rainfall during 15-17 September 2022 over Uttar Pradesh. H-Heavy Rainfall; VH-Very Heavy Rainfall; EH-Extremely Heavy Rainfall (Source: IMD)

3. Results and Discussion

Daily Rainfall data is collected from IMD. IMD-GFS model analysis charts are collected from the Numerical Weather Prediction (NWP) division of IMD, and synoptic charts are collected from IMD Pune. Additionally, for synoptic systems, all India weather bulletins from IMD have been collected; dynamical parameters from Cooperative Institute for Meteorological Satellite Studies (CIMSS) / University of Wisconsin-Madison (https://tropic.ssec.wisc.edu/) and upper air temperature, Relative humidity (RH) and Omega from Physical Science Laboratory, National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis page https://psl.noaa.gov/data/composites/day/ (Kalnay, E. and Coauthors, 1996). Otherwise, the sources of most of the images are mentioned at the bottom of the respective images. Mathematical formulation of dynamical variables and units of different quantities are listed in Appendix I. The methodology is summarized in Figure 3.

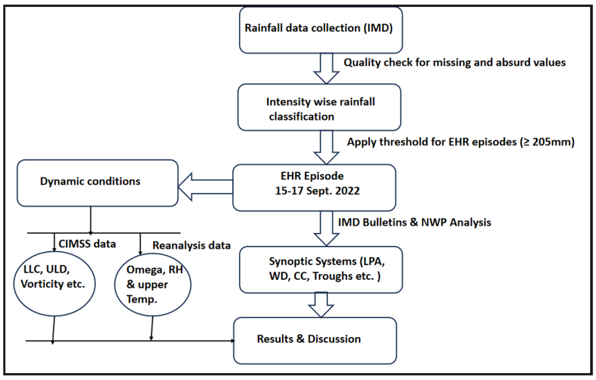

Figure 3. Data and methodology

Synoptic conditions and other meteorological analyses are discussed at four tropospheric levels:

i. **Surface Analysis**. For surface analysis, operational weather forecasting is mainly done using isobaric and wind analysis. During SWM (June to September), surface analysis is most important to identify the monsoon trough, heat low, and other synoptic systems. It is important to mention that in the Indian region, 10 m winds are considered surface winds, and an analysis of the same has been done to identify the LPA/Well Marked LPA or Cyclonic Circulation at the surface.

ii. **Lower tropospheric levels**. The tropospheric levels up to 600 hPa (4.5 km above mean sea level) are usually considered in the lower levels. In this paper, the analysis at the three standard levels of 925, 850, and 700 hPa is done. Wind analysis, upper Air Temperature & Omega at 850 hPa (NCEP re-analysis), relative vorticity at 850 & 700 hPa (from CIMSS), and RH (from NCEP re-analysis) will be discussed.

iii. **Middle tropospheric levels**. For this wind analysis from the NWP model (IMD-GFS), Air Temperature & Omega Analysis at 500 hPa (from NCEP re-analysis) and relative vorticity at 500 hPa (from CIMSS) will be discussed.

iv. **Upper tropospheric Levels.** Analysis at 200 hPa will be discussed for Jet streams. Additionally, air temperature analysis (from NCEP re-analysis) and upper-level divergence (from CIMSS) will be considered.

3.1 Synoptic Analysis

3.1.1 Surface Analysis:

In this sub-section, Mean Sea Level Pressure (MSLP) analysis (mainly isobaric) and wind (10 m) analysis are adopted to identify synoptic systems like LPA [or cyclonic circulation at the surface] during the period of study. MSLP analysis showed a well-marked LPA over northwest Madhya Pradesh & adjoining Uttar Pradesh, and the associated cyclonic circulation was visible in 10 m winds. It lay over central parts of Uttar Pradesh on the 16th of September, and the well-marked LPA weakened on the 17th of September. However, a remnant cyclonic circulation was seen over north Uttar Pradesh.

