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Analysis of Dynamic and Thermodynamic Moisture Budgets for Extreme Rainfall Events in Telangana Utilizing ERA5 Reanalysis

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Abstract

In recent decades, there has been a rise in extreme precipitation events, particularly over short durations, which can ultimately result in flash floods. These occurrences have become more frequent and intense across the Indian subcontinent, especially in the Deccan Plateau area that includes Telangana. Such events pose significant hydrometeorological risks, such as urban flooding, damage to crops, and the collapse of infrastructure. Understanding the dynamical and thermodynamical characteristics of these events is crucial. A more profound comprehension of the moisture budget dynamics that drive such impactful rainfall is vital for enhancing predictive capabilities. In this research, we utilize reanalysis data from 2020 to 2024 to analyze the complete moisture budget comprising Total Column Water Vapor (TCWV), Horizontal moisture flux divergence, and vertical advection during three extreme rainfall events (exceeding 200 mm/day) in Telangana during the years 2021, 2022, and 2023. Each event was examined within a 3-day synoptic window and compared to a five-year (2020–2024) month-specific climatology. The findings indicate that low-level convergence and unusually high moisture levels were consistent precursors to these events, Strong positive anomalies in vertically integrated moisture convergence acted as robust precursors, while vertical moisture advection substantially intensified deep convection and amplified rainfall extremes. These findings highlight the critical role of moisture budget dynamics in driving extreme monsoon rainfall. Beyond scientific insights, the results have direct implications for disaster Risk Management and forecasting. Recognizing dynamical and thermodynamical precursors can enhance predictive skill, early warning systems, and resilience strategies, supporting better preparedness against urban flooding, agricultural losses, and infrastructure risks in vulnerable regions like Telangana.

1. Introduction

Extreme rainfall events rank among the most damaging hydrometeorological occurrences, significantly impacting socio-economic conditions in response to global warming. This is attributed to a warming climate, coupled with considerable internal dynamical variability in certain regions (Fischer and Knutti, 2014). Furthermore, instances of extreme rainfall are projected to increase even in areas where the average precipitation intensity is decreasing (Field et al., 2012). In recent decades, various regions of South Asia, particularly the Indian subcontinent, have experienced a surge in extreme rainfall events during the monsoon season.

The Indian monsoon system, characterized by a complex interaction of thermodynamics, dynamics, and large-scale atmospheric oscillations, plays a crucial role in providing the majority of annual rainfall. Understanding the reasons behind recent changes in Indian Summer Monsoon Rainfall (ISMR) and its extremes has significant implications for water resource management and policy development (Mall et al., 2006; Archer et al., 2010), as well as for disaster management strategies (Vittal et al., 2020). In this context, differing conclusions from various studies have linked recent modifications in extreme rainfall characteristics either to global warming (Rajeevan et al., 2008; Mani et al., 2009) or to local influences such as urbanization (Kishtawal et al., 2010; Vittal et al., 2013). Numerous investigations have demonstrated the occurrence of extreme rainfall events within a large-scale monsoon context (Das, 2005; Gouda et al., 2023; Joshi et al., 2020; Rajagopal and Iyengar, 2005; Srinivasan et al., 2005).

Recent case studies highlight the impacts of extreme rainfall across diverse regions, including landslides in Uttarakhand and urban flooding in Mumbai, as well as extensive inundation in Kerala (Chaudhuri et al., 2015; Vijaykumar et al., 2021). Understanding the atmospheric moisture budget is essential for climate diagnostics and weather forecasting. Several studies have explored moisture transport mechanisms during heavy rainfall using both observational and reanalysis datasets. Trenberth and Guillemot (1995) conducted an early diagnostic analysis of moisture flux convergence during storms, highlighting the importance of dynamic vertical motions. Dirmeyer et al. (2006) illustrated how land–atmosphere interactions influence regional precipitation through moisture recycling.

Long-term analyses (Gimeno et al., 2012) also indicate increasing atmospheric moisture availability and shifts in moisture source regions. Recent studies using ERA5 reanalysis have demonstrated its capability in diagnosing moisture transport, circulation anomalies, and thermodynamic contributions associated with extreme precipitation (Li et al., 2022; Kumar et al., 2025; Prabha et al., 2025). Recent advances in reanalysis-based studies, particularly those using ERA5, have significantly improved understanding of moisture budget dynamics in extreme rainfall events. These studies show that ERA5 effectively captures horizontal moisture flux convergence, vertical motion, and thermodynamic variability at synoptic and mesoscale levels. Furthermore, dynamic–thermodynamic decomposition approaches reveal that extreme precipitation can arise from circulation-driven convergence, enhanced atmospheric moisture loading, or a combination of both. Despite these advances, event-scale

diagnostics over inland regions such as Telangana remain limited, motivating the present study.

Telangana, situated on the semi-arid Deccan Plateau, has experienced increasing frequency and intensity of extreme rainfall events during the southwest monsoon (June–September). These events have caused significant socio-economic impacts and exposed limitations in forecasting and disaster risk management frameworks. City-scale evidence from Hyderabad further shows pronounced spatial variability and changing rainfall extremes, including increasing dry and wet spell characteristics under rapid urbanization (TSDPS and DES, 2024; Hari and Kasa, 2024).

In the Indian context, Rao and Rajeevan (2008) examined the interannual variability of the Indian Summer Monsoon and its connection to moisture flux anomalies. Bhardwaj et al. (2021) utilized ERA5 data to analyze convective instability and vertical velocity within monsoon depressions. Moisture budget studies over India consistently emphasize the role of large-scale transport and local convergence in shaping monsoon rainfall. For example, Prakash et al. (2019) highlighted the contribution of moisture flux convergence to extreme rainfall events over central India, while Chakraborty et al. (2022) demonstrated that thermodynamic enhancements, particularly increased precipitable water, significantly intensify monsoon extremes under warming conditions. Similarly, Unnikrishnan et al. (2017) showed that moisture transport from the Arabian Sea and the Bay of Bengal dominates the South Asian water budget, while Byju et al. (2024) decomposed CMIP6 rainfall extremes into dynamic and thermodynamic drivers. Long-term analyses (Sarkar et al., 2023) also indicate rising atmospheric moisture availability and shifting source regions. These findings collectively highlight the importance of both dynamical convergence and thermodynamic moisture loading in driving monsoon extremes. Studies on rainfall variability over Telangana and the Deccan Plateau (Jyostna et al., 2022; Bhunia, 2024; Awasthi, 2024) provide valuable insights into spatial and temporal precipitation patterns. However, there has been a marked increase in rainfall variability, underscoring the need for improved understanding of regional climate dynamics for water resource management, agricultural planning, and disaster preparedness. Despite these efforts, comprehensive moisture budget analyses for short-duration, high-intensity rainfall events over inland regions such as Telangana remain limited. This study addresses this gap by providing a detailed event-scale assessment of moisture transport mechanisms and their role in extreme precipitation.

The specific objectives of this study are:

1. To analyze the vertical and horizontal moisture transport processes associated with extreme precipitation events in Telangana.
2. To quantify the contributions of vertical moisture advection and moisture flux convergence to event-scale rainfall.
3. To assess thermodynamic (e.g., TCWV) and dynamical (e.g., flux divergence, vertical advection) indicators for understanding extreme precipitation development.
4. To evaluate the potential of these diagnostics in enhancing operational forecasting and early warning systems.

2. Data and Methodology

Data

The present study utilizes ERA5 reanalysis data produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period 2020–2024. ERA5 provides hourly atmospheric fields at a horizontal resolution of approximately $0.25^\circ \times 0.25^\circ$, with improved model physics, data assimilation, and enhanced use of satellite and in-situ observations compared to earlier ECMWF reanalysis products (Hersbach et al., 2020).

The atmospheric variables used in this study include horizontal winds (u , v), vertical velocity (ω), specific humidity (q), and total column water vapor (TCWV), extracted from the surface up to 300 hPa.

ERA5 was selected for several key reasons: (i) its superior spatial resolution ($\sim 0.25^\circ$) and hourly temporal resolution are essential for diagnosing short-duration, high-intensity rainfall events.

(ii) ERA5 reanalysis data provide a reliable and dynamically consistent representation of monsoon circulation and moisture fields over the Indian region, which is essential for diagnosing extreme rainfall episodes. The high temporal (hourly) and spatial ($\sim 0.25^\circ$) resolution of ERA5 enables accurate estimation of moisture transport, convergence, and vertical advection associated with short-duration, high-intensity rainfall events such as those examined in this study. ERA5 has been shown to outperform other reanalyses (MERRA-2, JRA-55, NCEP-NCAR) in representing monsoon circulation and moisture transport over the Indian subcontinent (Tarek et al., 2020; Mahto and Mishra, 2019); and (iii) its data assimilation system better incorporates the dense network of satellite and in-situ observations

available over South Asia during the study period. While multi-reanalysis comparisons are desirable for robustness, several recent moisture budget studies over India and the Deccan Plateau have demonstrated ERA5's reliability as a standalone product for event-scale moisture diagnostics (Chakraborty et al., 2022; Bhardwaj et al., 2021). A July climatology was constructed using ERA5 data for the recent five-year period (2020–2024). This climatology serves as a short-term reference state and is employed solely for the purpose of diagnosing event-scale anomalies associated with extreme rainfall episodes. Since all selected events occurred during July—the peak phase of the southwest monsoon over Telangana—a month-specific climatology provides a dynamically consistent background for anomaly computation.

It is emphasized that the five-year climatology is not intended to represent long-term climate variability or trends. Instead, it is used to isolate departures from the prevailing large-scale circulation and moisture conditions relevant to the event period. Such an approach is appropriate for synoptic- and mesoscale diagnostics, where the focus is on understanding the physical mechanisms governing individual extreme rainfall events rather than climatological trend analysis.

2.1 Study Region and Event Selection

The study focuses on the Indian state of Telangana, located between latitudes 15°N–20°N and longitudes 77°E–82°E (Fig. 1 is the map of Telangana). Three major extreme rainfall events were selected for detailed analysis, each recording daily precipitation exceeding 200 mm within a 24-hour period, based on observations from the India Meteorological Department (IMD). The 200 mm day⁻¹ threshold was adopted in accordance with IMD classification criteria for very heavy to extremely heavy rainfall and has been widely used in previous studies to identify high-impact rainfall events associated with flooding and severe socio-economic impacts over peninsular India.

The three primary extreme rainfall events, each exceeding 200 mm within a 24-hour period, were identified during the monsoon seasons of the past five years using observations from the India Meteorological Department (IMD). The precipitation values listed for each event correspond to specific IMD rain gauge stations located within the affected districts, as monitored and validated by IMD / Meteorological Centre (MC) Hyderabad.

Table 1 summarizes the selected extreme rainfall events, including the event date, observed rainfall amounts, corresponding rain gauge station locations, and data source.

For each event, a 3-day analysis window was selected to capture the pre-conditioning phase, peak rainfall period, and post-event evolution, allowing a comprehensive assessment of synoptic conditions and moisture transport processes associated with the extreme precipitation.

Table 1. Summary of Selected Extreme Rainfall Events in Telangana

Event	Date	Rainfall (mm)	District(s)	Source
1	21 July 2021	237 / 217	Baoth (Adilabad) / Sarngapur (Nirmal)	IMD/MC Hyderabad
2	13 July 2022	290 / 211	Lakshman Chanda (Khanapur, Nirmal) / Nizamabad	IMD/MC Hyderabad
3	26–27 July 2023	651 / 616	Venkatapuram (Mulugu) / Chityal (Jayashankar Bhupalpally)	IMD/MC Hyderabad

2.2 Methodology

A comprehensive moisture budget framework was applied to analyze the three extreme precipitation events. Atmospheric moisture transport was decomposed into its constituent dynamic and thermodynamic components, following recent advances in moisture budget diagnostics. Using high-resolution reanalysis datasets such as ERA5, several studies have demonstrated the effectiveness of these formulations in quantifying horizontal moisture transport, vertical advection, and their respective dynamic and thermodynamic contributions to rainfall extremes (Dey et al., 2023; Saeed et al., 2024; Li et al., 2022). These studies highlight that the classical moisture budget framework, when combined with dynamic–thermodynamic decomposition, provides a robust approach for diagnosing the physical mechanisms underlying extreme rainfall events.

1. Horizontal moisture flux divergence – to quantify moisture transport across the region.
2. Vertical moisture advection – to identify upward or downward transport of moisture.
3. Anomaly estimation relative to climatology – to distinguish extreme-event characteristics from normal seasonal variability.

