



Assessment of Spatio-Temporal Variability and Associated Atmospheric Drivers of Extreme Rainfall Events over Uttarakhand Using Long-Term Climatological Data

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ABSTRACT

Due to complex geography interconnections, varying monsoon behaviour, and shifting large scale atmospheric circulation systems monsoon season (JJAS). Extreme rainfall characteristics are assessed spatially and temporally to identify areas and periods of enhanced rainfall variability and extreme-event occurrence. Furthermore, composite atmospheric analyses are used during the 1985-2025 period, Uttarakhand, which is located in the Central Himalayan region, is more susceptible to heavy rainfall events. In recent decades, the region has experienced multiple high-impact events including landslides, flash floods, and cloudbursts, which have caused major environmental and socioeconomic devastation. This study examines long-term climatological datasets from 1985 to 2025 to investigate the underlying climatic and spatiotemporal variability of extreme rainfall events over Uttarakhand. Using percentile-based thresholds (90th, 95th, and 99th percentiles) and extreme rainfall indices, rainfall extremes are quantified using IMD Daily gridded rainfall data and ERA5 reanalysis datasets. In this study, associated synoptic and thermodynamics conditions are examined using ERA5 derived atmospheric parameters, such as U & V zonal wind, relative humidity, vertical velocity, and potential vorticity, are used to analyze related synoptic and thermodynamic conditions. The intensity and frequency of extreme rainfall events increased significantly, according to the results, especially across the southern and central regions of Uttarakhand after the early 2000s. The study provides a better way to policy making and disaster risk reduction strategies towards extreme events.

KEYWORDS:

- Extreme Events, Precipitation, Climate Change, Himalayan Synoptic level, Percentile based threshold.

Sources

- IMD Gridded datasets:**
<https://www.imdpune.gov.in/lrfindex.php>
- ERA5 hourly reanalysis datasets:**
<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=download>

INTRODUCTION

The present study investigates the spatio-temporal variability of extreme rainfall events over Uttarakhand using long-term climatological data for 1985–2025, with particular emphasis on the to investigate the associated meteorological environment, including MSLP, relative humidity, specific humidity, wind circulation, and Potential vorticity (300 hPa).

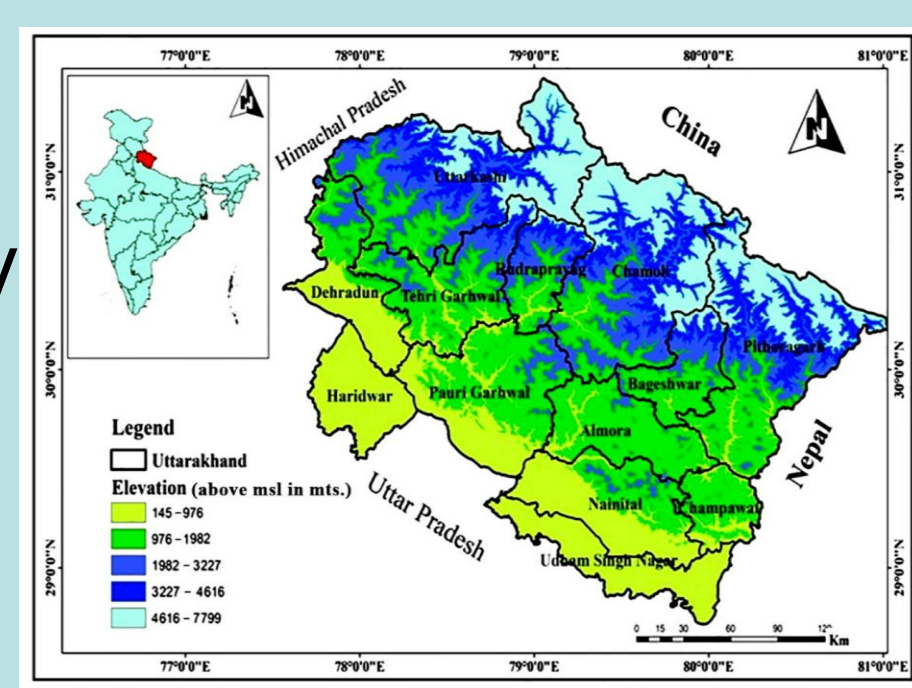
The specific objectives of this study are to:

- characterize the spatial and temporal variability of rainfall over Uttarakhand during 1985–2025;
- quantify changes in rainfall extremes using percentile-based thresholds and ETCCDI-type indices;
- identify the most spatially extensive and intense extreme rainfall events; and
- investigate their associated synoptic, moisture and vertical-motion characteristics using ERA5 reanalysis.

