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Decoding the dynamics: interaction of western disturbances and easterly troughs driving extreme weather over India

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सार – पश्चिमी विक्षोभ (WD) महत्वपूर्ण मध्य अक्षांशीय मौसम प्रणालियाँ हैं जो उत्तर भारत में शीतकालीन वर्षा को प्रभावित करती हैं। हालाँकि, पूर्वी गर्तो के साथ उनकी बातचीत, विशेष रूप से चरम मौसम की घटनाओं के दौरान, कम समझ में आती है। यह अध्ययन 26-29 दिसंबर 2024 के दौरान एक WD और एक पूर्वी गर्त के बीच एक दुर्लभ और उच्च-प्रभाव वाले समकालिक अंतःक्रिया की जाँच करता है, जिसके परिणामस्वरूप दिल्ली में रिकॉर्ड तोड़ वर्षा हुई और उत्तर-पश्चिम और मध्य भारत में व्यापक रूप से गंभीर मौसम रहा। समकालिक चार्ट, उपग्रह इमेजरी, बिजली के आंकड़े और नमी निदान (MIMIC-TPW2 और ERA5-व्युत्पन्न VIMDF) सहित बहु-स्रोत डेटासेट का उपयोग करके, हम इस घटना को रेखांकित करने वाली गतिशील और ऊष्मागतिक प्रक्रियाओं को डिकोड करते हैं। हमारा विश्लेषण WD की अनुक्रमिक तीव्रता और पूर्व की ओर प्रगति और इसके प्रेरित चक्रवाती परिसंचरणों पर प्रकाश डालता है, बिजली की गतिविधि और नमी परिवहन पैटर्न ने वर्षा को बढ़ावा देने में अरब सागर और बंगाल की खाड़ी, दोनों के स्रोतों की भूमिका की पुष्टि की है। यह अध्ययन चरम मौसम को प्रभावित करने में समकालिक-स्तरीय अंतःक्रियाओं के महत्व को रेखांकित करता है और पूर्वानुमान की सटीकता बढ़ाने के लिए ऐसी युग्मित प्रणालियों की बेहतर निगरानी की वकालत करता है। इन निष्कर्षों का भारतीय उपमहाद्वीप में आपदा तैयारी और मौसम पूर्वानुमान पर प्रभाव पड़ता है।

ABSTRACT. Western Disturbances (WDs) are critical mid-latitude weather systems that influence winter precipitation across northern India. Their interaction with easterly troughs, however, remains less understood, particularly during extreme weather events. This study examines a rare and high-impact synoptic interaction between a WD and an easterly trough during 26-29 December 2024, which resulted in record-breaking rainfall over Delhi and widespread severe weather across northwest and central India. Using multi-source datasets including synoptic charts, satellite imagery, lightning data, and moisture diagnostics (MIMIC-TPW2 and ERA5-derived VIMDF), we decode the dynamic and thermodynamic processes underpinning this event. Our analysis highlights the sequential intensification and eastward progression of the WD and its induced cyclonic circulations, supported by active subtropical jet stream dynamics and strong upper-level divergence. The coupling with an easterly trough led to enhanced low-level convergence and deep convection. Lightning activity and moisture transport patterns confirmed the role of both Arabian Sea and Bay of Bengal sources in fueling the precipitation. The study underscores the significance of synoptic-scale interactions in driving extreme weather and advocates for improved monitoring of such coupled systems to enhance forecasting accuracy. These findings have implications for disaster preparedness and weather prediction over the Indian subcontinent.

Key words – Western disturbance, Easterly trough, VIMDF, Extreme weather.

1. Introduction

The Indian subcontinent's winter and pre-monsoon weather patterns are significantly shaped by mid-latitude disturbances, especially Western Disturbances (WDs), which frequently influence the region's precipitation and temperature variability (Malurkar, 1947; Mull & Desai, 1947). Originating in the Mediterranean region, WDs are extratropical systems that travel eastward under the influence of the subtropical westerly jet stream

(Chaudhury, 1950; Mohri, 1953; Riehl *et al*., 1954). As they traverse the mountainous terrain of Central and South Asia, these systems play a crucial role in delivering precipitation across the western Himalayan region and the Indo-Gangetic plains (Murray, 1953; Dimri *et al*., 2015). Their impact extends beyond immediate weather anomalies, influencing hydrology, agriculture, and disaster preparedness across northern India.

These systems typically exhibit an eastward propagation speed of around 440 km/day and often bring snow to higher Himalayan altitudes and rain to the northwestern plains (Chand & Singh, 2015). The influence of WDs can be further intensified when they interact with other synoptic-scale features, such as induced low-pressure systems or easterly waves (Ranganathan & Soundararajan, 1965). Cloud convection associated with WDs can extend far ahead of the trough axis, often accompanied by high cloud tops and extensive upper-level divergence, particularly when the subtropical jet stream is active (Chand & Singh, 2015; Dimri, 2015).

Easterly troughs, on the other hand, are frequently linked to westward-propagating equatorial waves such as Kelvin and Mixed Rossby-Gravity waves. These troughs modulate convective activity and moisture convergence, especially over eastern and central India, contributing to significant weather events when moisture-laden air is lifted over favorable terrain or under dynamic forcing.

The intersection of WDs and easterly troughs creates a synoptically active environment that is particularly conducive to severe weather. When these systems align, they often trigger strong vertical motions, leading to deep convection and widespread precipitation, which can include hailstorms, lightning, and localized flooding. Such interactions can be further intensified by favorable upper-level divergence and low-level convergence zones, particularly when aided by dual moisture influxes from both the Arabian Sea and the Bay of Bengal.

While climatological and statistical studies have extensively documented the seasonal behavior of WDs and their influence on regional precipitation (Dimri *et al*., 2015), the dynamic coupling between WDs and easterly troughs remains a relatively underexplored mechanism, especially in the context of high-impact, extreme weather events. Previous studies have suggested that this coupling can lead to the development of extended troughs and intensification of associated weather systems (Ranganathan & Soundararajan, 1965), but case-specific analyses of these interactions are still limited.