2.2.1 Moisture Budget Equation

The total column-integrated moisture budget equation is based on the atmospheric water vapour conservation principle, integrated from the surface to 300 hPa,(Seager et al., 2010; Oueslati et al., 2019; Jiang et al., 2020; Moon and Ha, 2020; Wen et al., 2022; Zhao et al., 2022; Sheng et al., 2023; Kenfack et al., 2024)

$$\partial q/\partial t + \nabla \cdot (Vq) + \partial(\omega q)/\partial p = E - P \dots\dots(1)$$

where q (kg kg^{-1}) is specific humidity, V (m s^{-1}) is the horizontal wind vector, ω (Pa s^{-1}) is the vertical pressure velocity, p (Pa) is atmospheric pressure, E (mm day^{-1}) is surface evaporation, and P (mm day^{-1}) is precipitation.

This equation is well established in the scientific community (Trenberth and Guillemot, 1995; Trenberth, 1997; Trenberth et al., 2007). For the purposes of event-scale diagnostics, anomaly fields are computed by subtracting the July climatological mean from the event-mean fields.

2.2.2 Residual Term

Residual consideration: In practice, the atmospheric moisture budget computed from reanalysis data includes a residual term arising from data assimilation increments and numerical truncation errors. The residual is defined as:

$$R = P - E - \partial W/\partial t - \nabla \cdot Q \dots\dots(2)$$

Where W is the total column water vapour and Q is the vertically integrated moisture flux. ERA5 is known to have relatively small residuals compared to earlier reanalyses due to its improved data assimilation system (Hersbach et al., 2020). Although a full residual quantification is beyond the scope of the present event-scale diagnostic study, we acknowledge that this term exists and may contribute to small imbalances in the budget. The dominant moisture convergence and vertical advection signals analysed in this study are sufficiently large relative to typical ERA5 residuals ($< 10\%$ of total moisture tendency for monsoon events; see Dey et al., 2023) to ensure robustness of our conclusions.

2.2.3 Horizontal Moisture Flux Divergence

The horizontal moisture flux divergence is computed as:

$$\nabla \cdot (qV) = \partial(qu)/\partial x + \partial(qv)/\partial y \dots\dots(3)$$

Where u and v (m s^{-1}) are the zonal and meridional wind components, and x and y denote the zonal and meridional directions. Negative values (convergence) indicate moisture accumulation, while positive values (divergence) indicate moisture export. The vertically

integrated moisture flux divergence (VIMFD) is obtained by integrating Equation 3 from the surface to 300 hPa.

2.2.4 Dynamic and Thermodynamic Decomposition of Moisture Budget Anomalies

The anomalous vertically integrated horizontal moisture flux divergence is decomposed as:

$$[\nabla \cdot (qV)]' = \nabla \cdot (q'V) + \nabla \cdot (\bar{q}V') + \nabla \cdot (q'V') \quad \text{.....(4)}$$

where the three terms on the right represent:

(i). $\nabla \cdot (q'\bar{V})$ — Thermodynamic component: is the

anomalous moisture divergence due to changes in specific humidity (q') acting on the climatological mean wind field ($\bar{V}$). This reflects thermodynamic enhancement — higher atmospheric moisture loading during extreme events.

(ii). $\nabla \cdot (\bar{q}V')$ — Dynamic component: is the

anomalous moisture divergence due to changes in circulation (V') acting on the climatological mean moisture field ($\bar{q}$). This reflects dynamical forcing — stronger or anomalous wind convergence patterns.

(iii). $\nabla \cdot (q'V')$ — Nonlinear (covariance) term: is the nonlinear term arising from co-variation of wind and humidity anomalies. This term is generally small but is retained for completeness.

Similarly, the anomalous vertical moisture advection term $\partial(\omega q)/\partial p$ is decomposed as:

$$[\partial(\omega q)/\partial p]' = \partial(\omega'\bar{q})/\partial p + \partial(\bar{\omega}q')/\partial p + \partial(\omega'q')/\partial p \quad \text{.....(5)}$$

where:

(i). $\partial(\omega'\bar{q})/\partial p$ — Dynamic vertical component: anomalous vertical velocity (

ω') acting on the climatological mean humidity profile ($\bar{q}$). This captures enhanced uplift driven by stronger-than-normal synoptic-scale ascent.

(ii). $\partial(\bar{\omega}q')/\partial p$ — Thermodynamic vertical component: mean vertical velocity (

$\bar{\omega}$) acting on the anomalous humidity profile (q'). This reflects enhanced vertical transport of anomalously high moisture content.

(iii). $\partial(\omega'q')/\partial p$ — Nonlinear term: covariation of anomalous vertical velocity and anomalous humidity .

2.2.5 Total Column Water Vapor Anomaly:

$$\text{TCWV_anomaly} = \text{TCWV_event} - \text{TCWV_climatology} \text{ -----(6)}$$

Where

TCWV (kg m^{-2}) denotes the **total column water vapor**.

TCWV event represents the column-integrated water vapor during the extreme rainfall event, and

TCWV climatology denotes the corresponding July climatological mean.

Positive TCWV anomalies indicate an enhanced atmospheric moisture column, whereas negative anomalies indicate reduced column moisture relative to climatology.

Event anomalies are computed relative to July month climatology to highlight deviations associated with extreme rainfall events:

This framework enables a quantitative assessment of moisture convergence, vertical transport, and extreme-event dynamics, providing insight into both the timing and intensity of rainfall over Telangana.

2.3 Synoptic Characteristics of the Events

2.3.1 Event one (21 July 2021-23 July 2021)

On July 19, 2021, a low-pressure system developed over the west-central Bay of Bengal near the Odisha coast. In the following days, it strengthened into a well-defined low-pressure area situated over the northwest Bay of Bengal, adjacent to the northern coasts of Odisha and West Bengal. The associated cyclonic circulation extended up to 5.8 km above mean sea level. This system later progressed inland, traversing Jharkhand and the neighboring northern region of Chhattisgarh, while preserving its cyclonic circulation that extended up to 5.8 km above mean sea level and inclined southward with altitude. The existence of this synoptic system resulted in widespread and significant rainfall across the northern regions of Telangana, with particular impact on the Adilabad and Nizamabad districts. Rain gauge measurements recorded extreme precipitation levels, including 237 mm at Boath (Adilabad) and 217 mm at Sarangapur (Nirmal). Satellite imagery and synoptic charts from this period reveal well-structured convective activity along the monsoon trough axis, which traversed

central India during this occurrence. The combination of low-level moisture convergence, upper-level divergence, and favorable vertical wind shear established conditions that were conducive to prolonged heavy rainfall.

2.3.2 Event Two (13 July 2022-15 July 2022)

A low-pressure system developed in the Bay of Bengal on 9th July, subsequently moving towards the coastal regions of south Odisha and north Andhra Pradesh. By 11th July, this low-pressure area, which had been situated over the coastal regions of south Odisha and north Andhra Pradesh, was now located over the Northwest Bay of Bengal, off the Odisha coast. The associated cyclonic circulation was observed to extend up to 7.6 km above mean sea level, with a southwestward tilt as altitude increased. On 12th July, the low-pressure area was identified as a well-defined system over south coastal Odisha and its surroundings, with the cyclonic circulation still extending up to 7.6 km above mean sea level and maintaining its southwestward tilt. The low-pressure area over south coastal Odisha and its vicinity has now shifted to north Odisha and its surroundings, with the cyclonic circulation continuing to extend up to 7.6 km above mean sea level, also tilting southwestward. By 14th July, the well-marked low pressure had weakened into a less defined low-pressure area over south coastal Odisha and its surroundings, now located over north Odisha and its vicinity, with the cyclonic circulation still extending up to 7.6 km above mean sea level and tilting southwestward. On 18th July, the low-pressure area transitioned from north Odisha and its surroundings to the region over east Vidarbha and its vicinity, now positioned over northeast Vidarbha and its surroundings. The associated cyclonic circulation continued to extend up to 7.6 km above mean sea level, tilting southwestward, and it became less pronounced by 19th July.

2.3.3 Event Three (26-27 July 2023)

Cyclonic circulation developed over the Northwest and West Central Bay of Bengal, as well as the Andhra Pradesh and Odisha coast, forming a low-pressure area on 24 July, extending up to 7.6 km above mean sea level. This area has diminished in intensity and now stretches to southeast Vidarbha and south Chhattisgarh as of 25 July 2023. On 26 July, the area strengthens into a well-defined low-pressure zone, remaining over the coasts of north Andhra Pradesh and south Odisha while moving inland. A shear zone is currently positioned along 20° N, slanting southward with altitudes from 17th to 26th July. The shear zone persists along 20° N, at heights of 3.1 to 7.6 km above mean sea level, tilting southward from 22nd to 24th July. Additionally, the shear zone extends along 17° N, at altitudes between 5.8 km and

7.6 km above mean sea level, and along 8° N, tilting southward with heights from 27th to 28th July.

The accumulated rainfall is over 24 hours, and the satellite imagery of three events are illustrated in Figures 2(a, b, c) and 3(a, b, c). The satellite images is sourced from the INSAT-3D/3DR satellite archive of the India Meteorological Department (IMD). The primary factors contributing to extreme precipitation in tropical regions, particularly during the monsoon season, are atmospheric instability, the water vapor column, and horizontal moisture transport. As noted by Trenberth et al., 2003, and Kunkel et al., 2020a, extreme precipitation events necessitate a continuous influx of humidity from external sources, specifically through significant horizontal moisture transport, to sustain elevated moisture levels in the atmospheric column. Consequently, horizontal moisture transport should be regarded as a crucial scaling variable for elucidating extreme precipitation.

In this present study, we are examining the complete moisture budget equation primarily through three key drivers: total column precipitable water vapor, horizontal divergence related to moisture transport, and vertical advection (the vertical movement of moisture), all of which work together to maintain low-level moisture convergence. We initiate our analysis to comprehend the mechanisms behind precipitation extremes during three specific events in Telangana.

3. Results and Discussions:

According to the Weather & Climatology of Telangana (2024) report, July is the peak monsoon month, contributing the largest fraction of seasonal rainfall over Telangana and exhibiting the highest frequency of heavy and extreme rainfall events (TSDPS and DES, 2024). The report highlights that July rainfall is closely associated with enhanced low-level monsoon circulation, synoptic-scale disturbances, and strong moisture convergence, making it climatologically distinct from June, August, and September. The three selected events, each exceeding 200 mm day⁻¹, occurred during this climatologically active period. In the analysis below, moisture budget diagnostics are interpreted through the dynamic–thermodynamic

decomposition outlined in Section 2.2.4. Positive TCWV anomalies (q') serve as the thermodynamic indicator of excess moisture loading, anomalous 850 hPa winds (V') serve as the dynamic indicator of enhanced circulation, and the vertically integrated vertical advection captures both upward moisture transport driven by anomalous uplift and that driven by anomalous moisture content.

3.1 Moisture Budget Analysis for event 1(21–22 July 2021):

Thermodynamic conditions

The examination of the total column water vapor on July 21-22, 2021, alongside the mean climatology depicted in Fig. 4, indicates a significant moisture presence throughout the Telangana region when compared to the climatological average for July. This moisture is crucial for facilitating convective rainfall. The mean TCWV surpassed 68 kg m^{-2} in northern Telangana, with slightly reduced values in the southern areas, ranging from approximately 54 to 60 kg m^{-2} . The anomalies revealed an increase of 3 to 5 kg m^{-2} above the climatological norm in the northern and central districts. The low-level jet plays a key role during the monsoon season; as the system approaches the coast, the strength of the jet is expected to intensify, as illustrated in Figure.5. This anomalous moisture loading reflects the thermodynamic component of the moisture budget specifically, mean monsoon upwelling acting on an anomalously deep moisture column $[\partial (\bar{\omega}q')/\partial p]$. The surplus atmospheric water vapour provided the primary thermodynamic fuel for deep convection over northern Telangana.

Dynamic Conditions:

At 850hPa, strong westerly to northwesterly winds exceeding 20 m s^{-1} are transporting moisture from the Arabian Sea and Bay of Bengal into Telangana. The convergence zone of these strong winds, along with the anomalies in total column water vapor, suggests abundant moisture incursion into the rainfall-affected areas. In addition, horizontal moisture divergence served as another mechanism for moisture transport at various altitudes, from 1000 to 500hPa, extending up to mid-tropospheric levels (Figure 6(a,b,c,d,e)). The coincidence of anomalous wind convergence with elevated TCWV indicates that both dynamic and thermodynamic forcing were active, consistent with Prakash et al. (2019) and Dey et al. (2023). Figure 6(a) shows that the moisture divergence at 925hPa and 1000hPa reveals strong low-level convergence over southern Telangana and the nearby Andhra Pradesh coast,

indicating a substantial influx of moisture from the Bay of Bengal. This low-level inflow creates conditions favorable for vertical moisture transport. At the 850hPa level, convergence is more pronounced in the northern regions of Telangana, suggesting that moisture is accumulating in the convergence zone. Meanwhile, at the 700hPa level, there is notable divergence in the southern and western areas, which is critical for deep convection. The plot at the 500hPa level shows strong outflow in the northern zone and significant inflow in eastern Telangana, indicating a robust mid-tropospheric inflow system. Mid-tropospheric divergence at 700–500 hPa supports organised deep convection.