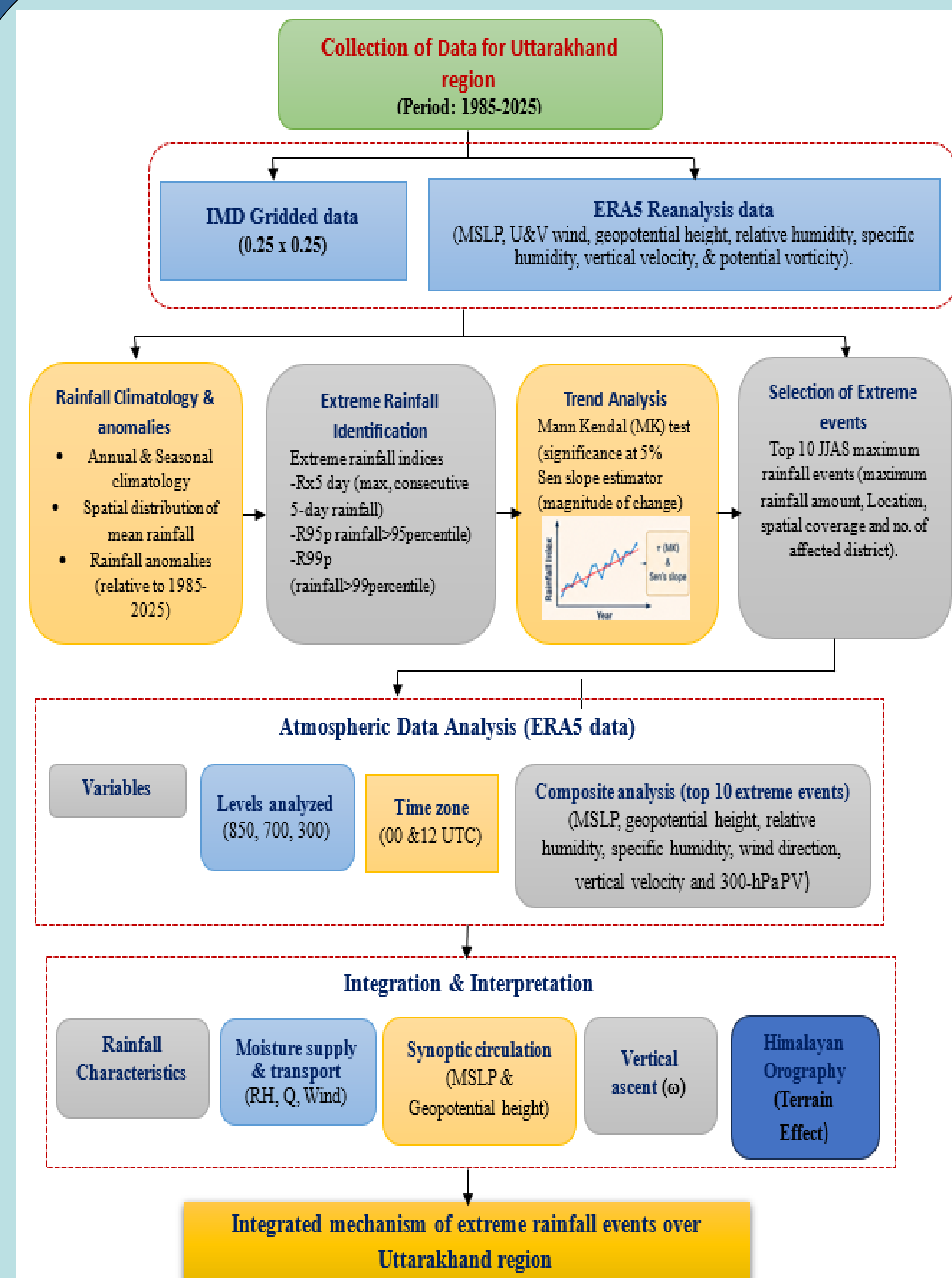
By integrating long-term rainfall characteristics with the associated atmospheric circulation and moisture conditions, this study aims to improve understanding of the physical mechanisms responsible for extreme rainfall over Uttarakhand and provide a scientific basis for improved monitoring, prediction and disaster-risk assessment in the Himalayan region.

Study Area

Uttarakhand, located in the central Himalaya of northern India, extends approximately between 28°43'–31°28' N lat and 77°34'–81°03' E lon and covers an area of about 53,483 km².