This study focuses on a rare and impactful instance of WD-easterly trough interaction that resulted in record-breaking rainfall over Delhi and widespread severe weather across northwestern and central India from 26 to 29 December 2024. The event was marked by intense convection, driven by strong synoptic-scale uplift, significant upper-level divergence, and deep moisture convergence. Moisture transport from both the Arabian Sea and Bay of Bengal played a pivotal role, fueling persistent rainfall, hailstorms, and widespread lightning activity. By conducting a comprehensive synoptic and dynamical analysis, this work aims to (*i*) delineate the evolution of the WD and its interaction with the easterly trough, (*ii*) assess the moisture transport mechanisms underpinning the event, and (*iii*) examine the thermodynamic and dynamic processes that triggered the observed extreme weather.

2. Data and methodology

2.1. *Surface meteorological observations*

Surface meteorological data from IMD observatories and state government stations were utilized in this study to validate the occurrence of weather events from 26 to 29 December 2024. These ground-based observations provide critical evidence of rainfall, and wind patterns, effectively complementing upper-air and satellite-derived datasets.

2.2. *Upper-air data*

RSRW (Radiosonde/Radiowind) wind observations offer crucial insights into the vertical structure of the atmosphere during high-impact weather events. By analyzing wind profiles, this study captures the three-dimensional dynamics of interacting weather systems. Parameters such as vertical wind shear, divergence patterns, and jet stream characteristics derived from RSRW data help elucidate the role of upper-level dynamics in modulating the interaction between westerly and easterly troughs. These observations are also vital for identifying regions of enhanced moisture convergence and vertical velocity-key to understanding the initiation and intensification of convection.

2.3. *Satellite data*

Satellite-derived products, particularly Atmospheric Motion Vectors (AMVs) from Meteosat-9, provide essential information for analyzing wind fields and moisture transport dynamics associated with extreme weather events. AMVs offer high-resolution insights into horizontal wind patterns across various atmospheric levels, enabling detailed assessments of interactions between Western Disturbances (WDs) and easterly troughs. Additionally, satellite-derived wind products help identify regions of strong convergence and divergence-crucial for understanding convection mechanisms and precipitation enhancement. Integrating satellite data with in-situ observations allows for a comprehensive depiction of the synoptic and mesoscale processes driving high-impact weather over India.

2.4. *Lightning data*

Lightning data from the Indian Lightning Detection Network (ILDN) are incorporated to validate the spatial and temporal distribution of thunderstorm activity across the study region. Providing real-time, spatially resolved lightning strike information, ILDN data are crucial for assessing the intensity and coverage of convective systems. This dataset significantly enhances the robustness of the analysis by integrating an additional layer of observational evidence for storm diagnostics.

2.5. *ERA5 data*

This study utilizes the vertical integral of moisture flux derived from the ERA5 reanalysis dataset. This parameter represents the horizontal transport rate of moisture per meter across the flow in a column of air from the Earth's surface to the top of the atmosphere. The horizontal divergence of this flux indicates the net outflow (positive) or inflow (negative) of moisture at a point, corresponding to divergence or convergence, respectively. Thus, this metric is instrumental in diagnosing whether atmospheric motions contribute to moisture depletion or accumulation in a vertical column. A moisture flux of 1 kg/m^2 is equivalent to 1 mm of precipitable water, assuming standard water density. The units are therefore interpreted as millimeters of liquid water per second.

2.6. *Total precipitable water (TPW) data*

The MIMIC-TPW2 (Morphed Integrated Microwave Imagery at CIMSS – Total Precipitable Water, Version 2) product, developed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin–Madison, is used to assess atmospheric moisture content. This satellite-derived dataset provides a near-global representation of TPW, defined as the total column-integrated water vapor from the surface to the tropopause. TPW is derived from passive microwave observations collected by polar-orbiting satellites (*e.g.*, SSMIS, AMSU, ATMS, GMI) and temporally and spatially interpolated through a morphing technique. Version 2 of MIMIC-TPW features enhanced retrieval algorithms and improved continuity, enabling seamless animations of global water vapor transport. The morphed product fills observational gaps using motion vectors computed from successive satellite passes, allowing for detailed tracking of moisture plumes and convergence zones.

3. **Result and discussion**

3.1. *Realized weather in association with WD*

In association with the active Western Disturbance and its induced systems, widespread weather activity was observed over northwest and adjoining central and eastern India during 26th to 29th December 2024. On 26th, light rainfall occurred at many places over Haryana, and at isolated pockets of Himachal Pradesh, Punjab, Rajasthan, and West Madhya Pradesh. As the system intensified and moved eastward, rainfall significantly increased on 27th December, with most places receiving rain over Jammu & Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Haryana-Chandigarh-Delhi, West Uttar Pradesh, and West Madhya Pradesh. Widespread precipitation also extended to Punjab and East Rajasthan, while scattered rain occurred in East Uttar Pradesh and East Madhya Pradesh, and isolated rain in West Rajasthan. Notably, heavy rainfall was reported at isolated places over Haryana, and heavy rain/snow occurred over Jammu & Kashmir. Additionally, ground frost conditions were recorded in isolated areas of Himachal Pradesh.

On 28th December, rainfall activity continued, with most places in Himachal Pradesh and Uttarakhand, and many areas in Jammu & Kashmir and Ladakh region receiving precipitation. A few locations in Haryana-Chandigarh-Delhi and Uttar Pradesh, and isolated places in Punjab, East Rajasthan, Bihar, Jharkhand, and Odisha also recorded rain. Heavy rainfall/snowfall was again observed at isolated places over Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, indicating the continued intensity of the system as it tracked eastward.