Vertical Moisture Transport:

The budget analysis presented in Figure 7 illustrates the vertically integrated vertical advection. This vertically integrated vertical moisture advection is a primary driver for the upward transport of moisture to the mid-levels, as depicted in Figure 7. Figure shows positive values over Nizamabad and Adilabad, indicating upward moisture transport driven primarily by anomalous vertical motion acting on the mean humidity profile $[\partial(\omega'\bar{q})/\partial p]$. The co-located TCWV surplus amplified total vertical transport beyond what the circulation anomaly alone would produce, resulting in extreme precipitation of 237 mm at Boath and 217 mm at Sarangapur.

Dynamic and Thermodynamic Decomposition of Moisture Budget :

The dynamic–thermodynamic decomposition of the moisture budget for this event is presented in Figure 8. Across all four panels, a clear and consistent result emerges: the anomalous wind field is the overwhelmingly dominant mechanism governing moisture transport during Event 1. Figure 8 (c), representing the dynamic horizontal moisture flux divergence $[\nabla \cdot (\bar{q}\bar{V})]$, shows deep, spatially extensive negative values (convergence) across virtually the entire Telangana domain, with magnitudes reaching approximately $-1.6 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ by far the strongest signal in the decomposition. In contrast, Figure 8 (d), the thermodynamic horizontal flux divergence $[\nabla \cdot (\bar{q}'\bar{V})]$, is near-neutral throughout, with only a negligible isolated signal in the northeast, confirming that the mean wind acting on the humidity anomaly played a minimal role in horizontal moisture convergence.

Similarly, in the vertical advection row, Figure 8(a) the dynamic vertical term $[\partial(\omega'\bar{q})/\partial p]$ shows weak, diffuse positive values over northern and central Telangana, while Figure 8(b) the thermodynamic vertical term $[\partial(\bar{\omega}q')/\partial p]$ is essentially blank across the entire domain. Both vertical components thus exhibit considerably weaker signals compared to the dominant dynamic horizontal flux divergence term $[\nabla \cdot (\bar{q}V')]$. With this result we can identify the anomalous wind-driven horizontal moisture convergence as the controlling mechanism for this event, with thermodynamic contributions remaining secondary throughout.

3.2 Moisture Budget Analysis for event 2(13–15 July 2022):

Thermodynamic conditions

The changes in total column water vapor from July 13 to 15, 2022, alongside the average climatology depicted in Figure 9, which shows a significant moisture presence in the northeastern section of the Telangana region. This is in contrast to the climatological mean water vapor for July, which supports a robust supply for convective rainfall. The mean TCWV surpassed 70 kg/m² in the northeastern areas, particularly in the Komurumbheem Asifabad, Mancherla, Jayashankar Bhupalapally, and Mulugu Districts of Telangana, with slightly reduced values observed to the south (approximately 54 kg/m²). The anomalies revealed an increase of +4–5 kg/m² above the climatology in the northern regions, especially in Adilabad, where the entire column of water vapor is concentrated over a small area.

Dynamic Conditions:

The winds at 850hPa, illustrated in Figure 10, are strong westerly to northwesterly winds exceeding 25 m s⁻¹, carrying moisture from the Arabian Sea and Bay of Bengal into Telangana. The wind streamlines at 850hPa also depict the crossing of the low-pressure system, where convergence above the area of intense rainfall coincided with the strong wind convergence zone. Additionally, the total column water vapor anomalies indicate a significant influx of moisture into the rainfall region. The horizontal divergence terms for the levels between 1000-500hPa are presented in Figures 11(a,b,c,d,e). In Figure 11(a), the moisture divergence at 925hPa and 1000hPa is examined, revealing strong low-level convergence from the southern to northern parts of Telangana, adjacent to South Chhattisgarh, which signifies considerable moisture influx from the Wainganga and Pranahita

regions, where the Godavari River Basin is located. This low-level inflow establishes the conditions for vertical moisture transport. At 850hPa, convergence is more pronounced in the northern regions of Telangana, with the highest convergence observed in the Asifabad district, suggesting moisture accumulation in the convergence zone. At the 700hPa level, notable convergence is evident over the northern districts of Telangana, specifically Nirmal, Imamabad, and Adilabad. This mid-level convergence is vital for deep convection, as moisture is transported to the upper levels. The plot at the 500hPa level indicates strong outflow in the northern zone and significant inflow in eastern Telangana, suggesting a robust mid-tropospheric inflow system. The northern zone experiences strong divergence due to subsidence, along with further insights regarding the tilting of the system.

Vertical Moisture Transport

The vertical advection represents the upward movement of moisture to the mid-levels and higher levels, as depicted in fig12. It indicates that the positive vertical advection values in the Nirmal and Nizamabad districts correspond to significant moisture uplift, accompanied by considerable moisture convergence, while the strong negative values observed over Komurumbheem Asifabad indicate that the air at higher levels is drying out, resulting in strong convergence near the Nizamabad and Nirmal Districts. The peaks of vertical advection coincide with regions of increased TCWV anomalies, implying that the moisture present near the surface was effectively transported to the mid- and upper troposphere, thereby promoting deep convection that results in extreme precipitation in the Nirmal and Nizamabad Districts.

Dynamic and Thermodynamic Decomposition of Moisture Budget event 2:

The dynamic–thermodynamic decomposition of the moisture budget for Event 2 is presented in Figure 13, and it reveals a distinctly different character from Event 1. In the vertical advection row, Figure 13(a) the dynamic vertical term $[\partial(\omega'\bar{q})/\partial p]$ shows a weak and diffuse positive values across northern Telangana, with a single intense but geographically confined ($>0.00012 \text{ kg m}^{-2} \text{ s}^{-1}$) over the Komurumbheem Asifabad district. This indicates that anomalous vertical motion was locally intense but not well-organised at the regional scale. The thermodynamic vertical term $[\partial(\bar{\omega}q')/\partial p]$ remains negligible across the domain, with only isolated, small-amplitude signals. Figure 13(c) is the dynamic horizontal flux divergence $[\nabla \cdot (\bar{q}\mathbf{V}')]]$ retains a significant convergence signal over northern Telangana ($\sim 18^\circ\text{--}20^\circ\text{N}$), with areas of strong convergence in the north coexist with equally prominent divergence

across the southern and eastern portions of the domain, reflecting the spatially heterogeneous circulation imposed by the passing Bay of Bengal low-pressure system. Figure 13 (d) the thermodynamic horizontal flux divergence $[\nabla \cdot (q' \bar{V})]$ — is the defining feature of the Event 2 and shows a intense cluster of convergence ($\sim -0.9 \times 10^{-4}$ to $-1.29 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) is anchored precisely over north-central Telangana at approximately $18^\circ\text{--}19^\circ\text{N}$, $79^\circ\text{--}80^\circ\text{E}$, directly overlying the Komurumbheem–Nirmal–Mancherla rainfall zone. This signal represents the mean monsoon wind field converging over the anomalously moist air column — a genuine and significant thermodynamic contribution to moisture accumulation. Figure 13 establishes that Event 2 was thermodynamically modulated, While the dynamic horizontal convergence $[\nabla \cdot (\bar{q} V')]$ remained the primary large-scale moisture delivery mechanism, the thermodynamic horizontal flux divergence $[\nabla \cdot (q' \bar{V})]$ made a meaningful secondary contribution by concentrating moisture convergence precisely over the districts of highest TCWV anomaly. This thermodynamic reinforcement, combined with persistent mid-level convergence at 700 hPa sustaining vertical lifting over a longer duration than Event 1, explains why extreme precipitation was concentrated and prolonged over northeastern Telangana during 13–15 July 2022.

3.3 Moisture Budget Analysis for event 3:

Thermodynamic Conditions:

Figure 14 indicates a significant moisture presence throughout the Telangana region, particularly in the northern and northeastern areas from July 25 to 27, 2023. This is in contrast to the climatological average for July, which supports a substantial supply for convective rainfall. The mean TCWV surpassed 68 kg/m^2 in northern Telangana, with slightly reduced values in the southern regions (approximately $54\text{--}60 \text{ kg/m}^2$). The anomalies revealed an increase of $+3\text{--}5 \text{ kg/m}^2$ above the climatological average in the northern and central districts.

Dynamic Conditions:

The winds at 850hPa, illustrated in, Figure 15, exhibit strong northwesterly wind flow ranging from 15 to 25 m s^{-1} , which are responsible for transporting moisture from the Bay of Bengal into Telangana. The wind streamlines at 850 hPa also indicate the intersection of the low-pressure system, leading to convergence above the area of intense rainfall, coinciding with a strong wind convergence zone. Additionally, the anomalies in total column water vapor suggest enhanced atmospheric moistening into the rainfall region. The horizontal

divergence term for levels 1000-500hPa is depicted in Figures 16(a,b,c,d,e). At the 925hPa and 1000hPa levels, there is pronounced low-level convergence across coastal Andhra Pradesh and throughout Telangana, indicating a substantial moisture influx from the Bay of Bengal. This low-level inflow establishes conditions favorable for vertical moisture transport. At 850hPa, convergence is particularly concentrated in the central and northeastern regions of Telangana, with the highest convergence observed in the eastern and northern districts of Warangal, Mulugu, Jayashankar Bhupalapally, and Bhadradri Kothagudem, suggesting moisture accumulation in the convergence zone. At the 700 hPa level, significant convergence is noted over the central and southern districts of Telangana, which is critical for deep convection. The winds at 500hPa level reveals strong outflow in the northern and northeastern areas, alongside significant inflow in eastern Telangana, indicating a robust mid-tropospheric inflow system. The northern region experiences strong divergence due to subsidence, along with further insights regarding the tilting of the system.

Vertical Moisture Transport:

The vertically integrated vertical advection shown in Figure 17 highlights the upward transport of moisture from the lower to the middle and upper troposphere. Strong positive vertical advection over the central and northeastern parts of Telangana, particularly across Mulugu, Bhadradri Kothagudem, Warangal, Hanumakonda, Jangaon, Khammam, and Mancherial districts, indicates enhanced moisture uplift associated with strong low-level moisture convergence. The overlap of positive vertical advection with enhanced TCWV anomalies suggests that abundant near-surface moisture was efficiently transported to higher levels of the atmosphere, promoting deep convection and resulting in widespread extreme rainfall over Mulugu, Bhadradri Kothagudem, Adilabad, Warangal, and Jayashankar Bhupalpally districts. During this event, several IMD rain-gauge stations recorded extremely heavy rainfall across northeastern Telangana. For clarity, only the representative stations with the highest observed 24-hour rainfall—Venkatapuram (Mulugu, 651 mm) and Chityal (Jayashankar Bhupalpally, 616 mm)—are presented in Table 1, while the analysis reflects the atmospheric conditions responsible for the widespread regional rainfall event.

Dynamic and Thermodynamic Decomposition of Moisture Budget event 3:

The dynamic–thermodynamic decomposition of the moisture budget for Event 3 is presented in Figure 18, In the vertical advection row, Figure 18(a) is the dynamic vertical term

$[\partial(\omega'\bar{q})/\partial p]$ which shows the most spatially extensive and well-organised positive signal of all three events, with the strongest anomaly ($\sim 0.9 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) centred over the Mulugu–Warangal Districts. This indicates that anomalous upward vertical motion acting on the mean moisture profile was both broad-scale and well-organised, driving widespread uplift across a far larger area than the localized dynamic vertical signal seen in Event 2. Panel (b) the thermodynamic vertical term $[\partial(\bar{\omega}q')/\partial p]$ is the critical distinguishing feature of Event 3 compared to both previous events. Figure 18(b) shows a discernible positive signal over eastern and northeastern Telangana, particularly over the Mulugu–Bhadrachalam Kothagudem Districts. This confirms that the mean monsoon upwelling was acting on a genuinely anomalous moisture column — the most widespread and intense TCWV surplus of the three events — and was thereby contributing a measurable thermodynamic component to vertical moisture transport. The spatial overlap of panels (a) and (b) over the Mulugu–Warangal region is directly responsible for the dual amplification of upward moisture flux and the resultant exceptional rainfall totals in that zone.

