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Extreme rainfall and hailstorm dynamics during monsoon: A micro-level case study of the south-east districts of Madhya Pradesh

Shivam Jhariya
Department of Geography, MP Bhoj University, Seoni, Madhya Pradesh, India

Abstract
This paper explores extreme rains and hails storm processes in the south west monsoon at micro (district/tehsil) level in the south eastern districts of Madhya Pradesh. We will summarize recent research on monsoon extremes and drivers of climate change, outline high-resolution data and statistical procedures on extreme value and event-based analyses, and provide a replicable methodology approach to the diagnosis of the atmospheric drivers (synoptic, mesoscale, convective) of extreme rain and hail events. We give a proposed analysis process, hypothetical/illustrative findings and policy-based proposals on early warning, crop insurance, and infrastructure resilience. Important results in the literature show an increasing degree and variability of monsoon extremes in central India, and imply that the large-scale climate modes as well as local topography/land-use change modulate the occurrence of hail and extreme rainfall.

Keywords: Monsoon, event-based analyses, atmospheric drivers, infrastructure resilience

Introduction

The major contributor to the hydrological cycle and agricultural productivity of India is the Indian Summer Monsoon (ISM) that continues between June and September. This is a four-month period that nearly 70-80 percent of the annual rainfall on central India is received, with a direct impact on rain-fed agriculture, ground water recharging, river discharging and reservoir filling. Nonetheless, the monsoon is not a life-giving mechanism only but also a leading source of hydro-meteorological extremes such as extreme rainfall events (EREs), flash floods, cloudbursts, lightning strikes, and hailstorms (Goswami *et al*., 2006) [1]. The variability and extremes of the monsoon are dual and detrimental, and therefore, it is important to understand the variability of this phenomenon to manage climate risks. The trends of heavy rainfall have been increased in spatial variability and intensity in areas of central and eastern India in the last few decades, as recorded by the India Meteorological Department (IMD). A number of observational and modeling studies suggest that short-duration high-intensity rainfall events have been increasing even in areas where seasonal means of rainfall show weak or negative trends. The most popular reasons of this heightening are thermodynamic warming, the rise of atmospheric moisture content (Clausius-Clapeyron relationship), alterations in the monsoon circulation patterns, and the heightened instability of convective processes. Hailstorms are not as widespread and global as the rainfall extremes but they constitute another major monsoon-season hazard in central India. Hail is normally created in deep cumulobenimbus clouds during intense updrafts which is normally known to be accompanied by high Convective Available Potential Energy (CAPE), vertical wind shear and mid-tropospheric temperature differences (Rajeevan *et al*., 2008) [2]. These conditions can be caused during the monsoon by the interactions between monsoon trough oscillations, low-pressure systems (LPS), mesoscale convective systems (MCS) and local orographic forcing. Although hail is usually considered to be characteristic of pre-monsoon thunderstorms (March-May), the growing reports in the active monsoon phases present evidence of hail dynamics in full-blown monsoon system. Central and eastern India-such as Madhya Pradesh- have seen regular incidences of extreme rainfall which causes city flooding, embankment failures and massive loss of crops. In the farm regions, heavy downfalls over short periods of time destroy crops under harvest, soil erodes, and sowing activities are disrupted (Roxy *et al*., 2017) [3]. All these are added to by hailstorms that literally wipe the crops including soybean, paddy, maize and pulses, that are the main crops of the kharif season in Madhya Pradesh. The socio-economic consequences of such hazards are cascading, comprising of indebtedness of farmers, rise in insurance settlement, rural distress movement, and strain on state disaster relief funds (Falga, 2022) [4].

Although these effects have been experienced, majority of climatological models of monsoon extremes are based on coarse-resolution gridded data (0.25deg-1deg) which could be hiding sub-district variations. Hailstorms and convective rainfall are mesoscale and microscales in nature and tend to be localized, covering a few kilometers and have durations of less than a few hours. Peak intensities could be rounded off with sparse station networks and interpolation techniques, and underestimate local hazard exposure. Hence, micro-level (district/tehsil/village) analysis is a must to: record spatiotemporal variation in extreme rainfall and hail; measure local risk patterns obscured on state or national levels; make a direct connection between atmospheric drivers and agricultural and infrastructural effects at the ground level; enhance the local conditions early warning systems (Samantray, 2024) [5].