3.2. *Synoptic analysis (25th – 29th December 2024)*

The Western Disturbance approached the Indian region on 26th December, initially seen as a trough in the lower and middle tropospheric westerlies with its axis at 5.8 km above mean sea level, running roughly along 57° E to the north of 30° N. The system advanced eastward through the day, reaching 60° E by mid-day and 62° E to the north of 22° N by night. By the morning of 27th December (Fig. 1), it evolved into a cyclonic circulation between 3.1 and 5.8 km, with an upper-level trough aloft (axis at 7.6 km) running along 67° E to the north of 22° N. This upper trough further shifted eastward along 68° E to the north of 17° N by evening and remained nearly stationary through the night.

On 28th December (Fig. 1), the system persisted as a cyclonic circulation over North Pakistan and adjoining Jammu & Kashmir, between 3.1 and 7.6 km, with the trough aloft further deepening, now reaching 9.1 km, and

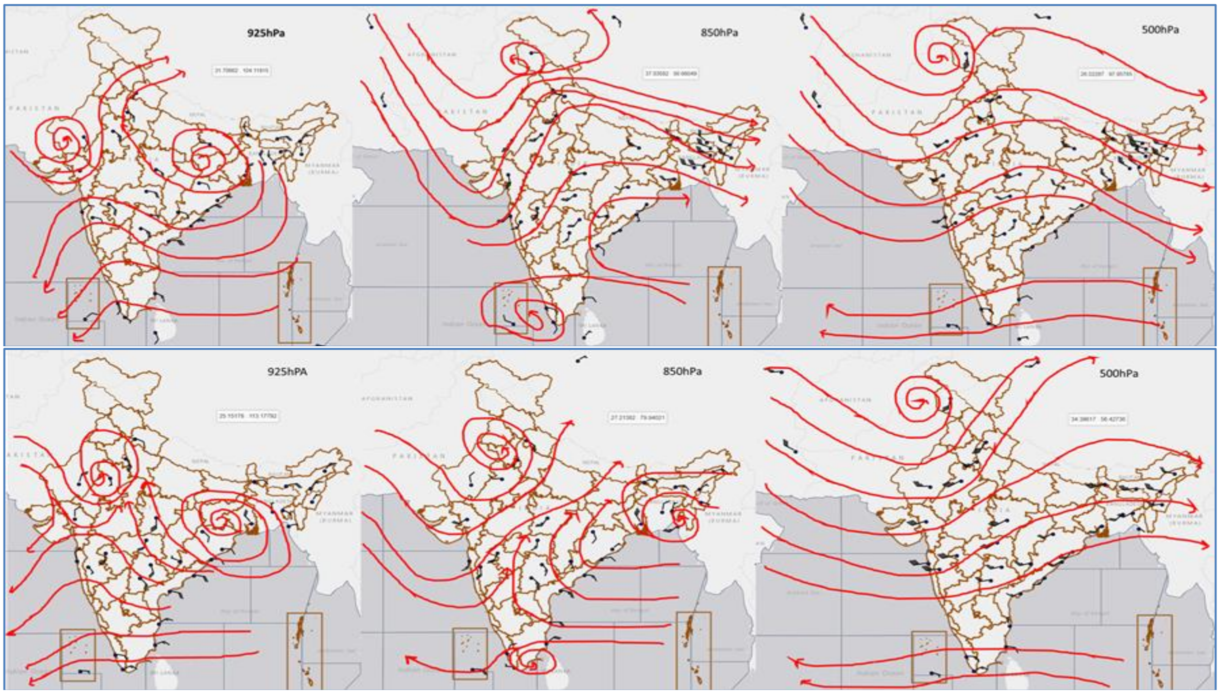


Fig. 1. The Upper Air analysis using RSRW ascent data for 00UTC of 27th December (top row) & 28th December 2024 (bottom row) [For remaining dates and hours not included for brevity]

extending along 72° E to the north of 15-19° N. By night, it had shifted eastward, placing the cyclonic circulation over North Punjab and the trough along 74° E to the north of 20° N at 7.6 km. On 29th December, the system continued its eastward movement, with the circulation positioned over Northwest Uttar Pradesh at 3.1 km and the upper-level trough observed along 80° E to the north of 23° N, first at 7.6 km (morning) and later 5.8 km (mid-day). The trough gradually moved further eastward, contributing to weather activity over eastern and northeastern India in subsequent days.

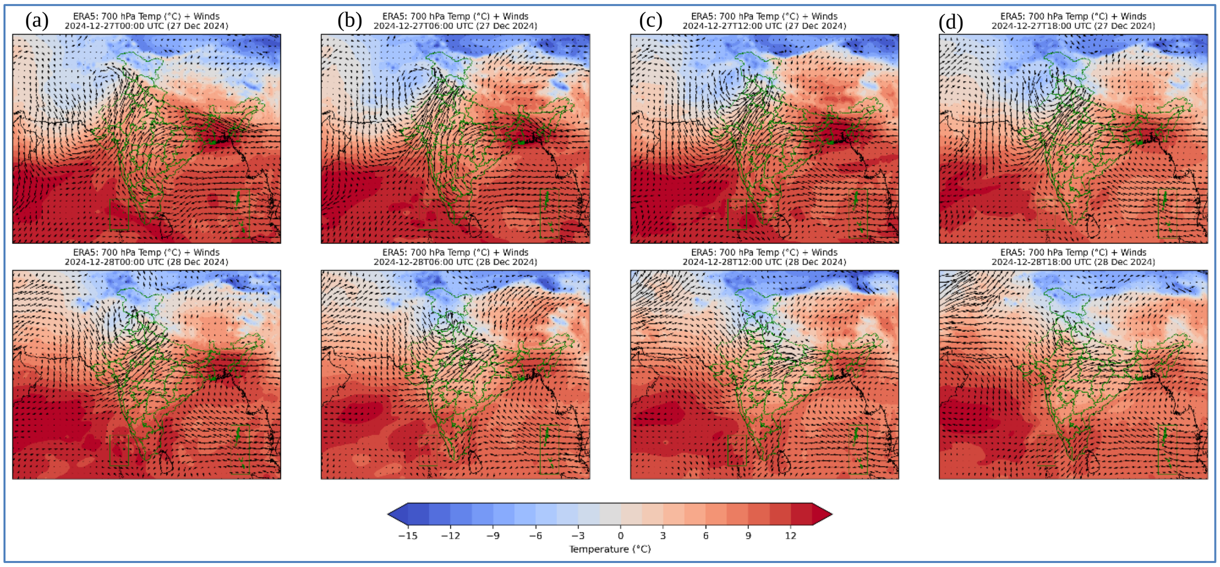
Associated with this Western Disturbance, an induced cyclonic circulation developed over southwest Rajasthan at 1.5 km on the night of 26th, persisted through 27th, and shifted to central Rajasthan by night. On 28th, it moved to north Rajasthan and adjoining Haryana in the morning and further to south Haryana for the rest of the day. By 29th December, it lay over northeast Rajasthan and neighbourhood at the same level.

