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Research paper

Analysis of temporal and spatial variations in extreme precipitation over Kerala

P. S. BIJU^{1,2}, RAJI PUSHPALATHA¹, THENDIYATH ROSHNI³, VIKRAM BHARTI³, HARIPRASAD K.M.⁴, GOVINDAN KUTTY⁵ and DHANYA M.⁴

¹Amrita School for Sustainable Futures, Amritapuri, Amrita Vishwa Vidyapeetham, Kerala, India

²India Meteorological Department, Thiruvananthapuram, Kerala, India

³National Institute of Technology Patna, Bihar, India

⁴Amrita Center for Wireless Networks & Applications, Amrita Vishwa Vidyapeetham, Amritapuri, Kerala, India

⁵Indian Institute of Space Science & Technology, Thiruvananthapuram, Kerala, India

Corresponding author's email: rajip@am.amrita.edu

ABSTRACT

Kerala, an ecologically sensitive state in southwestern India, is increasingly vulnerable to rainfall-induced disasters such as floods and landslides. This study analysed 124 years (1901–2024) of high-resolution daily rainfall data from the India Meteorological Department (IMD) to examine spatial and temporal trends across Kerala. The analysis assessed changes in rainy days and the frequency of heavy (HRF), very heavy (VHRF), and extremely heavy rainfall (EHRF) events, along with shifts in the onset of the southwest monsoon (SWM) and northeast monsoon (NEM) and rainfall irregularity using the Precipitation Concentration Index (PCI). Results revealed strong spatial heterogeneity: northern Kerala receives higher SWM rainfall (~3000 mm), while southern regions experience more intense rainfall during the NEM and winter seasons. Breakpoint analysis indicated a recent change in NEM rainfall around 2020, with a steep increase in slope from -0.527 to 23.048. High PCI values (11–21) in northern and central-western regions reflect strong rainfall concentration and elevated flood risks. Rainy days and EHRF events increased during the SWM and summer, while declines during the NEM and winter could affect water availability and winter cropping. Long-term projections suggest the SWM may advance toward May and the NEM extend into late October. These changing rainfall dynamics hold significant implications for agriculture, water management, and climate adaptation planning, emphasizing the need for location-specific strategies.

Keywords: Monsoon onset, Extreme rainfall events, Precipitation concentration index (PCI), Southwest monsoon (SWM), Northeast monsoon (NEM), Kerala

The changing climatic conditions impact society in terms of floods, drought, heatwaves, landslides, etc (Abhilash *et al.*, 2019; Wadhawan *et al.*, 2020). Krishnan *et al.*, (2020) reported the potential shifts in rainfall and temperature in India for different emission scenarios. The report highlights that the southern region in India, especially Kerala, will be witnessing extreme events, including heavy rainfall. Kerala received an unusually high cumulative rainfall of 2346.6 mm from June 1 to August 20, 2018, in contrast to the expected 1,649.5 mm during a similar timeframe (Joseph *et al.*, 2020). Most recently, in the year 2024, very heavy rainfall triggered landslides, erosion, and flash floods which resulted in over 400 deaths (Ramesh *et al.*, 2025). The temporal

and spatial variability analysis is essential in Kerala due to the state's diverse topography, which includes coastal plains, midlands, and the Western Ghats, leading to significant variations in rainfall distribution. Some districts, like Wayanad and Idukki, receive heavy rainfall, while others, such as the Palakkad gap, experiences relatively lower amounts. Understanding this variability is crucial for agriculture, as different crops require different water availability levels. It also plays a key role in water resource management, ensuring efficient allocation of water for drinking, irrigation, and hydropower generation. Additionally, spatial analysis helps in disaster preparedness, particularly in flood- and landslide-prone areas, by improving early warning systems (Thakur *et al.*, 2017;

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Wadhawan *et al.*, 2020) as Kerala is an ecologically sensitive region (Yewale and Jadhav, 2025; Aswathi *et al.*, 2022).