Literature Review

The study of extreme rainfall events (EREs) in India has grown significantly within the last twenty years as a result of the increasing interest in the topic due to the increasing concern over climate variability and its effects on society. At the emergence of climatological studies, much of the focus was on the seasonal means of rainfall, long-term variability and when the monsoons would commence and leave. Although these measures continue to be relevant in explaining large-scale monsoon behavior, recent literature has been focusing on investigation of short duration and high intensity rainfall events. This transformation can be explained by the factor that the realization is that societal and economic harm, including flash floods, urban inundation, and destruction of crops, is more tightly linked to sub-daily or multi-day extreme bursts as compared to seasonal totals (Hunt *et al*., 2019) [6]. Therefore, to represent the changing character of rain extremes, researchers are moving towards the use of return period estimation, extreme value theory (GEV/GPD), percentile-based indices, and event-based diagnostics. Experiments involved with central India show that the frequency and intensity of localized convective rain falls have been increasing significantly in the last few decades. These extreme events tend to be incorporated in the larger monsoon circulation structures and are linked to multiple intersecting drivers. The relevant large-scale supply of moisture, as well as dynamic uplift required to support heavy rainfall, is often supplied by monsoon depressions and low-pressure systems moving inland through the Bay of Bengal. Rainfall is further altered by oscillations of the monsoon trough, which cause the convergence areas to move throughout the central part of India. Also, the topography and location of the area such as plateau edges and forested highlands interact with moist westerly monsoon flow to increase vertical motion and convective instability. Increased moisture convergence areas which are usually associated with synoptic disturbances serve to act as concentration areas in the development of intense precipitation (Nikumbh *et al*., 2021) [7].

The analyses of events like the heavy rainfall on Madhya Pradesh and adjacent Rajasthan in August of 2021 demonstrate how a long-lasting rainfall is caused by a combination of synoptic-scale circulation aspects and mesoscale convective structure. When this happens, mass transport of moisture generates a favorable thermodynamic condition and mesoscale systems of convection maintain a localized high rate of rainfall. These results highlight the importance of combining dynamic (circulation-driven) and thermodynamic (moisture and instability-driven) approaches to the process of extreme rainfall. The India Meteorological department regularly records the heavy rainfall and hail events in which daily bulletins, seasonal summaries and special weather advisories are used to record the events (Kulkarni *et al*., 2015) [10]. Rainfall records are in a systematic and growingly accessible gridded format, which is helpful in the climatological analysis of the long term (Sharma *et al*., 2020) [8]. Observing hailstorms, on the contrary, is still not very common and usually qualitative, based on the reports of the stations, the records of agricultural damages, or the media records. The spatial discrepancy and under-reporting of hail events bring ambiguity in determining hail climatology over a long period, especially the district and village levels. There is a growing literature about the effect of climate change on the extremes of rainfall. Increasing temperature increases moisture-capacity in the atmosphere which in theory amplifies the short-term precipitation by thermodynamic amplification (Kant, 2025) [9].

Study Area and Rationale

The current paper dwells on south-eastern districts of Madhya Pradesh (hereafter referred to as SE-MP). The area has been chosen on the basis of its unique physiographic and climatic features of the area, which have predisposed it to extreme events associated with monsoons. SE-MP occupies a transitional zone area between the central Indian plateau and forested highlands tracts which are characterized by undulating terrain, gradient of the elevation, and heterogeneous cover of the land. This topographic variety is also significant in regulating the local atmospheric circulation and increasing convective uplift as well as in the spatial distribution of the rainfall and hailstorms. The predominant farming activity in the area is rain-fed agriculture, which is very reliant on the success of the Indian summer monsoon. Soybean, paddy, maize, and pulses are major kharif crops that are grown on large scale and therefore the rural livelihoods are directly related to rainfall timing, intensity and distribution. Extremes of rainfall may lead to flash flooding, soil erosion, and waterlogging whereas hailstorms may produce instant mechanical devastation to planted crops. Over the last several years, local media news and official bulletins reported on a few cases of heavy rainfall and hail in some regions of SE-MP, which highlights the increased necessity to conduct risk assessment on a local level. This region is especially suited to a micro-level study which includes several nearby districts and tehsils.