Additionally, a low-level cyclonic circulation over north Punjab was present from 26th mid-day to 27th morning, before becoming absorbed into the broader western disturbance circulation.

A trough in easterlies was also active during this period. It initially extended from the east-central Arabian Sea to the induced circulation over southwest Rajasthan on 26th night, then from the Arabian Sea to north Punjab via Rajasthan on 27th, reaching central Rajasthan by night. On 28th morning, it ran from north Punjab to northeast Arabian Sea via north Rajasthan and Kutch, and later aligned from north Punjab to Gujarat across south Haryana and Rajasthan at 0.9 km. By 29th December, this trough shifted southeastward, stretching from northeast Rajasthan to north Gujarat at 1.5 km.

The Subtropical Westerly Jet Stream remained active throughout this period with core wind speeds of 110–120 knots at 12.6 km over northwest India from 26th to 28th December. On 29th December, the jet shifted slightly eastward over northeast India, weakening marginally to around 100 knots. Furthermore, velocity divergence was observed over Delhi in the jet stream, as seen in the 200 hPa winds (not shown for brevity). This feature also contributed to the favorable conditions for this record-breaking weather event.

ERA5 700 hPa fields from 27-28 December 2024 (Fig. 2) highlight the progressive intensification of the Western Disturbance (WD) as it traversed northwest India. On 27 December, the system was evident as a mid-tropospheric cyclonic circulation, accompanied by a well-defined upper-level trough. The large-scale flow featured strong mid-latitude westerlies interacting with relatively weaker easterly inflow from central India, creating a confluent zone centered over Rajasthan and adjoining



Figs. 2(a-d). ERA5 reanalysis of 700 hPa air temperature (°C, shaded) and horizontal winds (m s^{-1}, vectors) over the Indian region at (a) 00 UTC, (b) 06 UTC, (c) 12 UTC, and (d) 18 UTC on 27 December 2024 (top row) and 28 December 2024 (bottom row)

regions. This synoptic setup favored localized ascent and horizontal moisture transport, leading to the early stages of system organization. The spatial wind distribution also suggests enhanced shear along the western flank of the system, supporting further amplification of the trough.

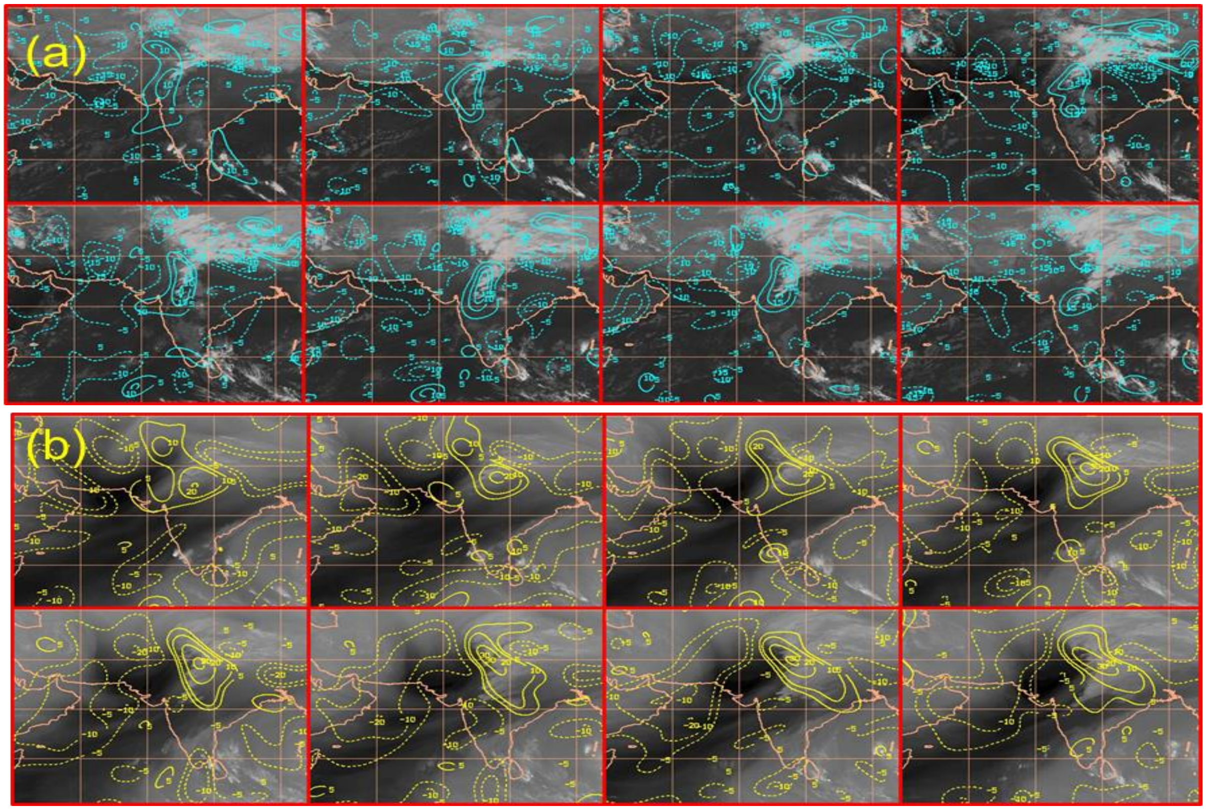
By 28 December, the WD deepened into a more vertically coherent and spatially extensive circulation, with its core shifting northward over north Pakistan and Jammu & Kashmir. The associated trough extended into the upper troposphere, allowing for stronger coupling between the mid- and upper-level dynamics. Enhanced confluence between westerly jets and easterly intrusions from the Indo-Gangetic Plains intensified vertical motion, while sustained moisture convergence along the foothills of the Himalayas provided favorable thermodynamic conditions for widespread precipitation. These dynamical and thermodynamical interactions underline the maturity of the WD, explaining the broad coverage of weather over northwest India during this period.