Hence given the prevalence of natural disasters in this region and the critical shortage of water for agricultural, industrial, and domestic purposes, this study is essential for identifying shifts and variations in rainfall, including the extreme events based on the latest data across Kerala. Compared to the existing analyses as presented previously, the current study focuses on (i) the spatial and temporal patterns and frequency of extreme rainfall during different seasons across Kerala using data from 1901-2024, across 60 station points in the 14 districts in Kerala (ii) to determine the shift in the onset of monsoon to support decision makers. These analyses are important to understand the decision-makers who are working with disaster risk reduction and management.

MATERIALS AND METHODS

Data and study region

The study region Kerala (Fig. 1) is in the southwestern part of the Indian subcontinent. With a coastline stretching approximately 590 km along the Arabian Sea, the region exhibits a substantial variation in elevation from 2,674 m above sea level to 28 m below. Corresponding to its diverse terrain, the intensity of rainfall across the state also varies considerably. The daily rainfall data required for the study for a duration of 124 years (1901 to 2023) was collected from the IMD for 60-point stations spread across Kerala. The station points are distributed across the fourteen districts in Kerala. The daily rainfall was analysed season wise viz. southwest monsoon (June to September), the northeast monsoon (October to December), winter (January to February) and summer (March to May). The data on the onset dates of the monsoon were obtained from the National Data Centre of the India Meteorological Department (IMD), Pune (IMD Monsoon page; Geetha and Raj, 2015).

Data analysis

The station’s data points were used to study the spatial variability of heavy, very heavy, and extreme rainfall events across Kerala as per criteria defined by India Meteorological Department (IMD, 2021). The rainfall amount: ≥ 64.5 mm is considered as

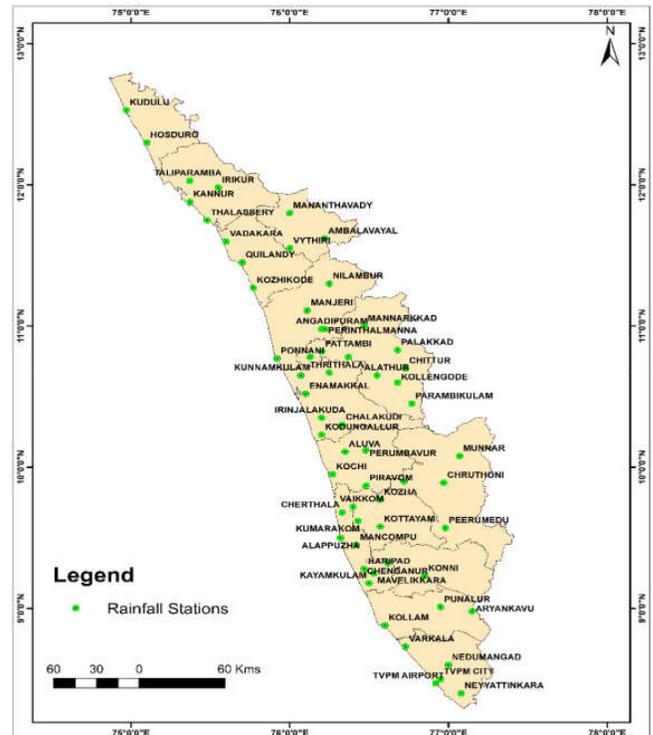


Fig. 1: Map of the study region Kerala with rainfall stations

heavy rainfall (HRF), ≥ 115.6 mm is considered as very heavy rainfall (VHRF), and ≥ 204.5 mm is considered as extremely heavy rainfall (EHRF). The spatial distribution of these three categories is analysed and discussed.

The Mann-Kendall (MK) trend test (Mann, 1945; Kendall, 1948) was conducted to understand the variability and change in rainfall along with the Chow test (Chow, 1960). It helps pinpoint shifts in rainfall patterns due to climate change. The Chow test is a specific statistical test used to determine whether there is a structural break at a known or hypothesized point in the data. It compares the goodness of fit of regression models before and after a specified point to assess whether the regression parameters differ significantly.