In the horizontal flux divergence Figure 18(c) the dynamic horizontal flux divergence $[\nabla \cdot (\bar{q}\bar{V}')]$ which presents the strongest and most spatially extensive convergence signal of all three events. Strong divergence shows the entire Telangana domain and extending well into neighbouring regions, with magnitudes exceeding $-1.5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$, reflect the broad, intense anomalous wind field driving moisture into the state from multiple directions simultaneously. Figure 18 (d) is the thermodynamic horizontal flux divergence $[\nabla \cdot (q'\bar{V})]$ — shows a weak, slightly positive to near-neutral signal across northern Telangana, with no concentrated convergence core. Taken together, Figure 18 establishes Event 3 as a qualitatively distinct type of extreme rainfall episode. The dynamic horizontal convergence $[\nabla \cdot (\bar{q}\bar{V}')]$ was the strongest and most widespread of the three events, the dynamic vertical term $[\partial(\omega'\bar{q})/\partial p]$ was broad and well-organized, and unique. The thermodynamic vertical term $[\partial(\bar{\omega}q')/\partial p]$ was also active, simultaneously amplifying upward moisture transport through the anomalously deep moisture column over the Mulugu–Warangal Zone. This triple reinforcement of dynamic horizontal convergence, dynamic vertical uplift, and thermodynamic vertical amplification, operating concurrently over a large spatial footprint, produced the highest rainfall totals, the greatest spatial extent of extreme precipitation, and the largest number of simultaneously affected stations of the three events studied, fully consistent with the findings of Byju et al. (2024) and Zhu et al. (2023) that the most severe monsoon extremes arise when dynamic and thermodynamic mechanisms act in concert.

Among the three extreme rainfall events analyzed over Telangana, the major precursors are anomalously high TCWV values ($\geq 68\text{--}70\text{ kg m}^{-2}$, or $+3\text{--}5\text{ kg m}^{-2}$ above climatology) nearly 6-9% and a strong southwesterly low-level jet, with wind speeds reaching $20\text{--}25\text{ m s}^{-1}$ at 850hPa which will transports the moisture from both the Arabian Sea and Bay of Bengal also with the Persistent low-level convergence (1000–850hPa) coupled with mid-tropospheric divergence (500hPa), a vertical structure conducive to deep convection. This results are consistent with earlier studies from Prakash et al. (2019) identified TCWV anomalies as robust precursors for heavy rainfall across India, while Chakraborty et al. (2022) highlighted the role of episodic moisture surges over the Deccan Plateau in fueling intense monsoon convection. The three events, however, differed in the relative dominance of dynamic and thermodynamic contributions. Event 1 was driven primarily by the dynamic vertical mechanism anomalous low-level uplift acting on the mean moisture profile with low-level convergence as the controlling factor. Event 2 was thermodynamically dominated, with the highest TCWV anomaly of the three events and persistent mid-level convergence sustaining moisture accumulation over northeastern Telangana for a longer duration. Event 3 was distinct in exhibiting simultaneous co-amplification of both mechanisms: broad anomalous upwelling comparable to Event 1 and widespread thermodynamic enhancement comparable to Event 2. This co-occurrence produced the highest rainfall totals, the most spatially extensive precipitation, and the greatest number of stations recording extreme rainfall. These results support the finding of Byju et al. (2024) and Zhu et al. (2023) that the most severe monsoon extremes arise when dynamic and thermodynamic amplification act in concert rather than in isolation. The comparative Results are shown in the Table 2. Of the above all three extreme events These findings reinforce the view that extreme rainfall events require both sustained horizontal moisture supply and dynamic vertical lifting mechanisms (Trenberth et al., 2003; Kunkel et al., 2020a). The presence of Bay of Bengal low-pressure systems, often tilted cyclonically, further enhanced the horizontal and vertical moisture fluxes during all three cases.

4. Conclusions:

The extreme precipitation events experienced in Telangana during the monsoon season in July of the years 2021, 2022, and 2023 were marked by a combination of significant atmospheric factors, including high atmospheric moisture availability, strong low-level moisture convergence, and effective vertical transport through vertical advection. From the

Figure 19 shows the schematic version of that the process of the extremely heavy rainfall events that occurs in the Deccan plateaus especially Telangana region which explains the southwest low-level jet transported abundant moisture into the region, while additional moisture supply from the Bay of Bengal further enhanced the inflow. This moisture-laden air converged over Telangana in the lower troposphere (1000–850hPa), creating a low-level convergence zone that forced the air to rise. The vertical uplift promoted condensation and latent heat release, fueling deep convection. Importantly, the presence of strong mid-level divergence around 500hPa acted as an efficient outflow mechanism, sustaining the upward motion and preventing stagnation of convection over Telangana. According to the (Min et al., 2011), the projected strengthening of lower-tropospheric moisture content and the enhanced moisture holding capacity of a warming atmosphere are expected to increase the frequency and intensity of convergence driven extreme rainfall events over vulnerable regions such as Telangana. Combined with projected variability in the strength and position of the monsoon low-level jet, the likelihood of co-amplification events, where dynamic and thermodynamic mechanisms reinforce each other simultaneously, as observed during Event 3 is expected to increase. Incorporating the dynamic–thermodynamic moisture budget diagnostics developed in this study into operational forecasting systems would meaningfully enhance predictive skill for extreme rainfall, support district-level early warning systems, and strengthen resilience planning against the urban flooding, agricultural losses, and infrastructure damage that such events increasingly impose on communities across Telangana and the broader Deccan Plateau region.

Novelty and Scope of Contribution

While the individual physical mechanisms examined here (low-level moisture convergence, TCWV surplus, and vertical advection) are well established in the broader monsoon literature, the specific contribution of this study is the event-scale dynamic–thermodynamic decomposition applied consistently across three extreme rainfall episodes over Telangana, a semi-arid inland region for which such diagnostics have not previously been reported. This analysis demonstrates that outwardly similar extreme-rainfall events (each exceeding 200 mm day⁻¹) can arise from distinct combinations of dynamic and thermodynamic forcing—Event 1 dominated by dynamic low-level convergence, Event 2 by thermodynamic moisture loading, and Event 3 by co-amplification of both mechanisms. This event-to-event heterogeneity, rather than a single generalized precursor signature, is the principal new

finding of this work and has direct relevance for designing region-specific early-warning indicators rather than relying on a one-size-fits-all precursor threshold.

Limitations and Future Work

This study is deliberately scoped as an in-depth, event-level diagnostic analysis rather than a climatological survey, and this scope carries specific limitations that should guide interpretation of the results. First, the analysis is based on three extreme rainfall events, all occurring in July across three consecutive years (2021–2023); this sample size is sufficient to characterize the physical mechanisms operating during each event in detail but is too small to support statistical generalization about the relative frequency of dynamically versus thermodynamically dominated extremes over Telangana. Second, the July-specific climatology, while adequate for computing event anomalies, spans only five years (2020–2024) and should not be interpreted as a long-term climatological baseline; extending this reference period using the full ERA5 record (available from 1940 onward) is a natural next step and would strengthen the robustness of the anomaly estimates. Third, this study relies on a single reanalysis product; while ERA5 has been shown to perform well over the Indian region relative to other reanalyses, multi-reanalysis or observational cross-validation would further test the robustness of the moisture budget estimates presented here. Future work extending this framework to a larger event set spanning multiple monsoon months and years, together with a longer climatological baseline, would allow the event-to-event heterogeneity identified here to be tested for statistical robustness and translated into operational precursor thresholds.

References

1. Archer D, Fowler H, Mortimore M, Hewitt K. 2010. Understanding the Hindu Kush–Himalayan region. *Mountain Research and Development*. 30:64–76. <https://doi.org/10.1659/MRD-JOURNAL-D-09-00038.1>
2. Awasthi N. 2024. Long-term spatiotemporal investigation of rainfall patterns in central India. *Hydrology*. 11:27. <https://doi.org/10.3390/hydrology11020027>
3. Bhardwaj R, et al. 2021. Convective instability patterns in monsoon depressions using ERA5. *Atmospheric Research*. 248:105175. <https://doi.org/10.1016/j.atmosres.2020.105175>
4. Bhunia PS. 2024. Land water storage dynamics over the Deccan Plateau. *Science of the Total Environment*. 870:160433. <https://doi.org/10.1016/j.scitotenv.2023.160433>
5. Byju P, Muriki S, Mathew M, Venkatramana K, Krishnamohan KS. 2024. Understanding the changes in moisture budget of extreme wet Indian summer monsoon precipitation in CMIP6. *International Journal of Climatology*. 44:5266–5279. <https://doi.org/10.1002/joc.8636>
6. Chakraborty A, et al. 2022. Sub-seasonal moisture surges over the Deccan Plateau. *Journal of Geophysical Research: Atmospheres*. 127:e2021JD036216. <https://doi.org/10.1029/2021JD036216>
7. Chaudhuri C, et al. 2015. Heavy rainfall events over the Indian subcontinent. *Theoretical and Applied Climatology*. 120:499–515. <https://doi.org/10.1007/s00704-014-1184-2>
8. Das PK. 2005. *Monsoon Meteorology*. National Book Trust
9. Dey A, et al. 2023. Moisture transport and its role in extreme rainfall over the Indian region. *Atmospheric Research*. 284:106632. <https://doi.org/10.1016/j.atmosres.2022.106632>
10. Dirmeyer PA, et al. 2006. Land–atmosphere interactions and the water cycle. *Geophysical Research Letters*. 33:L03403. <https://doi.org/10.1029/2005GL024951>
11. Field CB, et al. 2012. *Managing the Risks of Extreme Events and Disasters*. Cambridge University Press
12. Fischer EM, Knutti R. 2014. Intensification of extremes. *Geophysical Research Letters*. 41:2931–2940. <https://doi.org/10.1002/2014GL059123>
13. Gimeno L, et al. 2012. Oceanic and terrestrial sources of continental precipitation. *Reviews of Geophysics*. 50:RG4003. <https://doi.org/10.1029/2012RG000389>
14. Gouda KC, et al. 2023. Extreme precipitation events in the Indian monsoon. *Weather and Climate Extremes*. 39:100515. <https://doi.org/10.1016/j.wace.2022.100515>
15. Hersbach H, Bell B, Berrisford P, et al. 2020. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*. 146:1999–2049. <https://doi.org/10.1002/qj.3803>
16. Joshi P, et al. 2020. Extreme rainfall events in South Asia. *Climate Dynamics*. 54:243–258. <https://doi.org/10.1007/s00382-019-04991-x>
17. Jyostna B, et al. 2022. Rainfall trends in Telangana. *International Journal of Environment and Climate Change*. 12:3404–3412. <https://doi.org/10.9734/ijecc/2022/v12i111391>

18. Kenfack K, et al. 2024. Dynamic and thermodynamic contribution to extreme rainfall. *Weather and Climate Dynamics*. 5:1457–1472. <https://doi.org/10.5194/wcd-5-1457-2024>
19. Kishtawal CM, et al. 2010. Impact of urbanization on rainfall. *Geophysical Research Letters*. 37:L08802. <https://doi.org/10.1029/2010GL042715>
20. Li J, Zhao Y, Chen D, Kang Y, Wang H. 2022. Future precipitation changes in East Asia: roles of thermodynamics and dynamics. *Climate Dynamics*. 59:1377–1398. <https://doi.org/10.1007/s00382-021-06043-w>
21. Mahto SS, Mishra V. 2019. Does ERA5 outperform other reanalysis products for hydrologic applications in India? *Journal of Geophysical Research: Atmospheres*. 124:9423–9441. <https://doi.org/10.1029/2019JD031155>
22. Mall RK, et al. 2006. Climate change and water resources in India. *Current Science*. 90:1610–1626
23. Mani N, et al. 2009. Urbanization and rainfall extremes. *Journal of Hydrology*. 367:280–291. <https://doi.org/10.1016/j.jhydrol.2009.01.022>
24. Min SK, et al. 2011. Human contribution to more-intense precipitation extremes. *Nature*. 470:378–381. <https://doi.org/10.1038/nature09763>
25. Prakash S, et al. 2019. Total column water vapor anomalies as precursor to heavy rainfall. *Meteorological Applications*. 26:445–457. <https://doi.org/10.1002/met.1778>
26. Rajagopal EN, Iyengar GRN. 2005. Forecast system performance. *Current Science*. 88:947–956
27. Rajeevan M, et al. 2008. Extreme rain events over India. *Science*. 314:1442–1445. <https://doi.org/10.1126/science.1132027>
28. Rao SA, Rajeevan M. 2008. Indian monsoon variability. *Journal of Climate*. 21:4524–4541. <https://doi.org/10.1175/2008JCLI2059.1>
29. Saeed F, et al. 2024. Thermodynamic and dynamic drivers of extreme precipitation. *Climate Dynamics*. <https://doi.org/10.1007/s00382-023-07012-3>
30. Sarkar S, Kuttippurath J, Patel VK. 2023. Long-term changes in precipitable water vapour over India. *Environmental Science: Atmospheres*. 3:749–759. <https://doi.org/10.1039/D2EA00139J>
31. Seager R, Naik N, Vecchi GA. 2010. Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle. *Journal of Climate*. 23:4651–4668. <https://doi.org/10.1175/2010JCLI3655.1>
32. Oueslati B, et al. 2019. Dynamic and thermodynamic processes of extreme precipitation. *Scientific Reports*. 9:2859. <https://doi.org/10.1038/s41598-019-39306-y>
33. Jiang J, et al. 2020. Future precipitation changes based on CMIP6 projections. *Environmental Research Letters*. 15:054009. <https://doi.org/10.1088/1748-9326/ab7d03>
34. Moon S, Ha KJ. 2020. Future changes in monsoon precipitation. *npj Climate and Atmospheric Science*. 3:45. <https://doi.org/10.1038/s41612-020-00151-w>
35. Wen N, et al. 2022. Dynamic and thermodynamic effects in extreme rainfall. *Journal of Meteorological Research*. 36:26–36. <https://doi.org/10.1007/s13351-022-1126-2>
36. Zhao D, et al. 2022. Anthropogenic forcing on precipitation. *Climate Dynamics*. 59:1939–1952. <https://doi.org/10.1007/s00382-022-06189-1>