Additionally, an important feature of 10 m winds was observed on the 15th of September. Strong southwesterly/ southerly winds (20-25 knots) have prevailed from the northwest & central Arabian Sea to LPA. Accordingly, the moisture supply was seen. Similar meteorological conditions prevailed on the 16th of September, and the intensity of winds reduced on the 17th of September and accordingly rainfall intensity over Uttar Pradesh reduced on 17th September.

3.1.2 analysis in lower tropospheric levels

The following synoptic systems on the 15th of September were identified;

i. The associated cyclonic circulation with the LPA over northwest Madhya Pradesh,

ii. A trough from the northwest & central Arabian Sea to Uttar Pradesh across Madhya Pradesh.

iii. The strong southwesterly winds over Arabian Sea, Central India, and Uttar Pradesh (20-30 kt) with isolated patches of 30-40 kt.

Two systems listed at (ii) & (iii) created a favorable channel for moisture transport from the Arabian Sea to Uttar Pradesh. This channel induced the LPA/Well Marked LPA to generate intense spells over Uttar Pradesh on the 15th of September. The moisture incursion from either the Arabian Sea or the Bay of Bengal remained favourable. The weather systems persisted on 16th September except for the associated cyclonic circulation with the LPA, which lay over central parts of Uttar Pradesh. LPA/Well Marked LPA continued to generate intense spells of rainfall over Uttar Pradesh. The weakening of the wind intensity was seen on the 17th of September with the cyclonic circulation over northern Uttar Pradesh. The trough also got weakened on the 17th of September. This was an indication of a reduction in rainfall from the 17th of September.

This paper also analyzes Air temperature composite anomaly & mean temperature at 850 hPa. A positive anomaly was reported over northwest India, including parts of Uttar Pradesh. An increase was reported on the 16th of September, and the same persisted on the 17th of September. The peak positive anomaly was reported on 16th September. Relative

Humidity (RH) analysis at 700 hPa showed that it was more than 80% on the 15th & 16th of September over Uttar Pradesh, over east & adjoining west Uttar Pradesh, and northeast Uttar Pradesh, with a reduction on 17th September. A significant reduction over many parts of Uttar Pradesh was seen on the 17th of September, a clear indication of the reduction in the intensity of rainfall over Uttar Pradesh. Accordingly, RH was consistent with the rainfall pattern.

The vertical velocity (often referred to as Omega,) in meteorology. It is used to describe the upward or downward motion of air. In the context of heavy rainfall, vertical velocity plays a key role in developing thunderstorms and heavy precipitation. It typically represents the rate at which air is rising or sinking in the atmosphere. A negative omega ($\omega<0$) represents upward motion in the atmosphere. This is the condition conducive to heavy rainfall because it signifies rising air, which is a key component in the development of clouds and precipitation. A positive omega ($\omega>0$) represents downward motion or subsidence, which is typically associated with dry, clear conditions rather than rain. Accordingly, the negative vertical velocity (Omega) is favorable for heavy rainfall. The negative Omega at 850 hPa was concentrated over northwest Madhya Pradesh & adjoining Uttar Pradesh (-0.4 Pa/s) on the 15th of September, over central parts of Uttar Pradesh on the 16th of September, and over extreme northeast Uttar Pradesh on the 17th of September. Hence, Omega was favourable.

Another important dynamic parameter is the relative vvorticity at different tropospheric levels. Mathematically, vorticity (ξ) is defined as (**Annexure I**):

$$\xi = \vec{\nabla} \times \vec{V}, \eta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}. \quad (1)$$

In operational weather forecasting, we monitor the vorticity profile mainly from two sources, namely CIMSS and Satellite products from INSAT 3D/R https://satmet.imd.gov.in/. The Vorticity profile is received from the CIMSS webpage (https://tropic.ssec.wisc.edu/archive/). The relative vorticity at 850 hPa (> 100×10^{-6} Sec^{-1}) was reported on the 15th & 16th of September with a reduction on 17th September. Therefore, the relative Vorticity profile at lower tropospheric levels was favorable for rainfall.