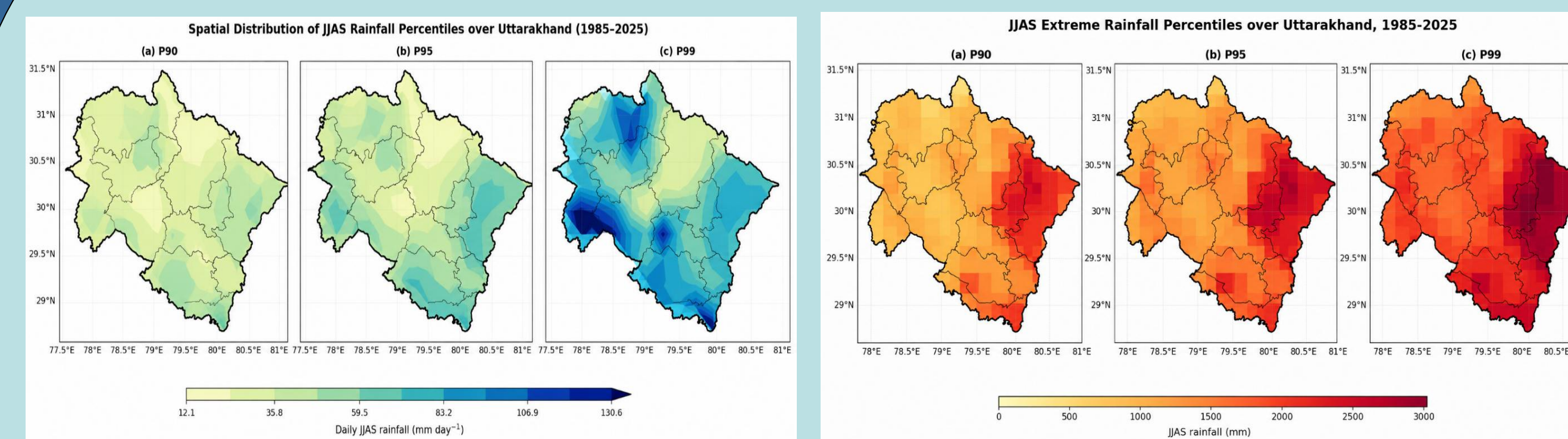


DATA AND METHODS

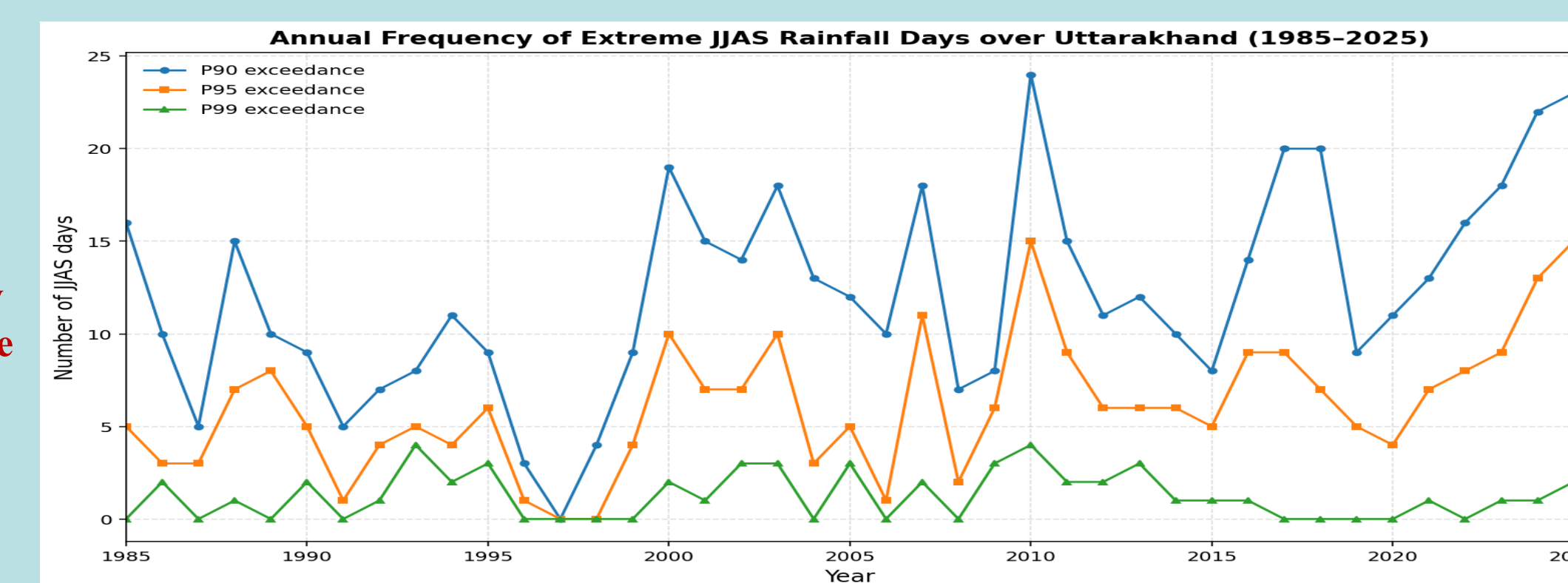


RESULTS

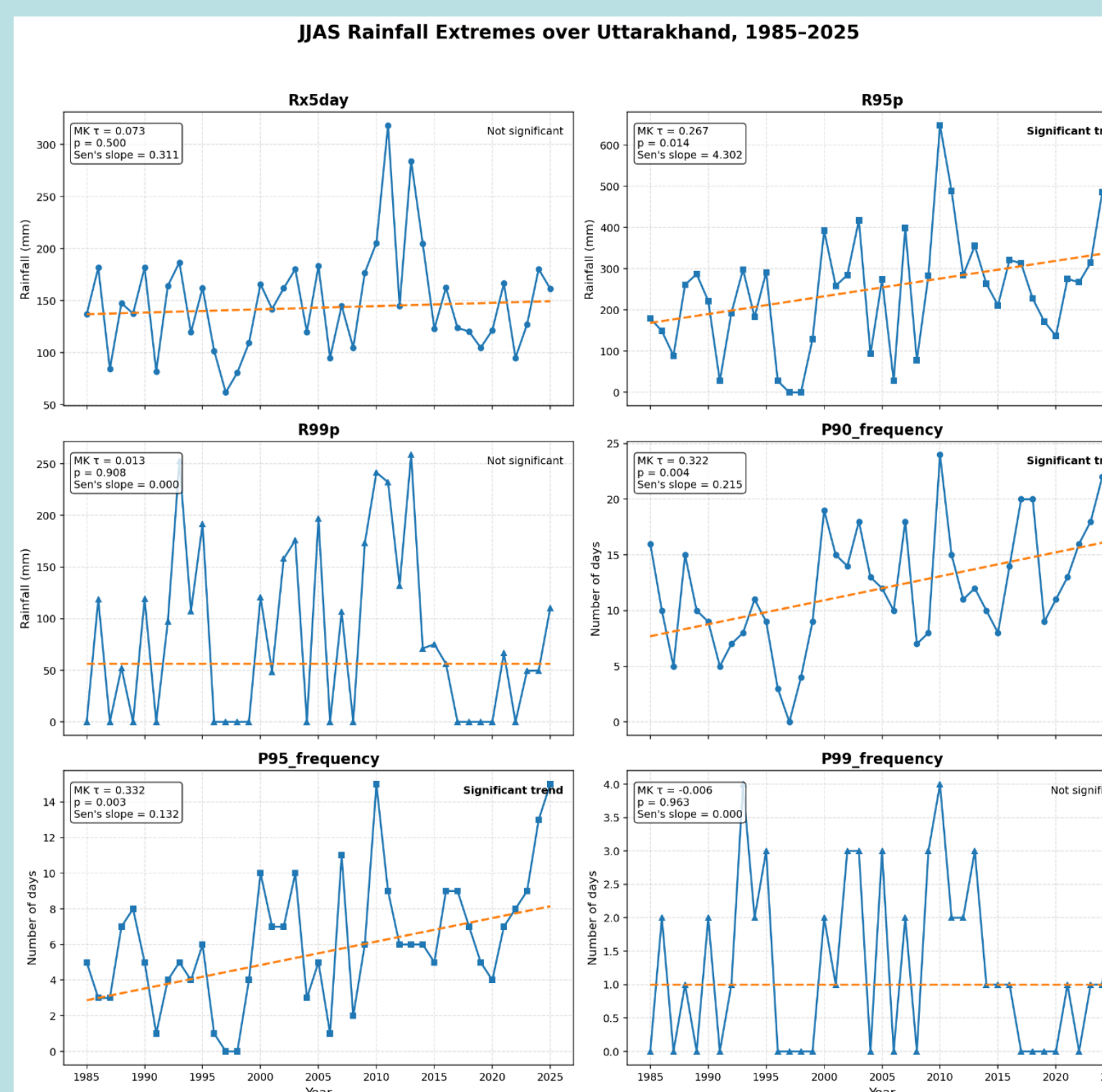
Spatial distribution and extreme rainfall characteristics of P90, P95 and P99 over Uttarakhand, 1985-2025 (JJAS)



Temporal variability and trends in extreme rainfall frequency (JJAS)



