

An overview of precipitation extremes in India

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An extreme (weather or climate), i.e., high/ low values of the variable of interest, is linked with the tail of a distribution which refers to the upper/lower part of the cumulative distribution function (CDF) (Rajulapati et al. 2020). The right tail of the distribution or the upper part of CDF describes the behaviour of extreme (rare) events. The heaviness of the tail quantifies the likelihood of extremes to occur and represents extreme events' frequency and magnitude. Therefore, assessing a tail's heaviness helps understand the likelihood of extremes and thus guides hazard risk management strategies. During the last few decades, significant weather and climate extremes, especially precipitation and temperature extremes (Ghosh et al. 2012; Mishra et al. 2021) have been observed in India. The discrepancies/differences in the previous extreme studies' conclusions create a great scope to study further. Observed records show intensification of precipitation extremes (IPCC 2023) with projections for further intensifications over India in future (Mishra et al. 2021). Hence, more investigative studies on human activities on the rise in temperature and its influence on seasonal rainfall characteristics are needed to understand the dynamics of seasonal rainfall variability under future climate scenarios for better planning and management of water resources in India.

The studies related to precipitation extremes have received considerable scientific attention over the last decade. These studies use a range of metrics, datasets, study domains, and methodologies based on applications (such as water resource management), physical processes (such as synoptic-scale circulation) or geographical features (such as river basins) (Singh et al. 2019). India-focused studies on extreme rainfall typically apply observation-based tests and indices (e.g., Pettitt, Mann-Kendall, ETCCDI) to detect trends, empirical attribution methods linking changes to drivers such as sea surface temperature patterns, aerosols, and moisture flux, and model-based approaches that compare observations with climate model ensembles under all-forcing versus natural-only scenarios. Event attribution studies increasingly use hindcasts and regional ensembles to assess anthropogenic influence on probability and intensity, while Lagrangian moisture tracking helps trace sources like the Arabian Sea and Bay of Bengal, offering insights into mechanisms even where full attribution is limited.

There are only a couple of studies on addressing the changes in extreme precipitation events over India based on station data (Sen and Balling 2004, 2006). Research on precipitation extremes in India has expanded in the past decade, employing diverse datasets, metrics, and methods, though early station-based studies were limited by sparse coverage (Singh and Xiaosheng 2019), data quality issues, and uneven networks, characteristics of precipitation data with varied domain (Das et al. 2009), nature of distribution and variability of precipitation on local and regional scales (Venkatesh and Jose 2007) particularly in mountainous regions (Rana et al. 2015; Kidd et al. 2016). To overcome these gaps, many studies have relied on gridded datasets and varied approaches, including analysis based on threshold (Goswami et al. 2006; Rajeevan et al. 2008), analysis based on homogeneous regions (Das et al. 2011), analysis based on wet and dry spells (Singh et al. 2014; Chaudhary et al. 2017) and analysis with a percentile-based definition of the frequency and intensity of rainfall extremes (Ajayamohan et al. 2010), though results differ due to inconsistent definitions of extremes, aggregation methods, and assumptions of homogeneity, especially over Central India. While recent studies highlight strong spatial heterogeneity in precipitation extremes across India. The heavy rainfall events (>95th percentile) are increasing over northwestern, western central, and peninsular regions, they are declining in eastern and northern areas, based largely on IMD's high-resolution gridded data. However, finer-scale trends remain noisy due to local variability, making regional analysis for planning challenging. Evidence on anthropogenic influence is limited and mixed, with some studies linking extremes to urbanization and greenhouse-gas forcing, while others find no clear human fingerprint.

Literature also reports the intensification of precipitation extremes (defined, for example, as a high percentile of daily precipitation) by both model simulations and physical observations (Min et al. 2011). Consequently, floods, agricultural damages, health and hygiene issues, water contamination, and soil erosion problems have aggravated. Extreme precipitations are more likely to occur with increases in temperature, expanding the atmosphere's water holding capacity (Allan et al. 2014). In simulations with comprehensive climate models, the rate of increase in

precipitation extremes varies widely among models, particularly in the tropics (Min et al. 2011). The uncertainties associated with future climate change coupled with our inability to quantify these uncertainties from climate change models introduce additional complications in adapting to future precipitation extremes and related drivers that influence future flooding mechanisms (Toreti et al. 2013). Given the uncertainties in changes in precipitation extremes in simulations and the difficulties in constraining these changes with observations, it is essential to assess more broadly how precipitation extremes change with climate in simulations through climate modelling. Key challenges in India-focused extreme event studies include uneven rain-gauge coverage and quality issues that complicate long-term trend detection, while satellite and reanalysis data carry their own biases. At regional scales, models struggle with convective processes and complex Himalayan terrain, and although bias correction helps, structural errors remain. Attribution is further complicated by internal variability and multiple forcings such as aerosols, which require large ensembles to disentangle from greenhouse-gas effects. Finally, defining rare events like cloudbursts and dealing with small sample sizes limit statistical confidence in attribution results.

Overall, studies consistently highlight the pronounced spatial heterogeneity of precipitation extremes across India. While many regions such as northwestern, west-central, and peninsular India show increasing intensity and frequency of heavy rainfall events, eastern central and northern parts indicate a declining trend. However, the presence of noisy signals at finer spatial scales underscores the need for caution when deriving localized inferences from regional or basin-scale analyses. Besides, observations and projections also showed that hydrological extremes in India have become more frequent and intense, and this trend will continue due to the warming climate. Therefore, strengthening climate models and observational analyses is crucial to better predict impacts and support adaptation planning. Moreover, the attribution of these extremes to anthropogenic influences, though suggested in some studies, remains inconclusive due to conflicting evidence. Therefore, future research should focus on high-resolution analyses, improved attribution frameworks, and integrated regional assessments to strengthen the scientific basis for climate-resilient planning and water resource management.

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