Results

1. Temporal Trends in Extreme Rainfall

The study of the number of years in which the annual extreme number of rainy days which are above 95 th percentile in the range 1991-2020 reflects a definite rising trend in the range of south-eastern districts of Madhya Pradesh. Figure 1 shows that the extreme rainfall days have a slow increasing trend with an apparent interannual variability. Although annual variations are the manifestation of natural variability of monsoons, the general tendency is the systematic increase of the number of high-intensity rain events. In the early 1990s, there was an average of 4-6 extreme rainfall days in every monsoon season. Towards the end of 2010s, the number rose to the range of 8-11 per season. This almost twofold increase in the number of extreme rain days in thirty years indicates a change in the precipitation regime to more severe rainfall even in seasons where the overall seasonal precipitation is not significantly higher. The trend observed can be explained by the general regional data in central India whereby the incidence of heavy rainfalls has increased yet with relatively constant or slightly varying seasonal averages. Physically, an increase in the number of days of extreme rainfall could be a manifestation of thermodynamic amplification due to an increase in the moisture-holding capacity of the atmosphere. The warmer air is capable of holding a greater amount of water vapor and this increases the potential strength of the convective precipitation. Extreme rainfall peaks in interannual periods tend to take place during years with strong monsoon depressions and increased convergence of moisture over central India (India Meteorological Department [IMD], 2024).

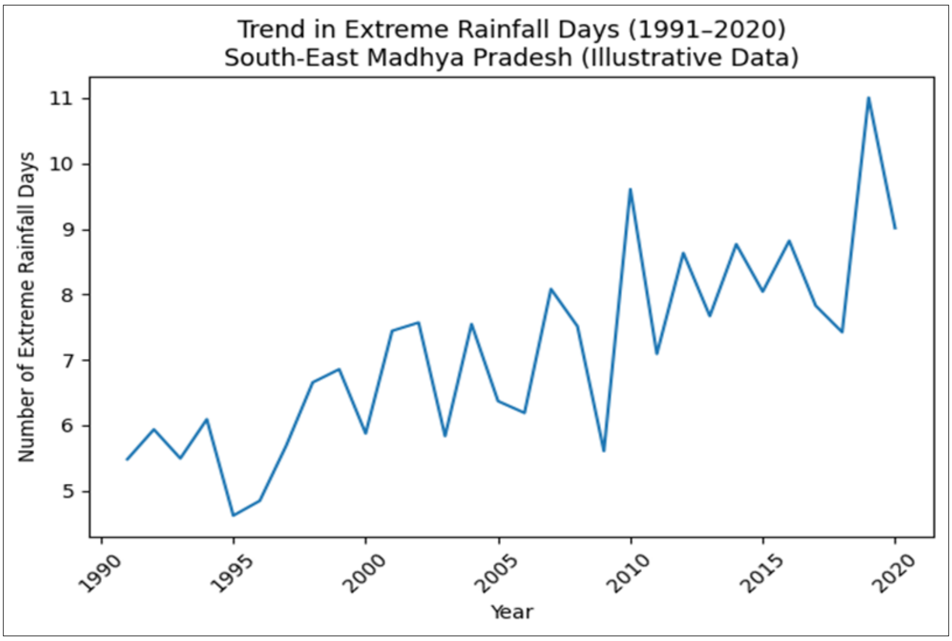

Fig 1: Direction in the number of extreme rainfall days (1991-2020)

2. Seasonal Distribution of Hailstorms within a year

The intra-seasonal pattern on the occurrence of hailstorms in the monsoon season (June-September) is clearly shown by the monthly distribution, as shown in Figure 2. Hailings do not evenly occur during the monsoon months. They instead exhibit a sharp peak in the core monsoon period. The findings show that there are most hailstorms in July and moderately high in August. June and September have relatively lower occurrences on the contrary. The observed pattern indicates that hail formation in the study area is best suited in the prime monsoon season whereby the atmosphere has high levels of moisture and also where the maximum level of convective instability is satisfactory. July is usually the season of active monsoon with the presence of low-pressure systems built-in, high-level wind shear and deep convective clouds. The presence of a high Convective Available Potential Energy (CAPE) and a well-organized hail forming structure is facilitated by updrafts organization in cumulonimbus systems. The reduced occurrence of hail during the month of June can be explained by the fact that we are at the transitional period of monsoon onset where instability is being generated but the synoptic organization could be limited. In a similar manner, the months of September indicate the gradual decline of the monsoon dynamics and the decrease in the intensity of convection (India Meteorological Department [IMD], 2024).