3.3. *Satellite analysis*

The analysis of 850 hPa relative vorticity fields from 00 UTC on 27 December to 21 UTC on 28 December (figure not shown because of brevity) highlights the evolution of low-level dynamical features associated with the synoptic system. Initially, a positive vorticity corridor extended from the east-central Arabian Sea to southwest Rajasthan. By 03 UTC on 27 December, this vorticity band became more organized and stretched northward into Punjab and adjoining North Pakistan. On 28 December, the vorticity patch over northwest India and the western Himalayan region remained intense and well-organized, indicating the sustained influence of the system in the region.

The 500 hPa relative vorticity fields (figure not shown because of brevity) illustrate the upper-level structure of the Western Disturbance (WD). Until 03 UTC on 27 December, the WD exhibited a northeast–southwest orientation, with significant vorticity over North Pakistan and a trough extending into the east-central Arabian Sea. The northern sector of the system advanced eastward more slowly than the southern sector. Between 06 and 15 UTC on 27 December, the trough reoriented into a north–south configuration, intensifying the relative vorticity in the northern sector and forming a more circular circulation. After 15 UTC, the southern sector progressed further eastward, reorienting the trough along a northwest–southeast axis. The northern circulation then weakened slightly and elongated along this axis until 03 UTC on 28 December, followed by a gradual decline in intensity after 06 UTC.

Upper-level divergence (ULD) in the forward sector of the westerly trough first appeared around 09 UTC on 26 December, stretching from North Pakistan to Gujarat. By 12 UTC, it intensified to 10 units, with distinct divergence cores over North Pakistan and Gujarat. This divergence further intensified and organized over northwest India by 00 UTC on 27 December (Fig. 3), reaching a peak of 30 units by 21 UTC over northwest India and the western Himalayan region. The divergence field then progressed eastward, becoming prominent over Uttar Pradesh, Bihar, and Jharkhand, and diminished by



Figs. 3(a&b). The LLC plots (a) & ULD (b) plots using Meteosat-9 data from 00 to 09UTC (top row) & 12 to 18UTC (bottom row) of 27th Dec

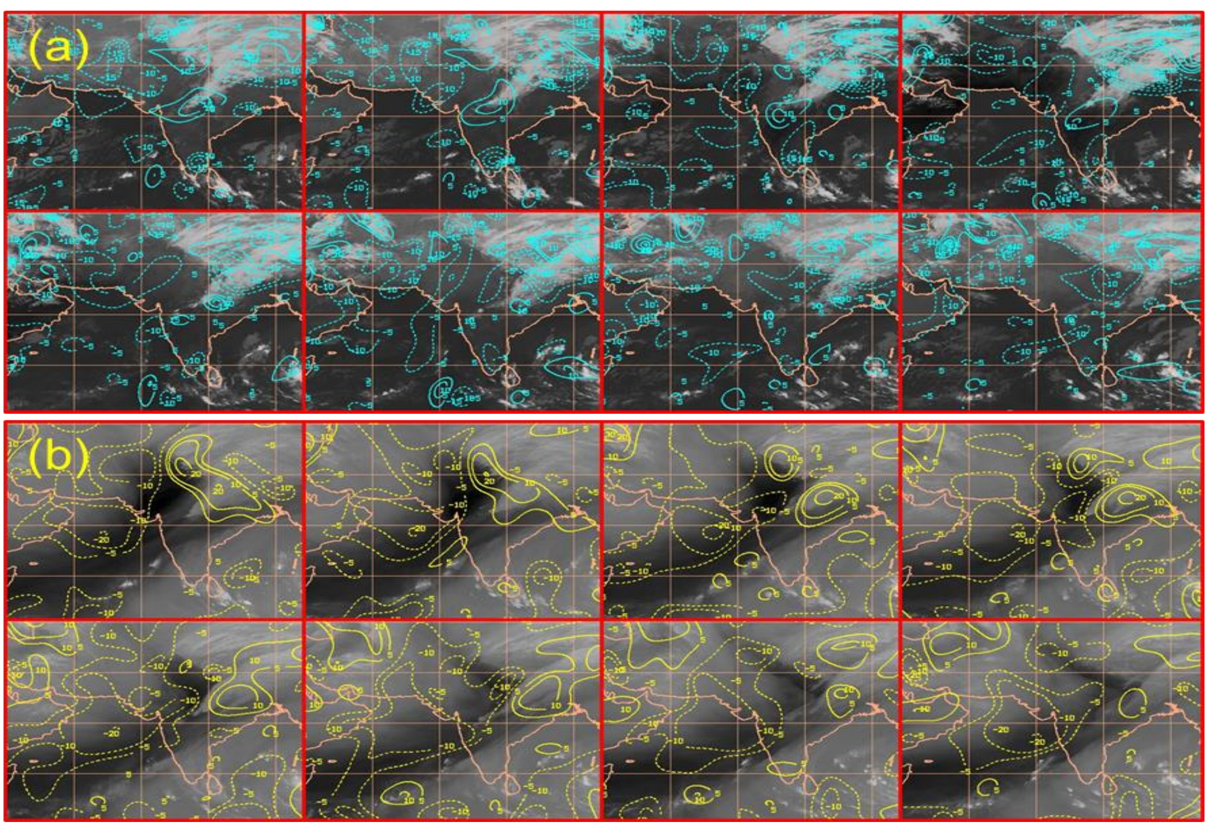


Fig. 4(a&b). The LLC plots (a) & ULD (b) plots using Meteosat-9 data from 00 to 09UTC (top row) & 12 to 18UTC (bottom row) of 28th Dec