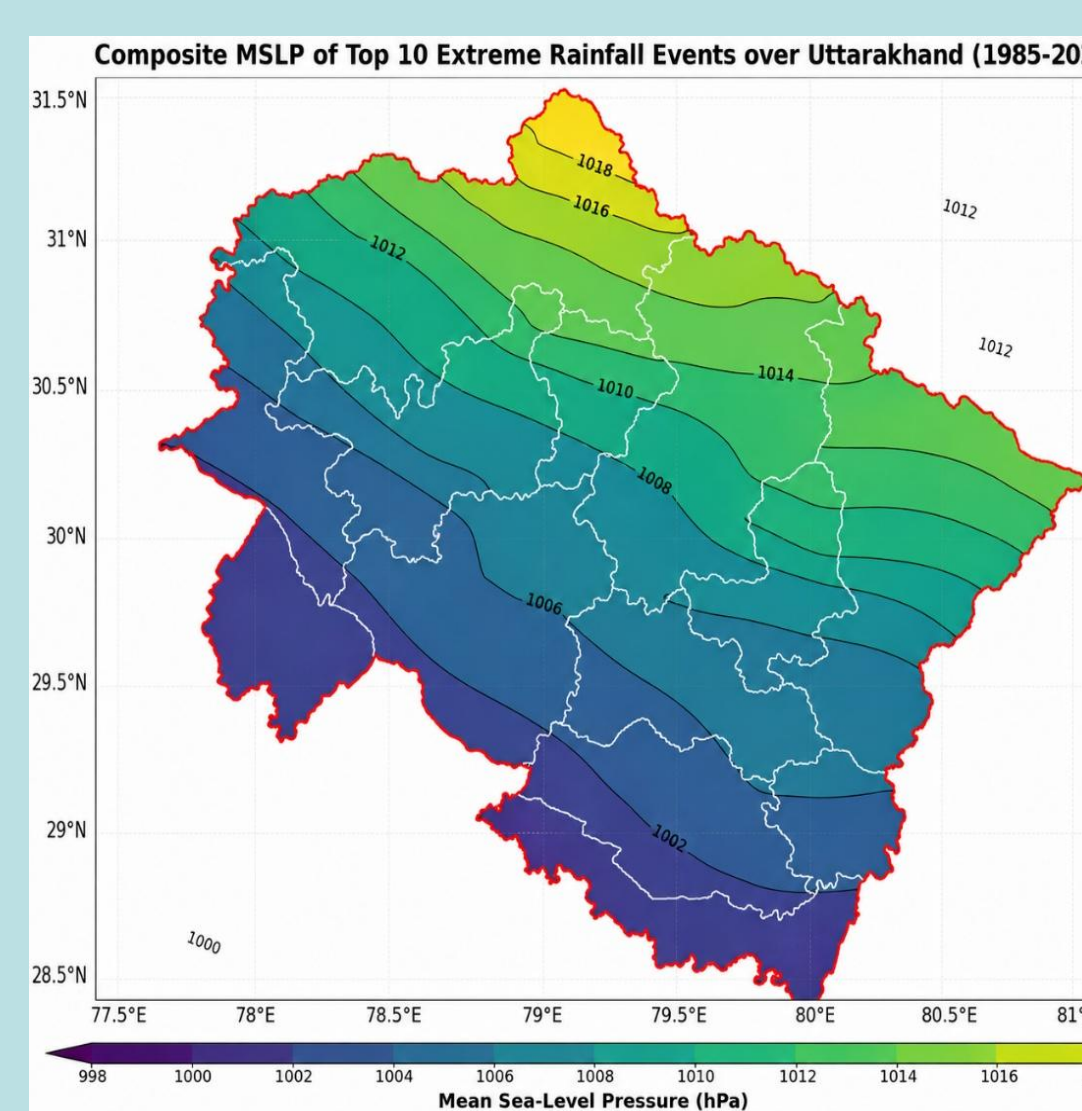
Trends in rainfall extreme indices



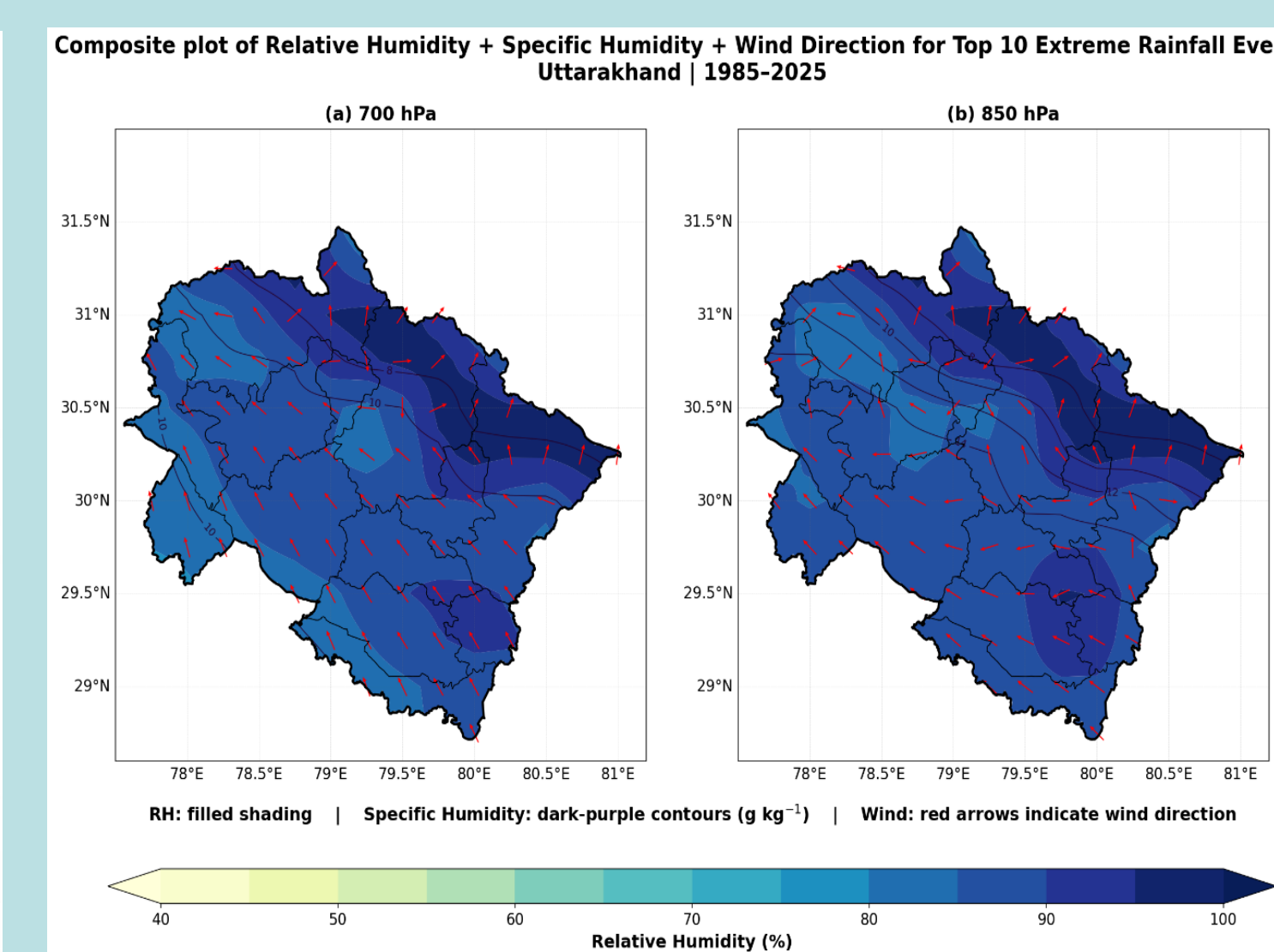
Top 10 extreme rainfall events occurred over the Uttarakhand during 1985-2025.

S.No.	Date	Maximum Rainfall (mm)	Location of maximum rainfall	P95 Coverage (%)	P99 Coverage (%)	Impacts of total No. of Districts
1	16 August 2011	234.3	Pithoragarh	98.8	96.39	13
2	17 June 2013	271.33	Dehradun	100	96.39	13
3	19 September 2010	217.79	Nainital	98.8	91.57	13
4	04 August 2012	131.97	Dehradun	100	90.36	13
5	18 June 2013	228.75	Nainital	93.98	81.93	13
6	26 June 2015	149.43	Udham Singh Nagar	93.98	75.9	13
7	06 September 1993	181.66	Haridwar	97.59	69.88	13
8	19 July 2014	154.28	Nainital	95.18	68.67	13
9	06 August 2025	201.01	Haridwar	90.36	66.27	13
10	05 July 2003	137.46	Pithoragarh	72.29	62.65	11