Mathematically, convergence (in two-dimensional cases) is written as,

$$Conv.\ \vec{F} = -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right). \quad (2)$$

For more details, refer to Annexure I. At 00 UTC (the 15th of September), lower level convergence was positive over south Uttar Pradesh, and it was over east Uttar Pradesh & Madhya Pradesh at 12 UTC. At 00 UTC (16th September), lower level convergence was positive over east Uttar Pradesh, and it was over east Uttar Pradesh and adjoining Bihar, and at 12 UTC, the same conditions prevailed. At 00& 12 UTC (the 17th of September), weakening of lower level convergence was seen only 5×10^{-6} Sec^{-1} over Bihar. Therefore, the lower level convergence was favourable for the weather and also suggest the reduction in rainfall from 17th September.

3.1.3Analysis at Middle Tropospheric Levels

Wind analysis at 500 hPa on the 15th of September showed a cyclonic circulation CC over northwest Madhya Pradesh associated with LPA. Also, westerly winds from the Arabian Sea prevailed and supported the moisture incursion over Uttar Pradesh. A similar wind pattern prevailed on the 16th, and cyclonic circulation was relocated to the central parts of Uttar Pradesh. The pattern of winds changed on the 17th of September; cyclonic circulation became less marked. This change indicated the reduction in the intensity of rainfall from the 17th of September.

Air Temperature (K) composite Anomaly (Climatology 1991-2020) at 500 hPa and composite mean are analyzed. On the 15th of September, positive anomalies (1.5-2.5K) were seen over most parts of northwest & west India. On the same day, warm core with the center of peak (the highest temperature) was seen over northwest India. The second layer (271-272K) of this warm core extended up to Uttar Pradesh. A shift in the direction of the northeast of warm core temperature and anomaly was observed on the16th of September and seen over Nepal with the second and third layers over September. A further shift was observed on the 17th of September and was seen over Nepal; however, a positive anomaly was seen over North Uttar Pradesh and the second layer over eastern parts of Uttar Pradesh. This feature was in agreement with the heavy rainfall.

Analysis of Omega showed that on 15th September, the major zone of negative Omega was over Nepal and Uttar Pradesh, with the maxima over Nepal (<-0.3 Pa/s). The second layer was seen over Uttar Pradesh (around -0.25 Pa/s). On the 16th of September, the major shifted towards Nepal with the maxima (<-0.3 Pa/s). The second and third layers were seen over Uttar Pradesh (around -0.25 Pa/s). This zone remained favourable for heavy rainfall. On the 17th of September, Omega increased, and only negative Omega (-0.1 Pa/s) was seen over Uttar Pradesh. Thus, the Omega was consistent with the heavy rainfall.

The maxima of vorticity at 500 hPa (> 50 $\times10^{-6}$ Sec^{-1}) over Uttar Pradesh on 00 & 12 UTC of 15th September. The maxima are seen over central Uttar Pradesh at 00 UTC on 16th September. The vorticity started decreasing from 12 UTC, indicating the weakening of the LPA. Patches of yellow color were seen till 00 UTC on 17th September. Further reduced at 12 UTC. Thus, the vorticity pattern at 500 hPa was consistent with the heavy rainfall.

3.1.4 Analysis at upper tropospheric levels

Referring to 200 hPa winds, no Jet winds prevailed over any parts of the country. Winds <40 kts prevailed over most parts of the country, including Uttar Pradesh from 15-17 September.

At the same time, air temperature analysis at 200 hPa showed the presence of the warm core over west Uttar Pradesh on the 15th & 16th of September, and temperature decreased on 17th September. This was consistent with the rainfall episode. Regarding anomaly, it was reported positive all three days and highest on the 15th& 16th of September. This showed that in the absence of any active Jet core at 200 hPa during monsoon season, very heavy/extremely heavy rainfall over Uttar Pradesh is possible.

The relative Vorticity profiles at 200 hPa remained negative over Uttar Pradesh on most days except isolated patches of the order of 0×10^{-6} Sec^{-1} on 16th September. This shows that during the monsoon period, even in the negative relative Vorticity profile at 200 hPa, an intense spell of rainfall over Uttar Pradesh is possible.