37. Sheng B, et al. 2023. Thermodynamic and dynamic effects of precipitation. *Weather and Climate Extremes*. 40:100560. <https://doi.org/10.1016/j.wace.2023.100560>
38. Tarek M, et al. 2020. Evaluation of ERA5. *Hydrology and Earth System Sciences*. 24:2527–2544. <https://doi.org/10.5194/hess-24-2527-2020>
39. Trenberth KE. 1997. Atmospheric moisture budgets. *Journal of Climate*. 10:2796–2809
40. Trenberth KE, Guillemot CJ. 1995. Evaluation of moisture budgets. *Climate Dynamics*. 14:213–231
41. Trenberth KE, et al. 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society*. 84:1205–1218
42. Trenberth KE, et al. 2007. Estimates of the global water budget. *Journal of Hydrometeorology*. 8:758–769
43. TSDPS & DES. 2024. Weather and Climatology of Telangana
44. Vijaykumar P, et al. 2021. Extreme rainfall case study. *Natural Hazards*. 107:971–989. <https://doi.org/10.1007/s11069-020-04387-5>
45. Vittal H, et al. 2013. Changes in extreme precipitation. *International Journal of Climatology*. 33:3237–3248
46. Vittal H, et al. 2020. Climate extremes in India. *Climate Dynamics*. 54:243–258
47. Hari D, Kasa RR. 2025. Rooftop rainwater harvesting potential in Hyderabad. *Grassroots Journal of Natural Resources*. 8:701–716. <https://doi.org/10.33002/nr2581.6853.080233>
48. Prabha TV, et al. 2025. ERA5-based dynamic and thermodynamic analysis of monsoon moisture transport over the Indian subcontinent. *Atmospheric Research*. <https://doi.org/10.1016/j.atmosres.2025.108090>
49. Pandidurai, D., Attada, R., Chakraborty, R., Kumari, A., & Kumar, P. (2025). Widespread monsoon extreme rainfall events over the central Indian region: Influence of dynamics and thermodynamics. *Climate Dynamics*, 63, Article 151. <https://doi.org/10.1007/s00382-025-07641-8>
50. Kunkel, K. E., Easterling, D. R., Kristovich, D. A. R., Gleason, B., Stoecker, L., & Smith, R. (2020). Meteorological causes of extreme precipitation with implications for future climate change. *Weather and Climate Extremes*, 26, 100229. <https://doi.org/10.1016/j.wace.2019.100229>

Figures and Tables:

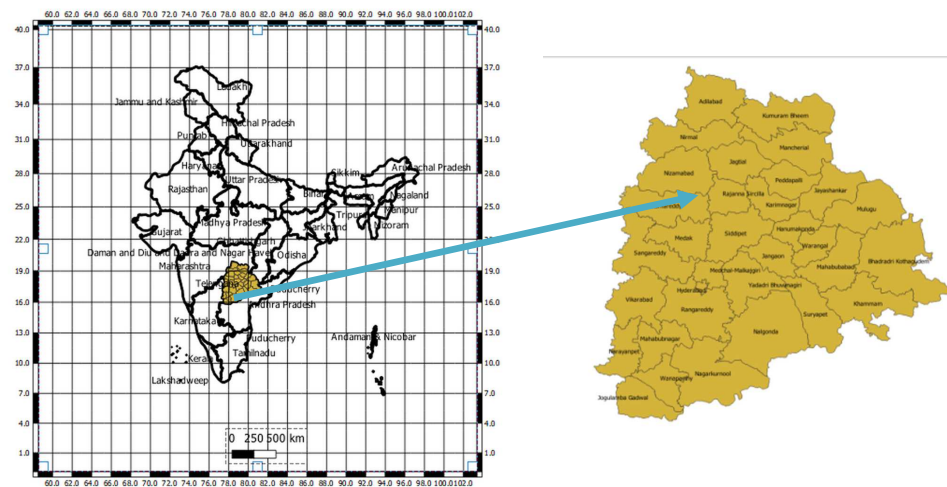


Figure 1. Map of the study region: Telangana, India.

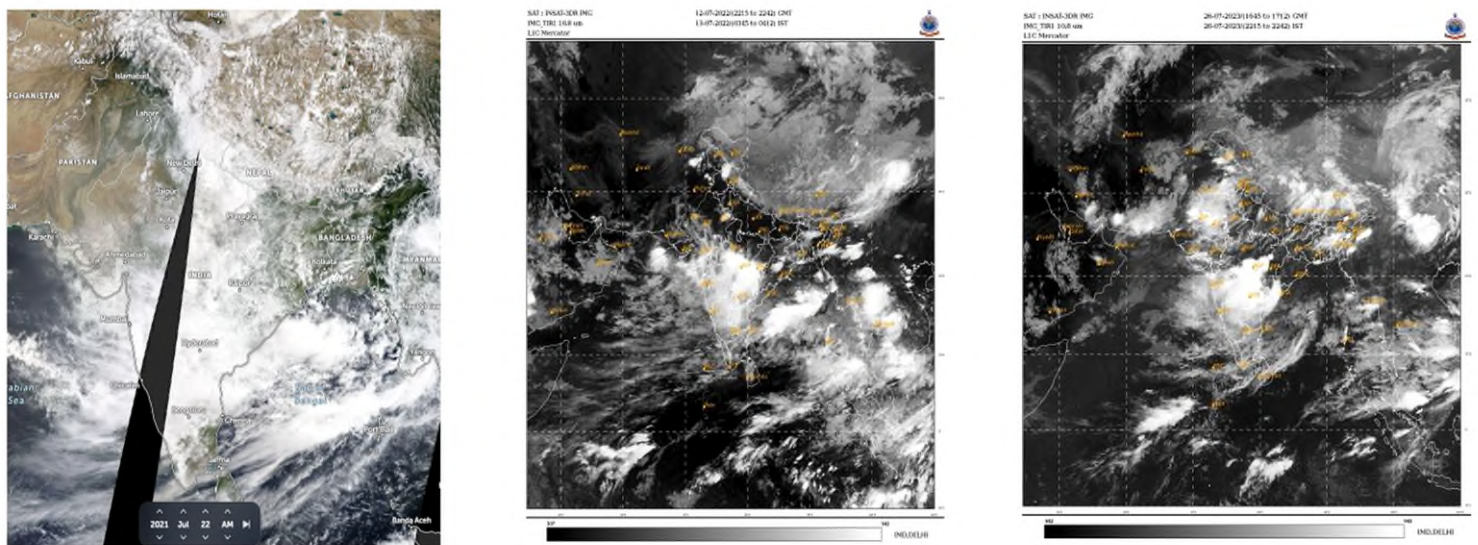


Figure 2. The INSAT satellite images from the SAT-MET archive for the three extreme rainfall events: (a) 21 July 2021, (b) 13 July 2022, and (c) 26 July 2023.

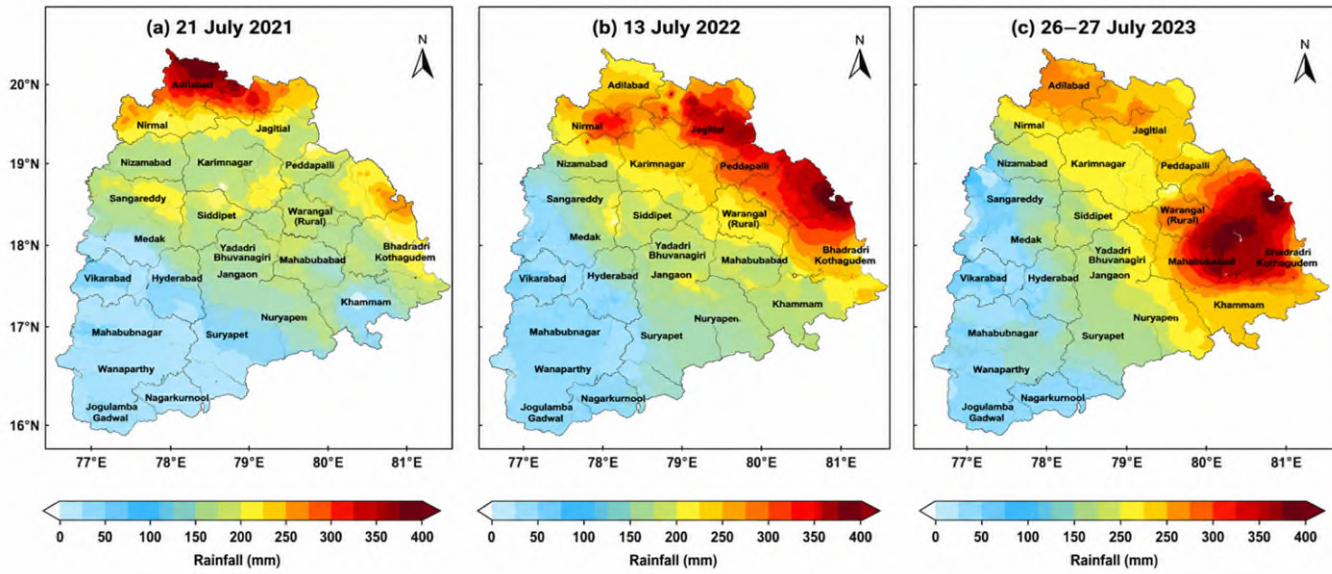


Figure 3. 24-hour accumulated rainfall (mm) for the three extreme rainfall events: (a) 21 July 2021, (b) 13 July 2022, and (c) 26–27 July 2023. Observations from IMD rain gauge stations.

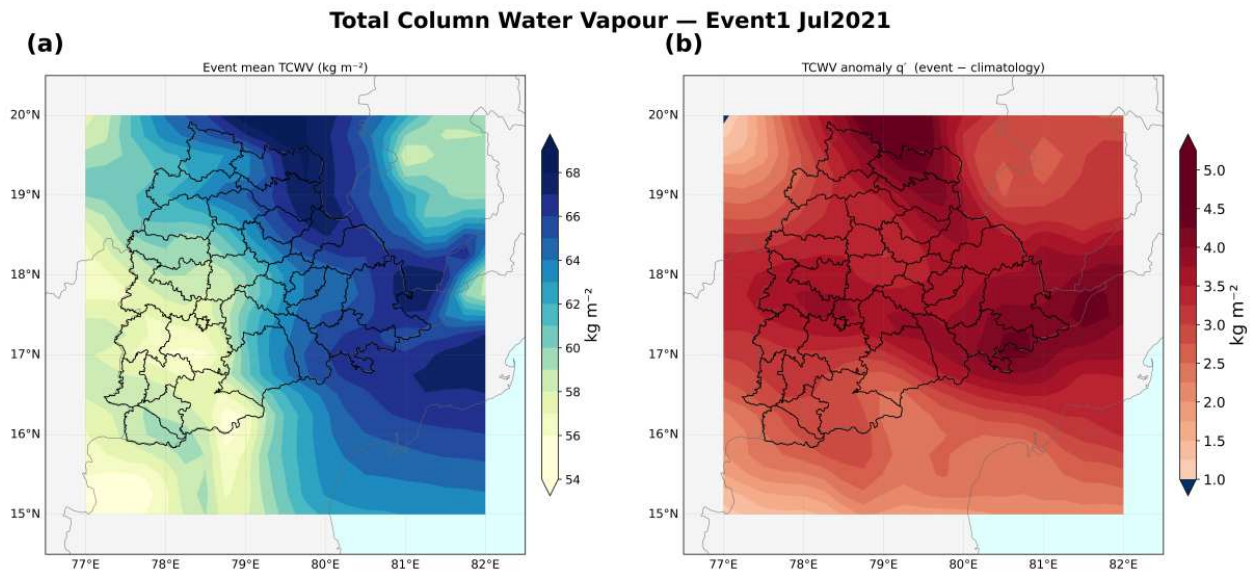


Figure 4. Spatial distribution of (left) mean Total Column Water Vapour (TCWV; kg m^{-2}) and (right) TCWV anomaly relative to climatology for Event 1 (21 July 2021).