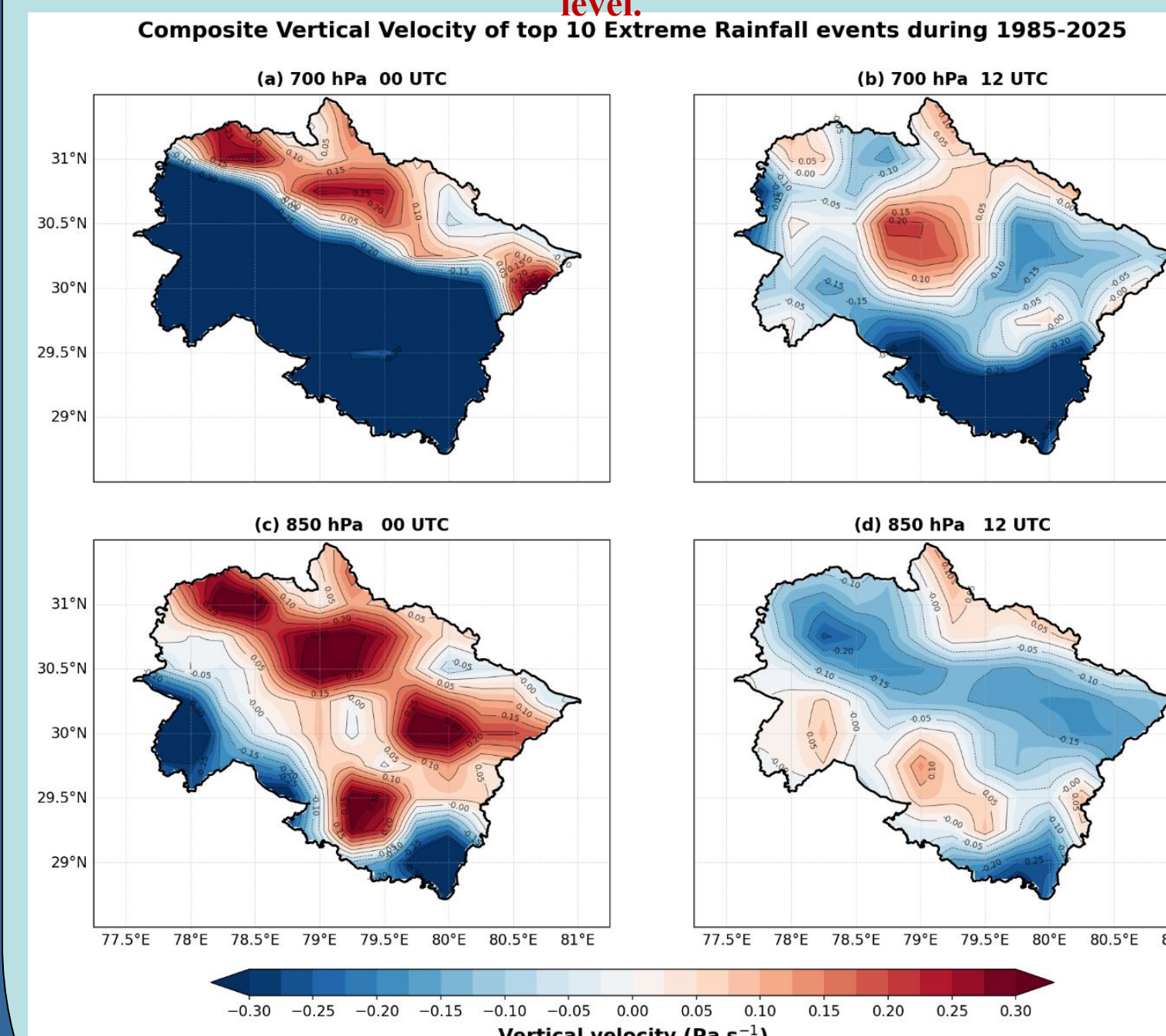
Composite MSLP of top 10 extreme events



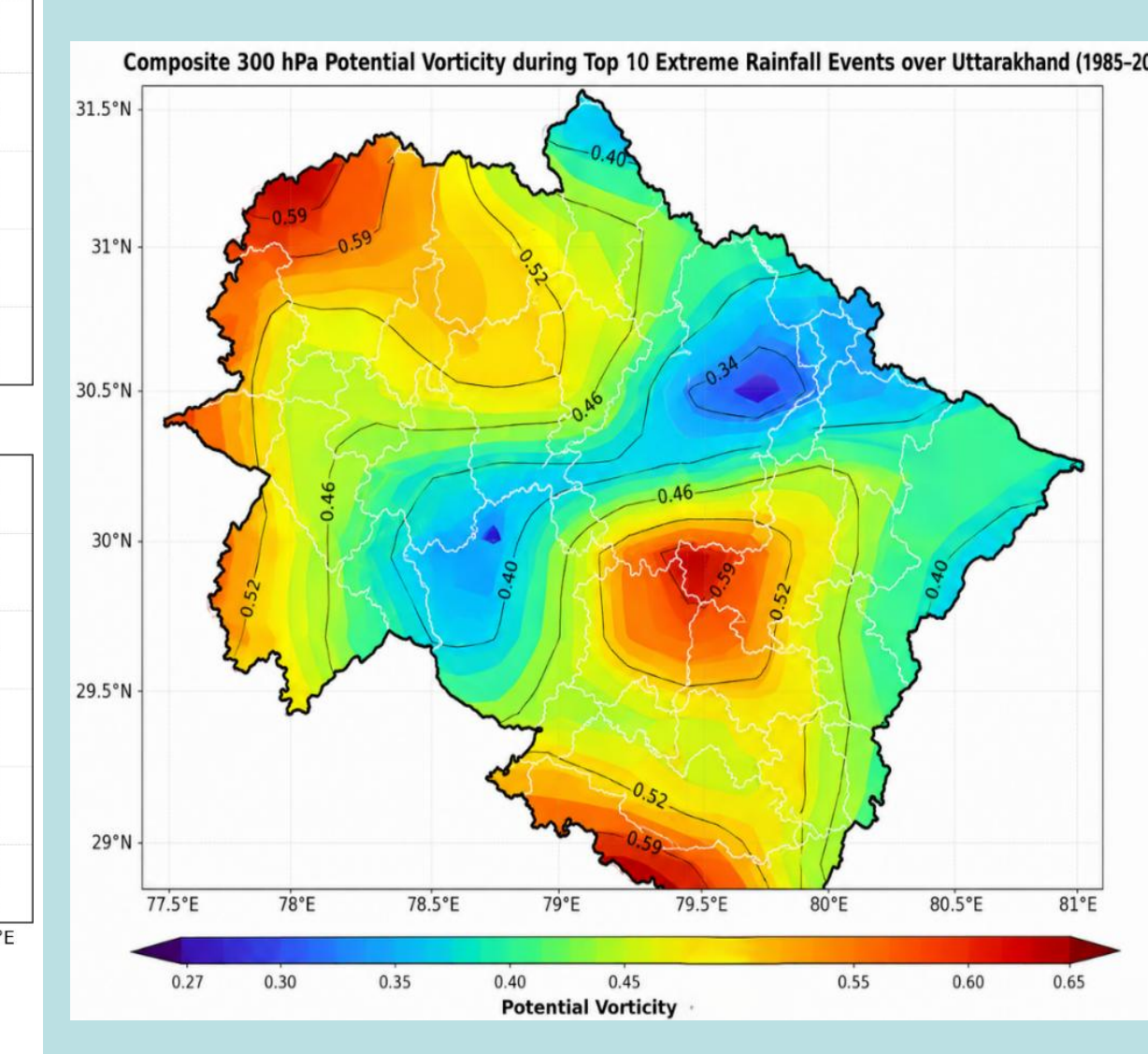
Composite plot of Relative Humidity + Specific Humidity + Wind Direction for top 10 extreme events at 700 and 850 hPa level.



Composite vertical velocity of top 10 extreme events at 700 and 850 hPa level.



Composite 300 hPa Potential velocity of top 10 extreme events (1985-2025)



DISCUSSION

The observed spatial variability, with advanced rainfall over eastern and southeastern Uttarakhand and peak rainfall during July–August, reflects the region's strong seasonal and topographic controls. The significant increases in P90 and P95 exceedance frequencies and R95p (Sen's slope ≈ 4.30 mm/year) indicate that heavy rainfall events are becoming more frequent and contribute in seasonal rainfall. In contrast, the absence of significant trends in R95p, R99p, P90, P95, P99 and Rx5day suggests that the change is more pronounced in the frequency of heavy rainfall than in the most extreme rainfall intensity. The 17 June 2013 event (271.33 mm) and other spatially extensive events proved that the potential for widespread impacts. Their association with enhanced moisture, favourable circulation, vertical ascent and upper-level dynamical support, together with orographic forcing, indicates that extreme rainfall results from the combined influence of large-scale atmospheric processes and local topography. These findings highlight the increasing heavy-rainfall risk and the need for improved monitoring and disaster-risk reduction in Uttarakhand.

CONCLUSION

The study revealed strong spatial and temporal variability of extreme rainfall over Uttarakhand during 1985–2025. Significant increases in P90, P95 exceedances and R95p indicate a growing contribution of heavy rainfall events, while the most extreme indices showed no significant trends. Extreme events were associated with enhanced moisture, favourable circulation, vertical ascent and orographic forcing. These findings highlight increasing heavy-rainfall risk and the need for improved monitoring, early warning and disaster-risk management.

ACKNOWLEDGEMENT

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