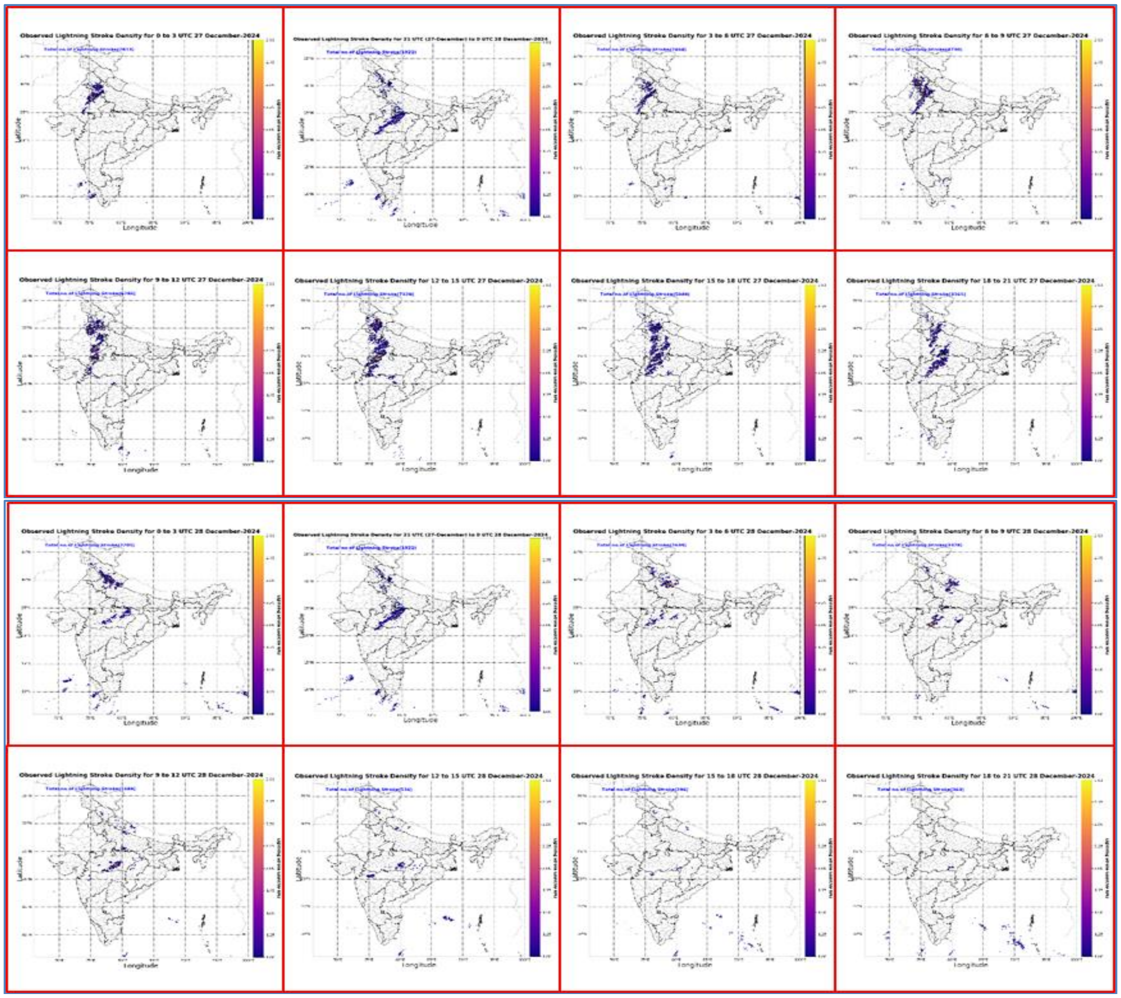


Fig. 5. The observed 3-hourly accumulated Lightning plots from ILDN network data from 00 to 09UTC (top row) & 12 to 18UTC (bottom row) of 27th December

21 UTC on 28 December. Concurrently, low-level convergence (LLC) began strengthening from 21 UTC on 26 December due to the interaction between the westerly and easterly troughs, forming an induced cyclonic circulation over southwest Rajasthan (Fig. 4). The LLC increased to 15 units, oriented north–south from Punjab to Gujarat, and remained strong until 18 UTC on 27 December before splitting into two zones: one over the western Himalayas and another over Madhya Pradesh and Maharashtra. The latter persisted and drifted slowly eastward until 12 UTC on 28 December, eventually dissipating over Chhattisgarh. The spatiotemporal alignment of enhanced ULD and LLC during the coupling of the easterlies and westerlies on 27–28 December was instrumental in triggering record-breaking rainfall over Delhi, widespread rainfall and hailstorms across Rajasthan, Madhya Pradesh, and Haryana, and heavy snowfall in the western Himalayan states of Jammu & Kashmir, Himachal Pradesh, and Uttarakhand.