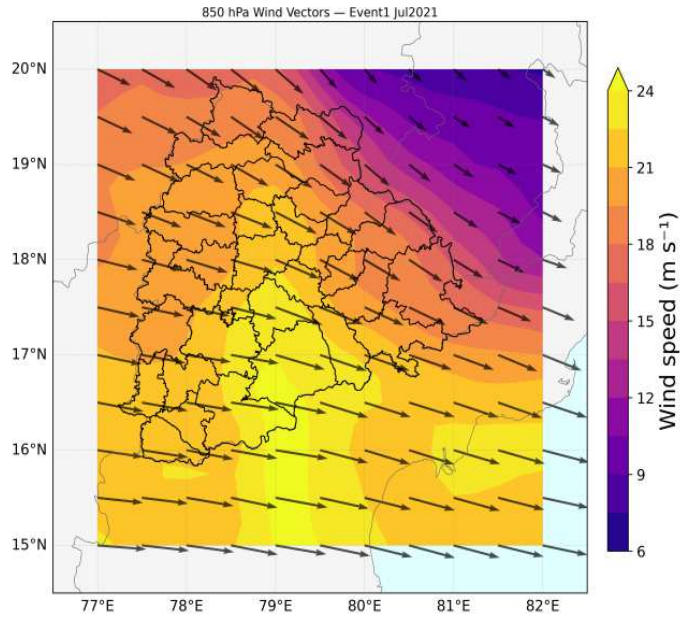


Figure 5. 850 hPa wind vectors (m s^{-1}) for Event 1 (21 July 2021)

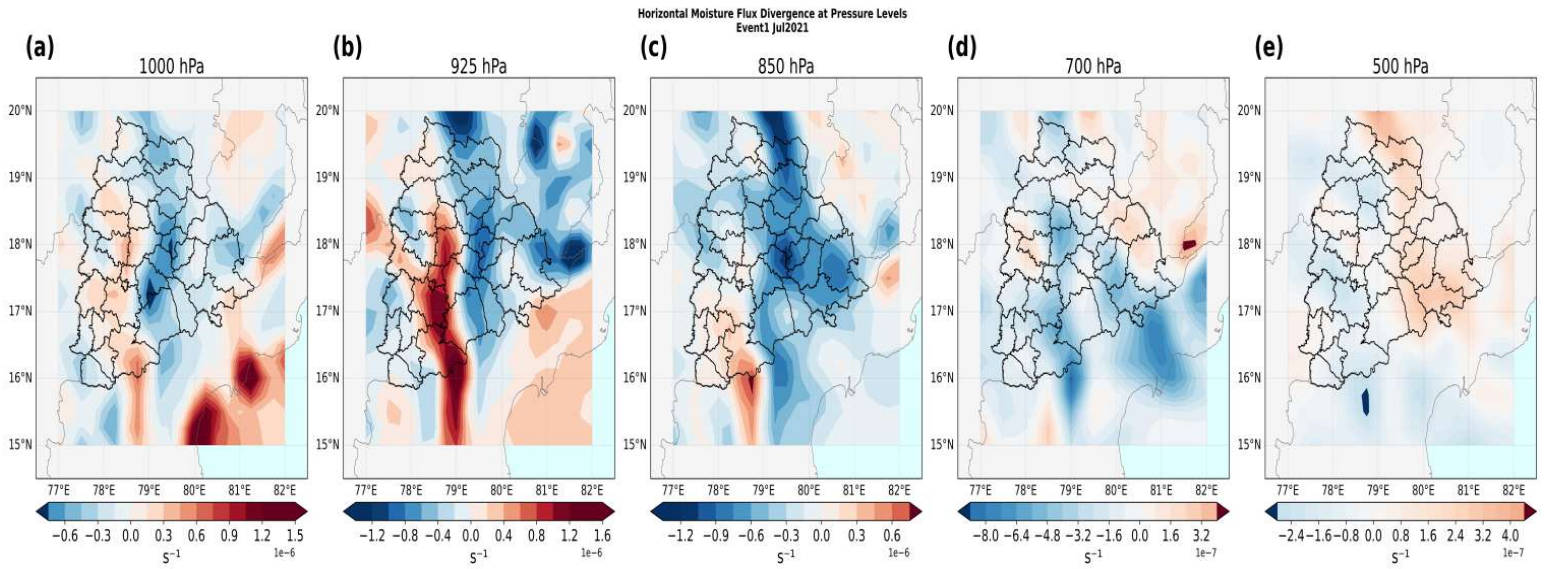


Figure 6. Horizontal divergence (10^{-5} s^{-1}) at (a) 1000 hPa, (b) 925 hPa, (c) 850 hPa, (d) 700 hPa, and (e) 500 hPa for Event 1 (21 July 2021).

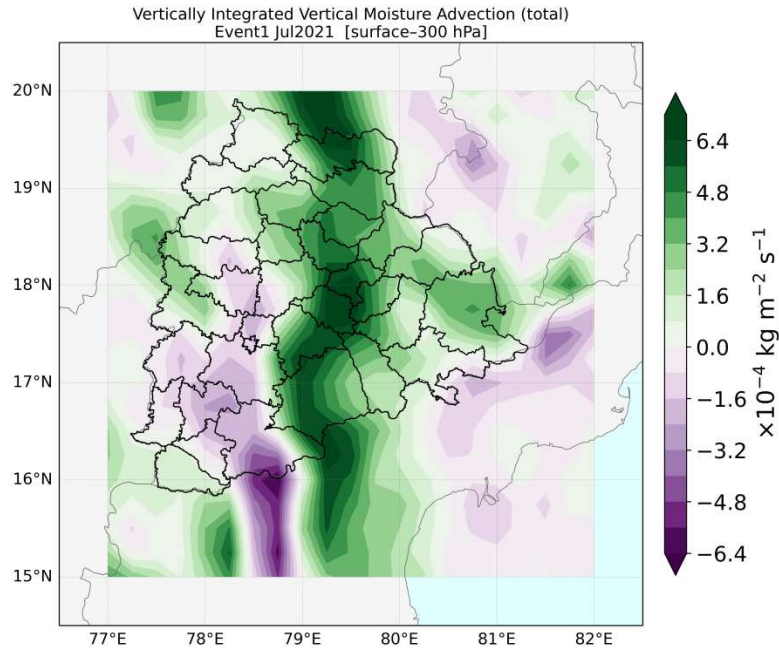


Figure 7. Vertically integrated vertical moisture advection ($\text{kg m}^{-2} \text{ s}^{-1}$; surface to 300 hPa) for Event 1 (21 July 2021), corresponding to the peak rainfall phase.

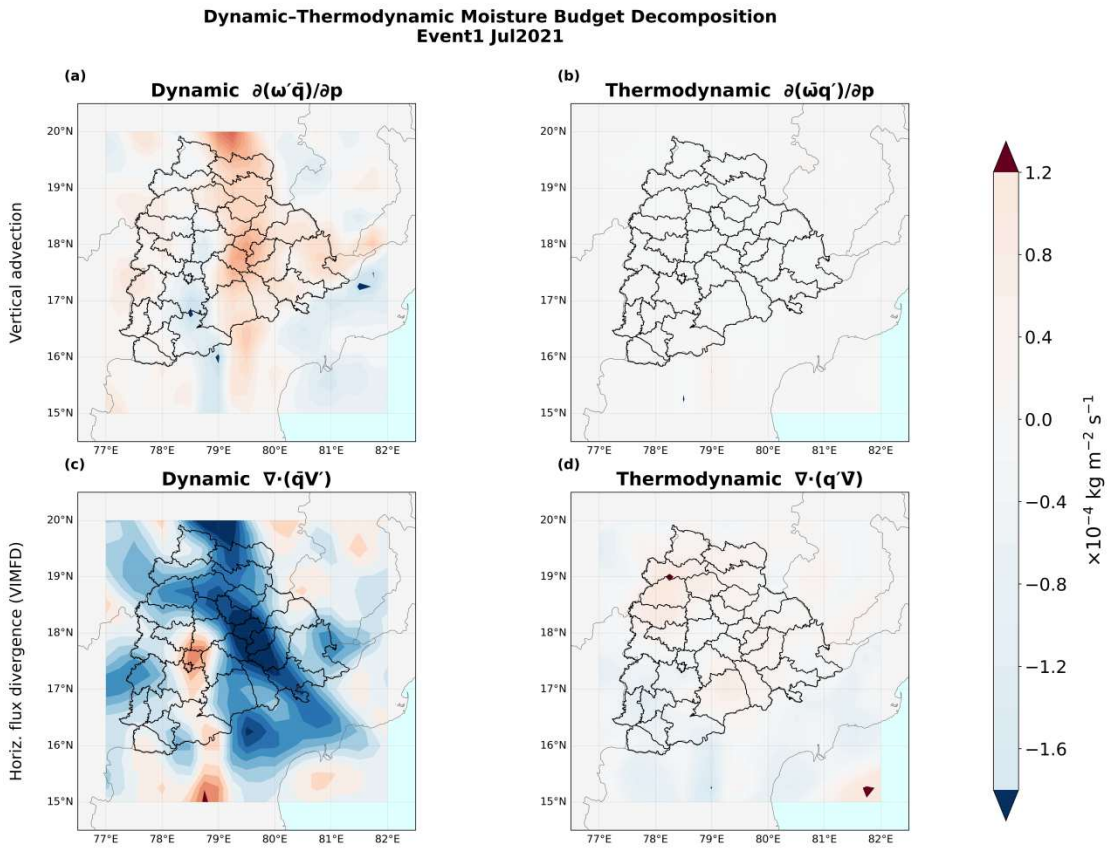


Figure 8. Dynamic and thermodynamic moisture budget decomposition ($\text{kg m}^{-2} \text{ s}^{-1}$) for Event 1 (21 July 2021). (a) Dynamic vertical advection $\partial(\omega'\bar{q})/\partial p$; (b) Thermodynamic vertical advection $\partial(\bar{\omega}q')/\partial p$; (c) Dynamic VIMFD $\nabla \cdot (\bar{q}\bar{V})$; (d) Thermodynamic VIMFD $\nabla \cdot (q'\bar{V})$. Colourbar values scaled by $\times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$.

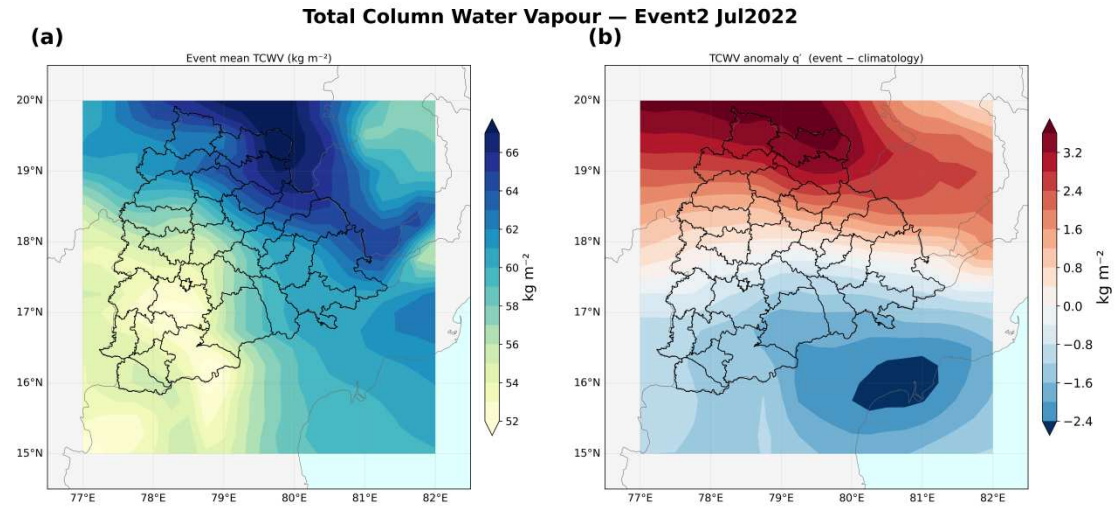


Figure 9. Spatial distribution of (left) mean Total Column Water Vapour (TCWV; kg m^{-2}) and (right) TCWV anomaly relative to climatology for Event 2 (13 July 2022).