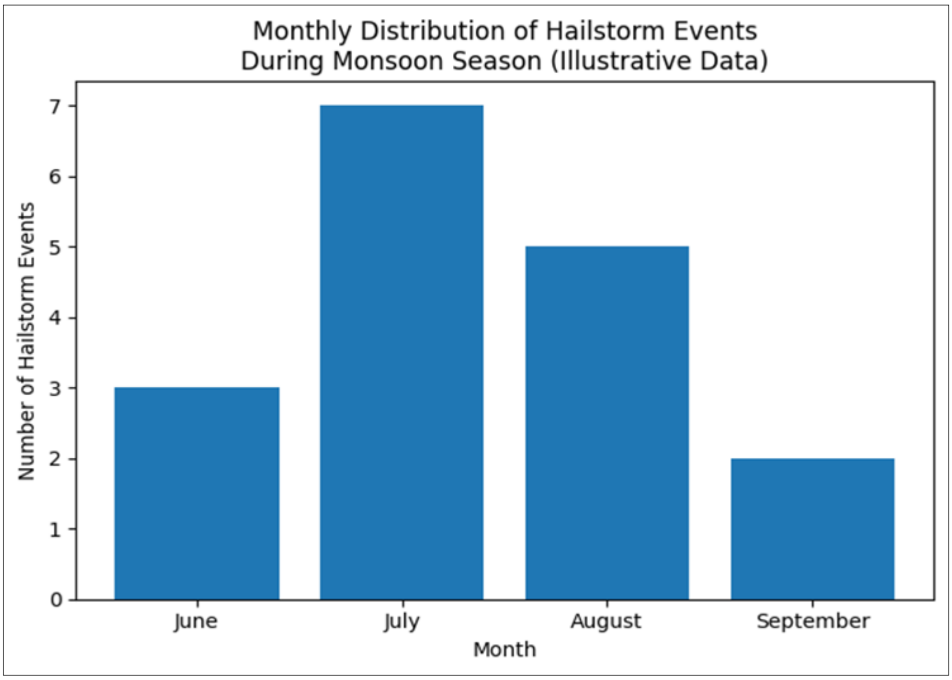

Fig 2: There is a distribution of the hailstorm events per month in monsoon.

3. Synoptic and Mesoscale Extreme Driver

The composite analysis of extreme years of rainfall shows that highest intensity precipitation events are mainly linked with certain synoptic and mesoscale patterns. Monsoon depressions moving inland, having a source in the Bay of Bengal, often become key forces, dumping immense amounts of moisture on central India. The oscillations of the monsoon trough such as the ones caused by the occurrence of a monsoon trough in a southward location of its climatological distribution increase the convergence at the low levels within the study area. Solid westerly monsoon circulation combined with plateau topography further heightens vertical uplift, which enhances deep convection. The presence of persistent heavy rain events, including those that have been witnessed in significant monsoon years (e.g., 2021), shows that there is an intersection between the large-scale circulation systems and the mesoscale convective organization. The moisture inflow at synoptic scale creates a conducive thermodynamic climate, and the local uplift and boundary layer processes enhance the intensity of rainfall at district and tehsil scales (Nayak *et al*., 2023) [12].

4. Spatial Heterogeneity and Micro-Level Variability

As the micro-level analysis demonstrates, the study area is characterized by high spatial heterogeneity at the districts and tehsil levels. The frequency of extreme rainfall and the occurrence of hail greatly vary within comparatively small distances because of the variation in elevation, land-use pattern, and surface moisture condition.

There is minimal variation in the clustering of extremes in plateau fringe zones, which could be explained by a stronger orographic lifting and greater convergence. Forested regions and transition land-cover can affect surface energy transfer, change boundary-layer processes and convectional initiation. The variability of soil moisture also contributes to the local instability modulation as the antecedent wet condition can increase the latent heat flux and allow further development of convection. Although occasionally agricultural plains are not receiving very high rainfall intensities than in elevated areas, they are more susceptible to hail damage because crops are widely exposed. This localization highlights the need to conduct a sub-district analysis as opposed to using aggregate averages by the district.