3.4. *ILDN lightning data analysis*

The 3-hourly accumulated lightning strike density plots from the ILDN network for 27 (Fig. 5) and 28 (Fig. 6) December 2024 reveal the temporal and spatial distribution of convective activity associated with the synoptic system. On 27 December, lightning activity was widespread and intense, particularly between 00 and 18 UTC, with maximum density observed over Madhya Pradesh, eastern Rajasthan, southern Uttar Pradesh, and parts of Haryana and Delhi NCR. The concentration and persistence of strikes during this period coincide well with enhanced moisture convergence and elevated TPW values, confirming vigorous deep convection driven by strong synoptic forcing. In contrast, lightning activity on 28 December was notably reduced and more fragmented. Early UTC hours (00–09) still exhibited moderate activity over Uttar Pradesh and Bihar, while afternoon to evening hours (12 – 18 UTC) showed further weakening and

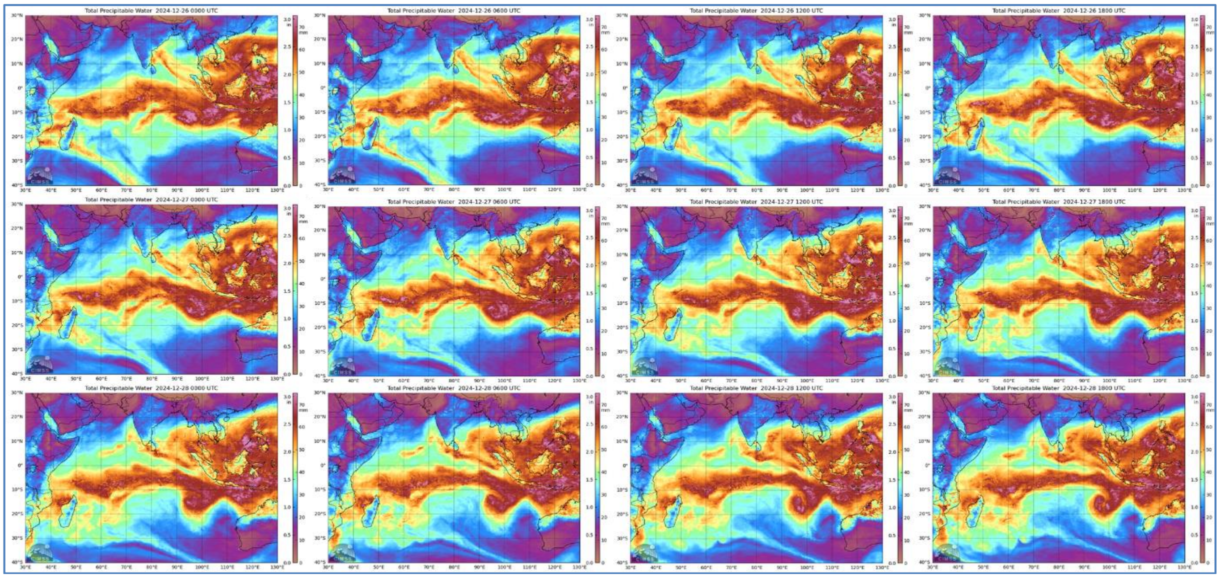


Fig. 7. The 6-hourly MIMIC-TPW2 plots from 00 to 18UTC of 26th April (1st row), 00 to 18UTC of 27th April (2nd row), & 00 to 18UTC of 28th April (3rd row)

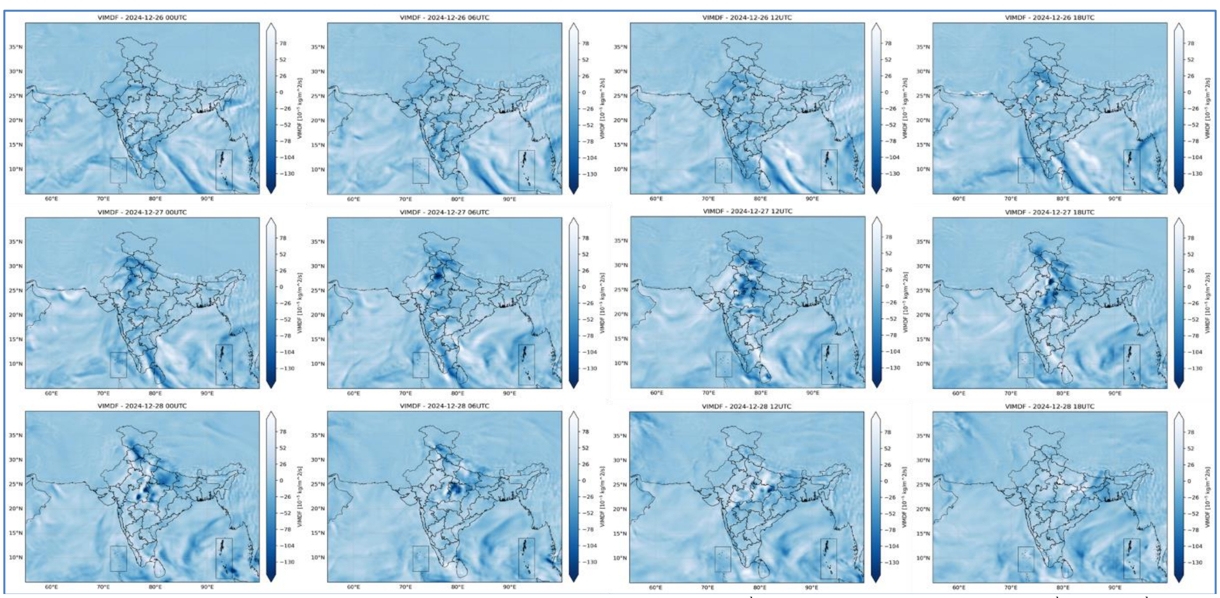


Fig. 8. The 6-hourly VIMDF plots using ERA5 reanalysis data from 00 to 18UTC of 26th April (1st row), 00 to 18UTC of 27th April (2nd row), & 00 to 18UTC of 28th April (3rd row)

eastward displacement of strikes into eastern India, including parts of Jharkhand and Odisha. The spatial shift and overall decline in lightning reflect the weakening and eastward progression of the system, consistent with the observed reduction in moisture flux convergence and rainfall over central and northwestern India by the 28th.