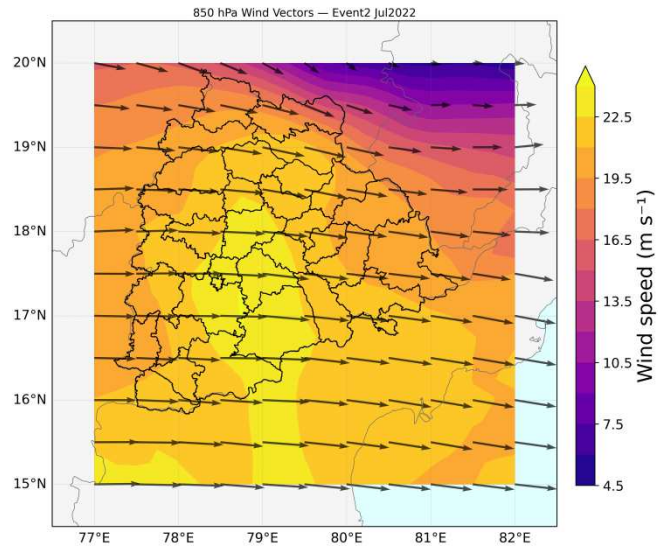


Figure 10. 850 hPa wind vectors (m s^{-1}) for Event 2 (13 July 2022).

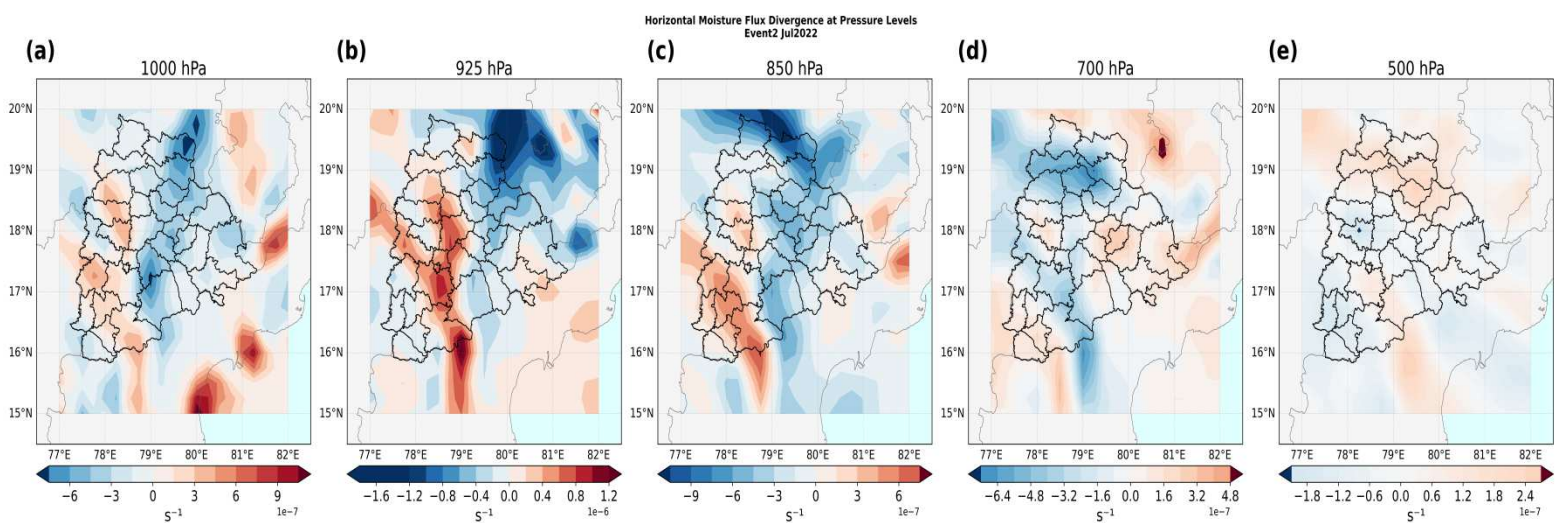


Figure 11. Horizontal divergence (10^{-5} s^{-1}) at (a) 1000 hPa, (b) 925 hPa, (c) 850 hPa, (d) 700 hPa, and (e) 500 hPa for Event 2 (13 July 2022).

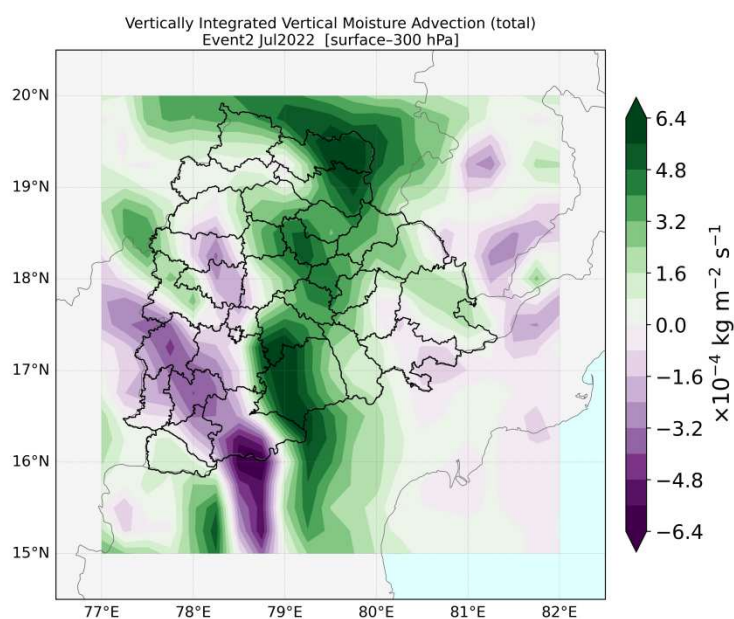


Figure 12. Vertically integrated vertical moisture advection ($\text{kg m}^{-2} \text{ s}^{-1}$; surface to 300 hPa) for Event 2 (13 July 2022).

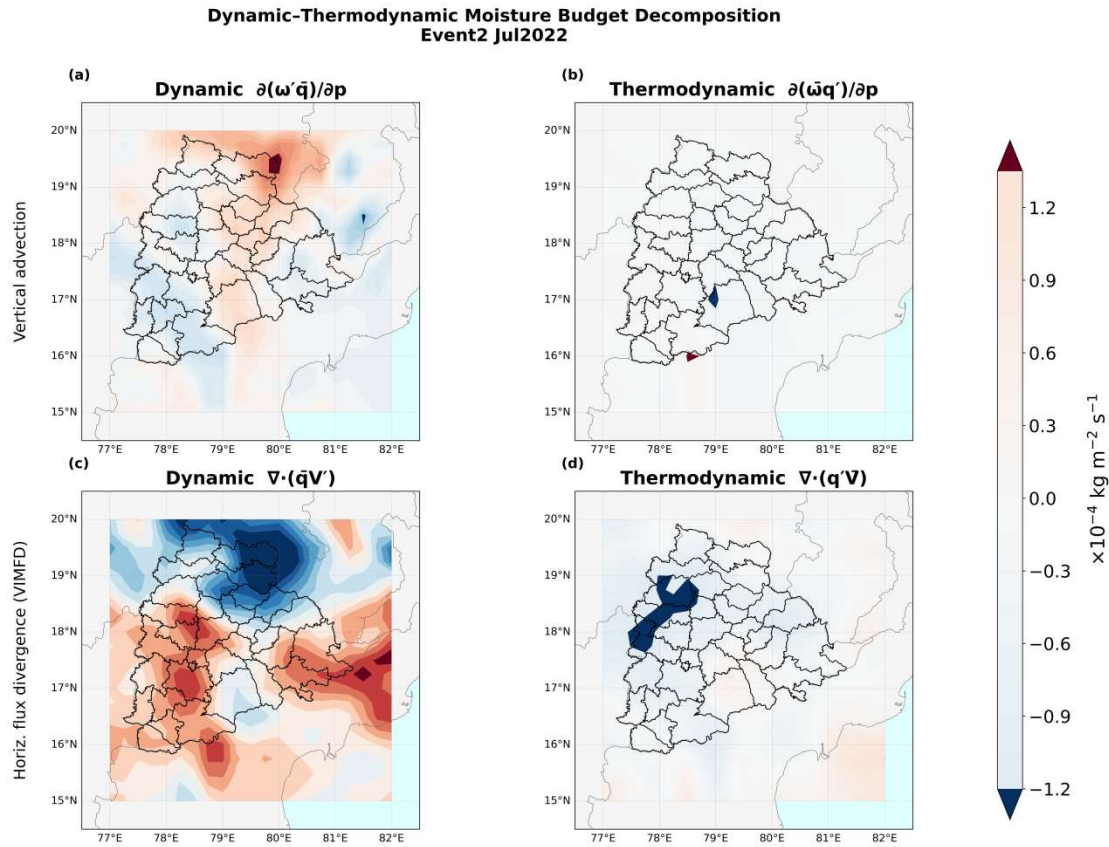


Figure 13. Dynamic and thermodynamic moisture budget decomposition ($\text{kg m}^{-2} \text{ s}^{-1}$) for Event 2 (13 July 2022). Colourbar values scaled by $\times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$. (a) Dynamic vertical advection $\partial(\omega'\bar{q})/\partial p$; (b) Thermodynamic vertical advection $\partial(\bar{\omega}q')/\partial p$; (c) Dynamic VIMFD $\nabla \cdot (\bar{q}\bar{V}')$; (d) Thermodynamic VIMFD $\nabla \cdot (q'\bar{V})$. Colourbar values scaled by $\times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$.

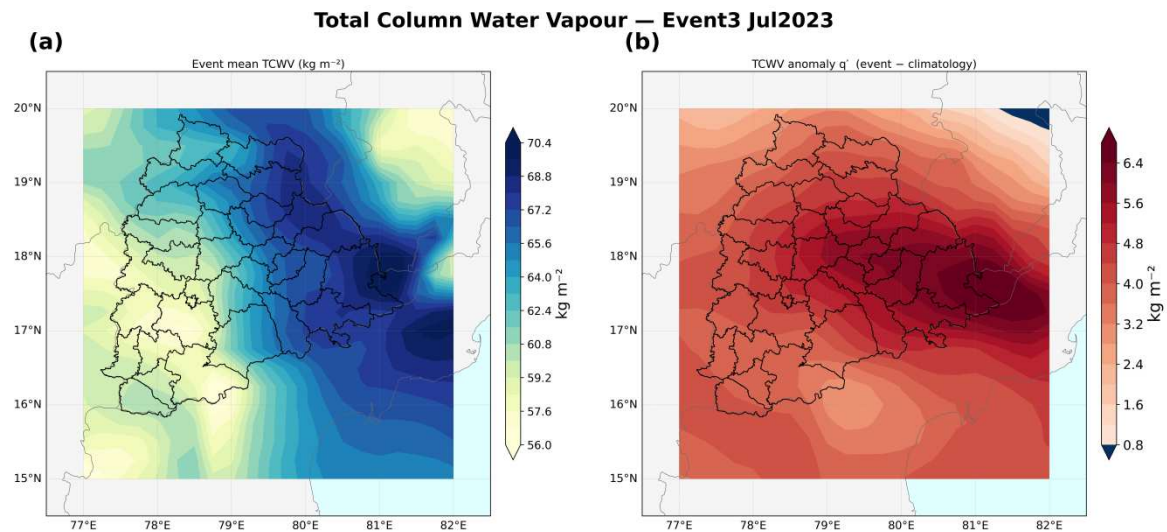


Figure 14. Spatial distribution of (left) mean Total Column Water Vapour (TCWV; kg m^{-2}) and (right) TCWV anomaly relative to climatology for Event 3 (26 July 2023).