Mathematically, divergence in two-dimensional case is written as, the negative of convergence as shown in Equation (2),

$$Div.\vec{F} = (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}). \quad (3)$$

For more details, refer to Annexure I. The patches of positive upper-level divergence remained favourable over Uttar Pradesh during the period till 12 UTC on 17th September. On 15th September, upper level divergence was reported of the order of 10×10^{-6} Sec^{-1}. It increased to 20-30 $\times10^{-6}$ Sec^{-1} on 16th September, reduced on 17th September, and moved east-northeast wards. This increase was an indication of a reduction in intensity of rainfall from 17th September.

4. Conclusion

- Before closing the discussion, the following meteorological conditions are highlighted;
- A Well Marked Low-Pressure Area lay over northwest Madhya Pradesh & neighbourhood on 15th September; it lay over central parts of Uttar Pradesh on 16th September; it weakened into an LPA over the same region in the early morning hours of 17th September before getting less marked in the morning of that day; its remnant cyclonic circulation lay over north Uttar Pradesh on 17th September.
- A trough in the lower tropospheric levels extends from Northwest / westcentral Arabian Sea to the cyclonic circulation associated with the above-mentioned Well Marked Low-Pressure Area. This helped transport the moisture from the Arabian Sea to Uttar Pradesh.
- Relative Vorticity remained favourable in lower and middle tropospheric levels. We observed that Relative Vorticity was positive up to the level of 500 hPa. The presence of positive vorticity at these levels also suggested that the weather systems were dynamically supportive of convection over several days, contributing to the intensity and persistence of the rainfall, especially on the 15th and 16th of September. Positive vorticity supported the favorable conditions for heavy rainfall by maintaining a cyclonic system that encouraged continuous rising motion and moisture transport. This likely contributed significantly to the rainfall observed over Uttar Pradesh, especially during the event's peak.
- Upper-level Divergence remained consistent with the rainfall episode. This showed the good weather activity on 15th & 16th September and a reduction from 17th September. Evolution of Upper-level Divergence was in good agreement for the weather event. On 15th September, it was relatively low but still supported some divergence aloft. This divergence likely helped to initiate upward motion at lower levels, facilitating cloud formation and the start of the rainfall event. On 16th September, it increased to 20-30 $\times 10^{-6}$ s^{-1}, which was a significant increase that indicated a stronger divergence aloft on the 16th September. This enhanced upward motion at lower levels, leading to more intense convection and, therefore, heavier rainfall. The increase in divergence was in line with the peak intensity of the rainfall on that day. On 17th September, it further decreased, suggesting that the divergence aloft had weakened. This would lead to less upward motion and a reduction in the conditions favorable for sustained heavy rainfall. As a result, the intensity of the rainfall started to decrease, aligning with the end of the heavy rainfall episode.
- RH profile, lower level convergence, and vertical velocity (Omega) showed consistency with the heavy rainfall episode. RH at 700 hPa was more than 80% on the 15th & 16th over Uttar Pradesh and reduced onthe 17th of September. High relative humidity at 700 hPa (approximately 3 km above sea level) indicated a substantial amount of moisture in the lower to mid-layers of the atmosphere. When RH was above 80%, it suggested conditions conducive for rainfall, as the air is saturated and can support cloud formation and precipitation. A drop in RH on the 17th of September suggested that moisture in the atmosphere decreased, possibly indicating that the rainfall event was ending or transitioning into a drier period.
- Discussion showed that during the monsoon period, even in the absence of any active Jet core at 200 hPa, extremely heavy rainfall may occur over Uttar Pradesh. The jet stream at 200 hPa (upper-tropospheric winds) plays a significant role in large-scale atmospheric circulation. An active jet core can enhance divergence aloft, promoting upward motion and creating favorable conditions for convection and rainfall. However, even in the absence of a strong or active jet core, extremely heavy rainfall can still occur, particularly over Uttar Pradesh. This suggested that other meteorological factors are at play in driving rainfall during the monsoon season.
- In addition to Cyclonic Circulation/LPA, the moisture supply from the Arabian Sea, with the help of westerly/southwesterly winds, was an important mechanism for the occurrence of rainfall episodes.