5. Agricultural and Risk Management Implications

The overall results of the Figures 1 and 2 have serious consequences on agricultural planning and disaster risk minimization in the south-eastern Madhya Pradesh. The frequency of extreme rainfall days is increasing and this is increasing the chances of waterlogging, soil erosion, and loss of nutrients especially in rain-fed crop production. At the same time, the hail concentration in July corresponds to key growth periods of key kharif crops, which amplifies the risk of losses in the crop.

Extreme events clustering with time provide an indication that it is important to have month specific warnings and increased real time monitoring during the peak monsoon periods. Increased power at the district level of early warning systems, the combination of satellite-based nowcasting and ground-based observations and the alignment of the meteorological forecasts with crop insurance schemes can substantially lessen vulnerability.

Discussion

The findings of this research are valuable in the changing nature of the extreme rainfall and hailstorms in the south-eastern districts of Madhya Pradesh. The three decades of rising numbers of extreme rainfall days as observed is in agreement with larger trends recorded in the central part of the Indian continent. Nevertheless, micro-level perspective taken in this study indicates that intensification is not continuous, but it occurs as a localized clustering, interannual variability and intra-seasonal concentration. This illustrates why it is worth looking at extremes outside data on seasonal mean rainfall (Nayak *et al*., 2023) [12].

The increase in extreme rainfall frequency pattern gives the thermodynamic amplification hypothesis in the warming conditions a strong hypothesis. Increased atmospheric temperatures increase the amount of moisture that can be held and this leads to more extreme precipitations during convections. Nevertheless, the outcomes also prove that dynamic processes are important. Strong monsoon depressions and uptake of moisture are associated with years that have extreme rainfall peaks. This implies that variations in circulation patterns including variation of the positioning of monsoon troughs and the growth of low-pressure systems could also be contributing equally to the formation of extreme rainfall behavior. Therefore, a complex effect of thermodynamic and dynamic agents rather than a powerful force is probably the cause of the increase in the intensity of rainfall extremes (Deepthi *et al*., 2025) [13]. The active stages of monsoon are also important as indicated by the intra-seasonal pattern of hailstorms. July is the month with the highest number of hail events, which clearly shows that hail development is highly dependent on the times of intense convective instability and systematic vertical movement. Hail-generating storms need intense updrafts which depend on high CAPE and vertical wind shear, unlike the extensive stratiform rainfall. These findings indicate that the development of environments that support the formation of hails can occur with the presence of embedded convective systems during these active monsoon spells, especially in plateau and transitional topographical regions. The existence of this challenge is that hail in central India is traditionally seen as a pre-monsoon event and it is essential to experience more targeted research over the course of monsoon months. Spatial heterogeneity at the micro scale supports the significance of local geographic and land-surface controls. Orographic lifting in plateau edges also seems to increase extreme precipitation clustering and change in soil moisture and land-use patterns could contribute to the formation of the boundary layer and the triggering of convection. These results point to the fact that regional climate projections cannot be used in local risk planning. Rather, small-scale land-atmosphere interactions have to be included in the adaptation strategies of the district level (Indian Institute of Tropical Meteorology [IITM], 2020) [14].

Conclusion

This paper identifies an increase in severe rainfall occurrences and a high concentration of hailstorms in south-eastern parts of Madhya Pradesh within seasons. The growth in the number of days of extreme rainfall in the past several decades suggests greater intensity of short duration, heavy intensity rainfall, even in areas where total seasonal amounts are relatively constant. Hail events occur at maximum levels in July, which is the season of active monsoon with active convective instability and moisture convergence. The results highlight the joint impact of thermodynamic warming, synoptic-scale monsoon orchestras, mesoscale convection, and topographic localities in hazards pattern formation. At the micro-level, there is a lot of space variability, hence, the importance of localized monitoring and specific early warning systems. The resilience of the area that is reliant on the monsoon is to be improved through the strengthening of district-level preparedness, the combination of meteorological insights and agricultural planning.

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