3.5. *Moisture transport analysis*

The evolution of moisture transport during 26–28 December 2024 was analyzed using MIMIC-TPW2 imagery (Fig. 7) and ERA5-derived vertically integrated moisture flux divergence (VIMDF) fields (Fig. 8). On 26 December, a distinct moist plume originating from the Arabian Sea extended across Gujarat, Madhya Pradesh, and southern Rajasthan, with a poleward bend toward Haryana and the western Himalayan foothills. This coincided with low to moderate VIMDF convergence, indicating the initial phase of moisture accumulation in these regions. Central India began to moisten gradually, laying the groundwork for subsequent convective activity.

On 27 December, both datasets indicated an intensification and eastward shift of the moisture plume. MIMIC-TPW2 showed elevated total precipitable water (TPW) values across central and northwestern India, including the Himalayan states. VIMDF fields revealed strong convergence over Punjab, Haryana, western Uttar Pradesh, and the western Himalayan region, suggesting enhanced large-scale uplift and moisture pooling. These patterns are consistent with the widespread and intense precipitation reported over these regions on this day, particularly due to the combined influence of a Western Disturbance and its induced cyclonic circulation over central India.

By 28 December, the moist axis had progressed further east, with TPW values increasing over eastern Uttar Pradesh, Bihar, and Jharkhand. This was accompanied by pronounced VIMDF convergence over east-central and eastern India, while values over the northwest and central India weakened. The observed shift in both moisture content and convergence zones reflected the eastward movement of the synoptic system, leading to reduced rainfall in northwestern India and enhanced activity over the eastern parts of the Indo-Gangetic Plain and adjoining areas. The spatial alignment between the moisture fields and reported precipitation confirms the utility of MIMIC-TPW2 and VIMDF as complementary tools for diagnosing moisture transport and rainfall evolution during such events.

4. Conclusions

This study presents a comprehensive analysis of the extreme weather event that unfolded over India from 26^{th} to 29^{th} December 2024, focusing on the intricate interaction between a Western Disturbance (WD) and an easterly trough. The synoptic evolution, moisture transport mechanisms, and associated dynamical and thermodynamical processes were examined using a multi-platform observational dataset, including surface observations, radiosonde profiles, satellite-derived wind products, lightning detection data, and reanalysis-based moisture flux diagnostics.

The analysis revealed that the WD progressed eastward across northern India, evolving from a mid-tropospheric trough into a deep and well-organized cyclonic circulation that extended into the upper troposphere. This evolution was accompanied by the development of an induced low-level circulation and the simultaneous activation of an easterly trough. Their coupling led to enhanced vertical motion and the establishment of a favorable environment for deep convection and widespread precipitation. The presence of strong subtropical westerly jet streams, coupled with significant upper-level divergence and low-level convergence, further intensified convective processes.

Moisture transport analysis highlighted the critical role of both the Arabian Sea and Bay of Bengal as key sources of moisture. The vertically integrated moisture flux divergence fields and TPW imagery confirmed strong convergence zones over northwest and central India on 27^{th} December, coinciding with the most intense rainfall, hailstorms, and thunderstorm activity observed during the event. The subsequent eastward shift in moisture and dynamic support led to a gradual transition of weather activity towards the eastern Indo-Gangetic Plain by 28^{th} December.

Additionally, lightning activity patterns derived from ILDN data provided independent evidence of vigorous convective activity driven by the WD-easterly trough interaction, with high strike densities over central and northern India on 27^{th} December aligning with peak synoptic forcing and moisture availability.

In summary, this study underscores the synergistic impact of WD and easterly trough interactions in producing high-impact weather over India. The findings emphasize the importance of real-time monitoring of upper-level dynamics, moisture transport pathways, and jet stream behavior to anticipate extreme weather events. A better understanding of these processes will contribute significantly to enhancing the forecasting capabilities and disaster preparedness frameworks in the region.

Data Availability

The Upper air RSRW data and daily rainfall data were provided by the India Meteorological Department's data supply portal, http://dsp.imdpune.gov.in/. The ERA5 reanalysis dataset was downloaded from https://cds.climate.copernicus.eu/datasets. The Upper Air Satellite data and MIMIC-TPW2 product were downloaded from https://tropic.ssec.wisc.edu/. The lightning data used in the study was taken from the Indian Lightning Detection Network, https://ildn.in/.

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Author contributions

Amit Kumar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, original draft, review and editing.
Naresh Kumar: Conceptualization, original draft, review and editing.
R.K. Jenamani: Original draft, review and editing.

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

References

Chand, R. and Singh, C., 2015, "Movements of western disturbance and associated cloud convection", *J. Ind. Geophys. Union*, **19**, 1, 62-70.

Chaudhury, A. M., 1950, "On the vertical distribution of wind and temperature over Indo-Pakistan along the meridian 76° E in winter", *Tellus*, **2**, 1, 56-62.

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T. and Sikka, D. R., 2015, "Western disturbances: a review", *Reviews of Geophysics*, **53**, 2, 225-246.

Malurkar, S. L., 1947, "Abnormally dry and wet Western Disturbances over North India", *Curr. Sci.*, **16**, 5, 139-141.

Mohri, K., 1953, "On the fields of wind and temperature over Japan and adjacent waters during winter of 1950–1951", *Tellus*, **5**, 3, 340-358.

Mohri, K., 1958, "Jet streams and upper fronts in the general circulation and their characteristics over the Far East", Part. I, *Geophys. Mag. (Tokyo)*, **29**, 45-126.

Mull, S., and B. N. Desai, 1947, The origin and structure of the winter depression of Northwest India *India Meteorological Department, Technical Note* No. 25:18.

Murray, R., 1953, "Jet stream over the British isles during June 14–18, 1951", *Meteorol. Mag*., **82**, 971.

Ranganathan, C. and Soundararajan, K., 1965, "A study of a typical case of interaction of an easterly wave with a westerly trough during the post monsoon period", *MAUSAM*, **16**, 4, 607-616.

Riehl, H., M. A. Alaka, C. L. Jordan, and R. J. Renard, 1954, "The Jet Stream, Meteorological Monographs", **2**, *Am. Meteorol. Soc*., Boston, Mass.