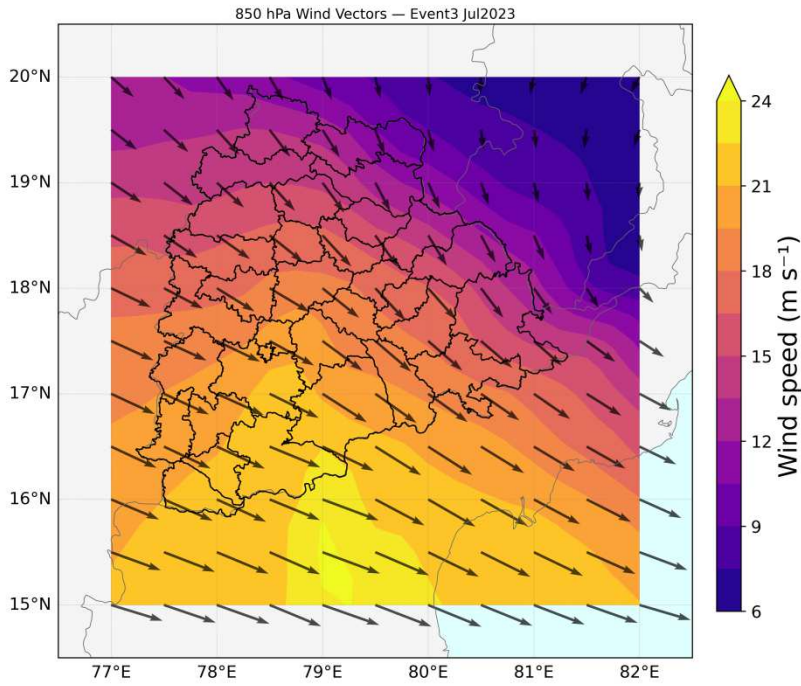


Figure 15. 850 hPa wind vectors (m s^{-1}) for Event 3 (26 July 2023).

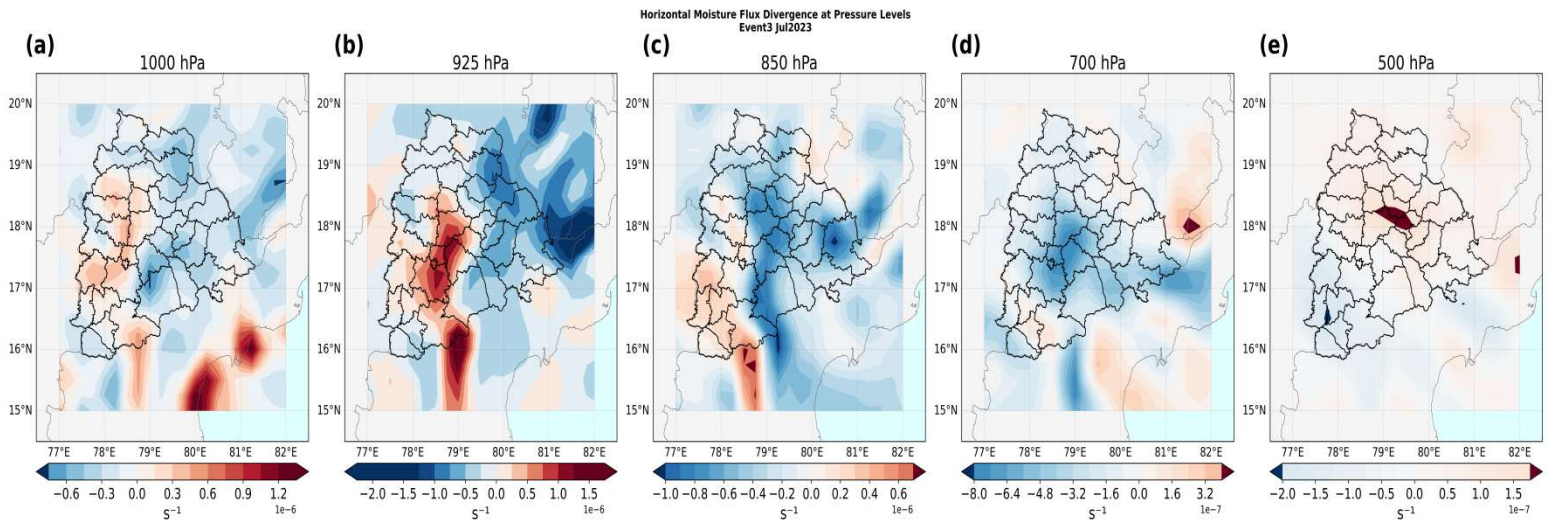


Figure 16. Horizontal divergence (10^{-5} s^{-1}) at (a) 1000 hPa, (b) 925 hPa, (c) 850 hPa, (d) 700 hPa, and (e) 500 hPa for Event 3 (26 July 2023).

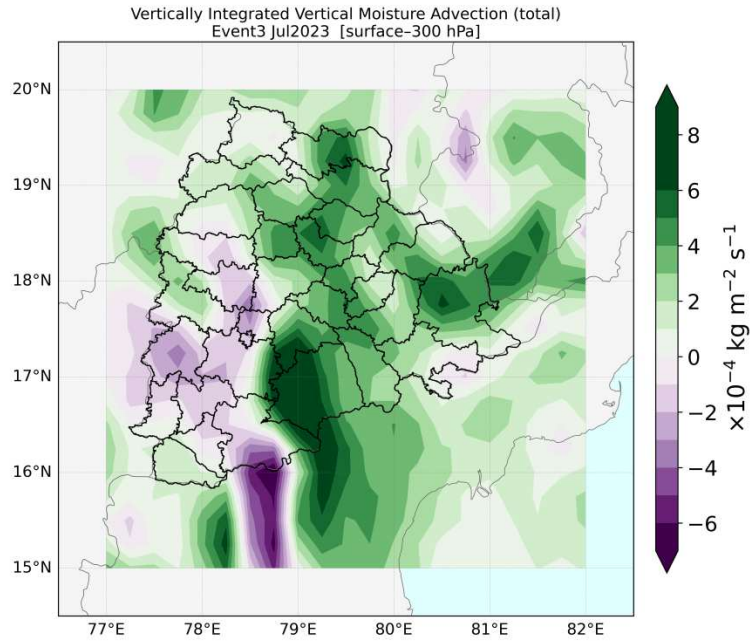


Figure 17. Vertically integrated vertical moisture advection ($\text{kg m}^{-2} \text{ s}^{-1}$; surface to 300 hPa) for Event 3 (26 July 2023).

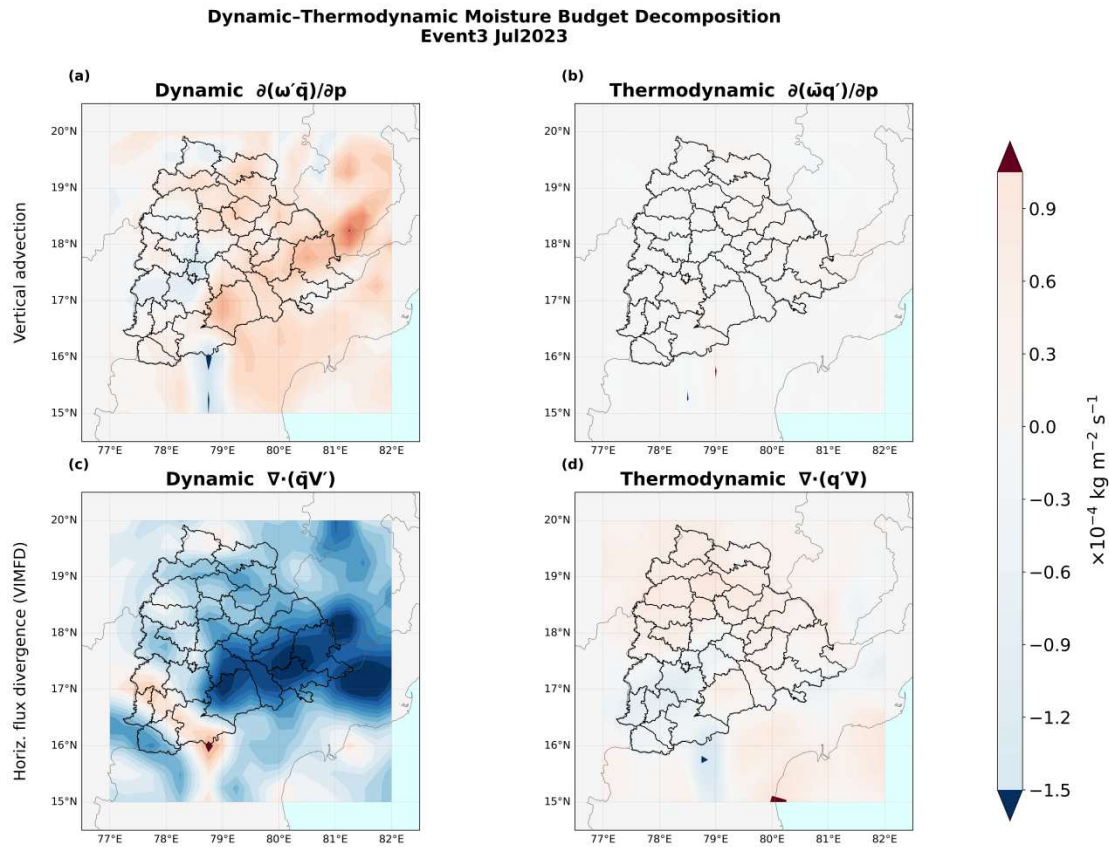


Figure 18. Dynamic and thermodynamic moisture budget decomposition($\text{kg m}^{-2} \text{ s}^{-1}$) for Event 3 (26 July 2023). Colourbar values scaled by $\times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$. (a) Dynamic vertical advection $\partial(\omega'\bar{q})/\partial p$; (b) Thermodynamic vertical advection $\partial(\bar{\omega}q')/\partial p$; (c) Dynamic VIMFD $\nabla \cdot (\bar{q}\mathbf{V}')$; (d) Thermodynamic VIMFD $\nabla \cdot (q'\mathbf{\bar{V}})$. Colourbar values scaled by $\times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$.

Event (Dates)	TCWV Anomalies	850 hPa Winds	Convergence / Divergence Pattern	Vertical Advection – Dynamic Component	Vertical Advection – Thermodynamic Component	Key Impacted Districts
21–22 Jul 2021	+3–5 kg m^{-2} (~6–8% above climatology)	W - NW >20 m s^{-1}	Strong low-level (1000–850 hPa) convergence; 700–500 hPa divergence	Positive anomalies over NW Telangana (Nizamabad–Adilabad); uplift dominated by vertical velocity forcing	Moderate contribution; strong moisture gradient amplified upward transport	Nizamabad, Adilabad
13–15 Jul 2022	+4–5 kg m^{-2} (~7–9% above climatology)	W-NW >25 m s^{-1}	Strong low-level convergence (1000–850 hPa) and persistent 700 hPa convergence	Moderate; vertical velocity supported sustained ascent	Thermodynamic gradient dominant, mid-level moisture concentration in NE Telangana enhanced uplift	Komurumbheem, Nirmal, Asifabad
25–27 Jul 2023	+3–5 kg m^{-2} (~6–8% above climatology)	NW 15–25 m s^{-1}	Low-level inflow (1000–925 hPa) + strong 850–700 hPa convergence; 500 hPa divergence	Strong dynamic forcing; broad-scale upward motion across central/east Telangana	Thermodynamic gradient also significant, especially over Mulugu–Warangal, enhancing deep convection	Mulugu, Warangal, Bhupalapally

Table 2. Comparative Moisture Budget Terms of Extreme Rainfall Events over Telangana

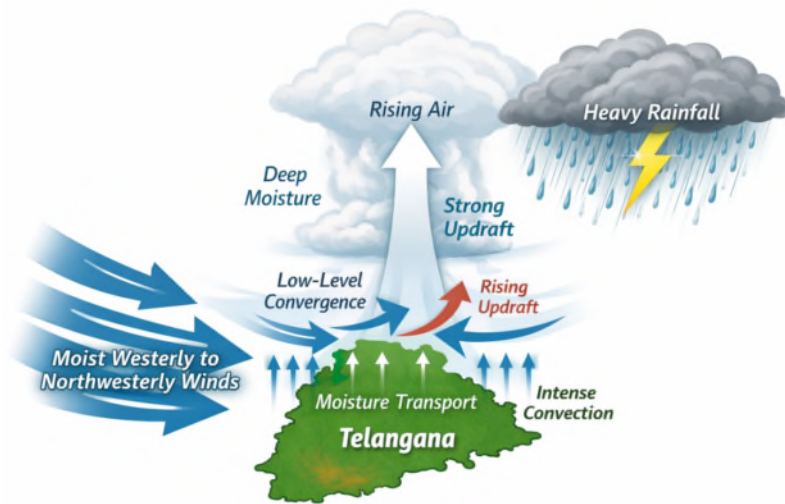


Figure 19. Schematic diagram illustrating the mechanism of extreme rainfall occurrence over Telangana.