We understand that each heavy rainfall episode provides valuable lessons and helps to enhance the experience during its monitoring, evaluation, and dissemination of its forecast to different users. This case study serves this purpose. It may be useful for policymakers, disaster managers, and those involved in disaster response and mitigation. Early warning is one of the most important pillars in the disaster management of natural extreme weather events. There are very few case studies addressing the synoptic aspects of heavy rainfall over Uttar Pradesh. During short to medium-range weather forecasting (3-10 days lead period), even in active monsoon conditions, synoptic-scale systems are a significant tool for issuing heavy rainfall warnings. This case study suggests that whenever a low-pressure system is located over northwest Madhya Pradesh or its vicinity, a heavy rainfall warning may be issued for Uttar Pradesh, keeping in mind the climatology of a particular district. Accordingly, this case study serves as a precedent for early warnings of heavy rainfall in the state of Uttar Pradesh. Future work will include the climatology of synoptic systems that induce heavy rainfall events over the state.

Acknowledgment

The authors are thankful to the Director General, IMD, for all their support and providing the rainfall data. The authors are thankful to CIMSS (https://tropic.ssec.wisc.edu/) for dynamical parameters, NOAA/ESRL Physical Sciences Laboratory, from their Web site at http://psl.noaa.gov/" for re-analysis data.

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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Annexure I. (Mathematical Formulation & units)

Physical Quantity	Unit	Mathematical Formulation
Lower-Level Convergence	10^{-6} /sec	$Conv.\ \vec{F} = -div\vec{F} = -\vec{\nabla} \cdot \vec{F} = -(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y})$. u, v: wind components (In two-dimensional case) refer to https://glossary.ametsoc.org/wiki/Convergence
Upper-Level Divergence	10^{-6} /sec	$div\vec{F} = \vec{\nabla} \cdot \vec{F}.div\vec{F} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$. (In two-dimensional case), refer to https://glossary.ametsoc.org/wiki/Divergence
Vorticity	10^{-6} /sec	Vorticity: $\xi = \vec{\nabla} \times \vec{V}, \eta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, the Vorticity equation (absolute vorticity of air) is written as; $\frac{d\eta}{dt} = -\eta \nabla_h \cdot \mathbf{v}_h - \left(\frac{\partial w}{\partial x}\frac{\partial v}{\partial z} - \frac{\partial w}{\partial y}\frac{\partial u}{\partial z}\right) - \frac{1}{\rho^2}\mathbf{k} \cdot (\nabla_h p \times \nabla_h \rho)$ Where, η: z component of vorticity, ρ: atmospheric density, u, v, w: wind components and ∇_h : two dimensional horizontal del operator. (https://en.wikipedia.org/wiki/Vorticity_equation)
Omega (Vertical velocity) $\omega = \frac{dp}{dt}$,	Pa/s	Omega equation is follows; $\sigma \nabla_H^2 \omega + f^2 \frac{\partial^2 \omega}{\partial p^2} = f \frac{\partial}{\partial p} [\mathbf{V}_g \cdot \nabla_H (\zeta_g + f)] - \nabla_H^2 \left(\mathbf{V}_g \cdot \nabla_H \frac{\partial \phi}{\partial p}\right)$ Where; f: Coriolis parameter, σ: static stability, $\boldsymbol{V}_g$: geostrophic velocity vector, ζ_g: geostrophic relative vorticity, ϕ: geopotential, ∇_H^2: horizontal Laplacian operator and ∇_H : horizontal deloperator. Omega can be generated from the above Omega equation.(https://en.wikipedia.org/wiki/Omega_equation)
Air Temperature	K	
Atmospheric Pressure	hPa	1 hPa=1mb
Wind speed	Knots	1Knot=1.852 Km/hour