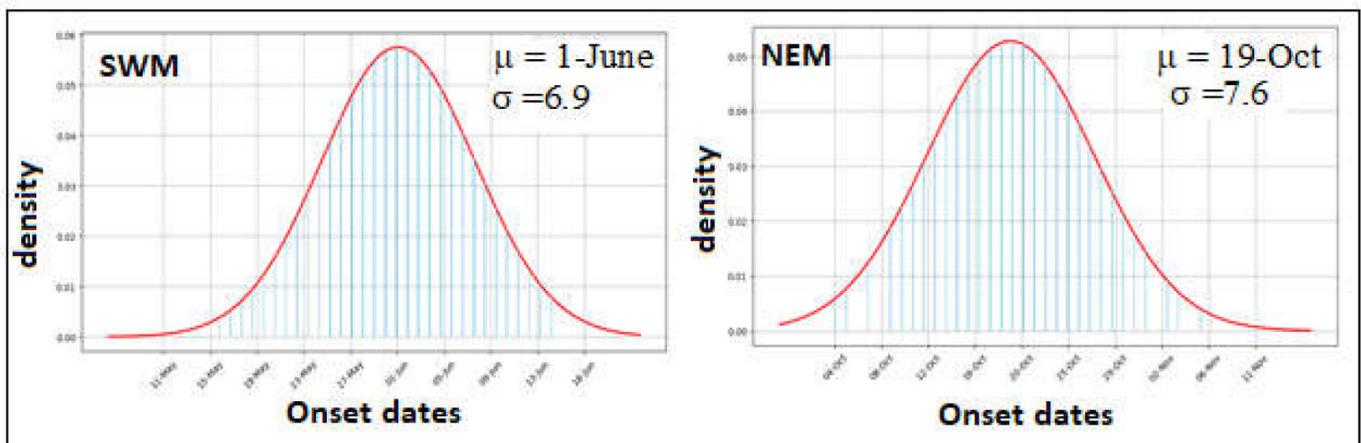


Fig. 2: The Gaussian fit of Onset dates of SWM and NEM

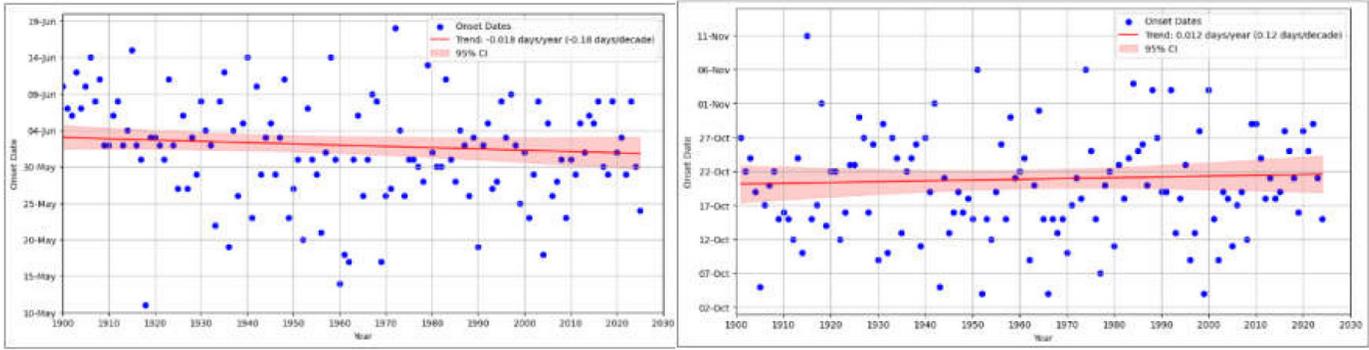


Fig. 3: Trend of onset of SWM and NEM with 95% confidence level

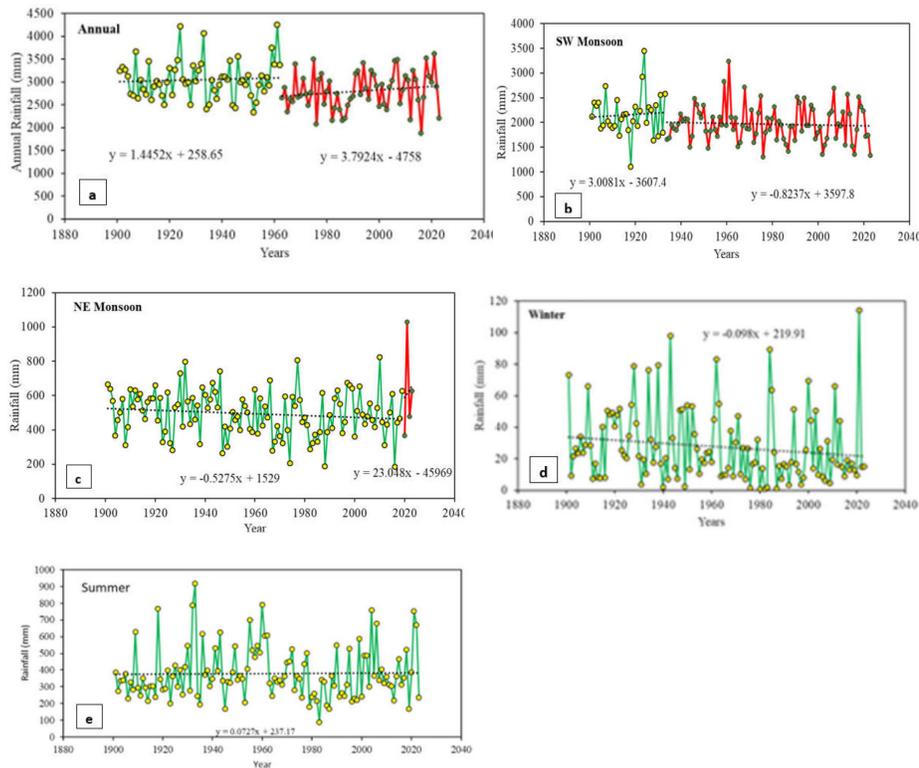


Fig.4: Breakpoint analysis of (a)annual, (b)SWM, (c)NEM, (d)winter, and (e) summer rainfall

The precipitation concentration index (PCI) provides overview of how evenly/unevenly the rainfall is distributed over a given time period. The PCI is categorized as uniform ($PCI < 10$), moderate ($11 < PCI < 15$), irregular ($16 < PCI < 20$) and significant irregular ($PCI > 20$) precipitation distribution (Sireesha *et al.*, 2020). The value of PCI can be calculated using the following formula:

$$PCI = \frac{\sum_{i=1}^{12} P_i^2}{(\sum_{i=1}^{12} P_i)^2}$$

where, P is the precipitation.

RESULTS AND DISCUSSION

Onset of SW and NE monsoon

An analysis of 124 years of onset data (1901–2024) for

the SWM and NEM reveals that both exhibit Gaussian distributions, as illustrated in Fig. 2. The Gaussian fit for SWM onset dates yields a mean (μ) of 1 June with a standard deviation (σ) of 6.9 days, indicating that the climatological onset typically occurs at the beginning of June, with most events clustered within approximately one week of this date. For NEM, the fitted Gaussian distribution shows a mean onset around 19 October, with a spread of 7.6 days, suggesting that most occurrences are concentrated within roughly one week on either side of the climatological mean. Together, these results indicate that interannual variability in monsoon onset dates is substantial, exceeding any detectable long-term linear trend.

The long-term analysis of monsoon onset dates indicates a marginally advancing trend, with a linear regression slope of -0.018 days per year (equivalent to approximately -0.18 days per decade). This suggests that the onset has shifted earlier by less than two days over the past century. The regression was accompanied by a 95% confidence interval, which defines the range of plausible

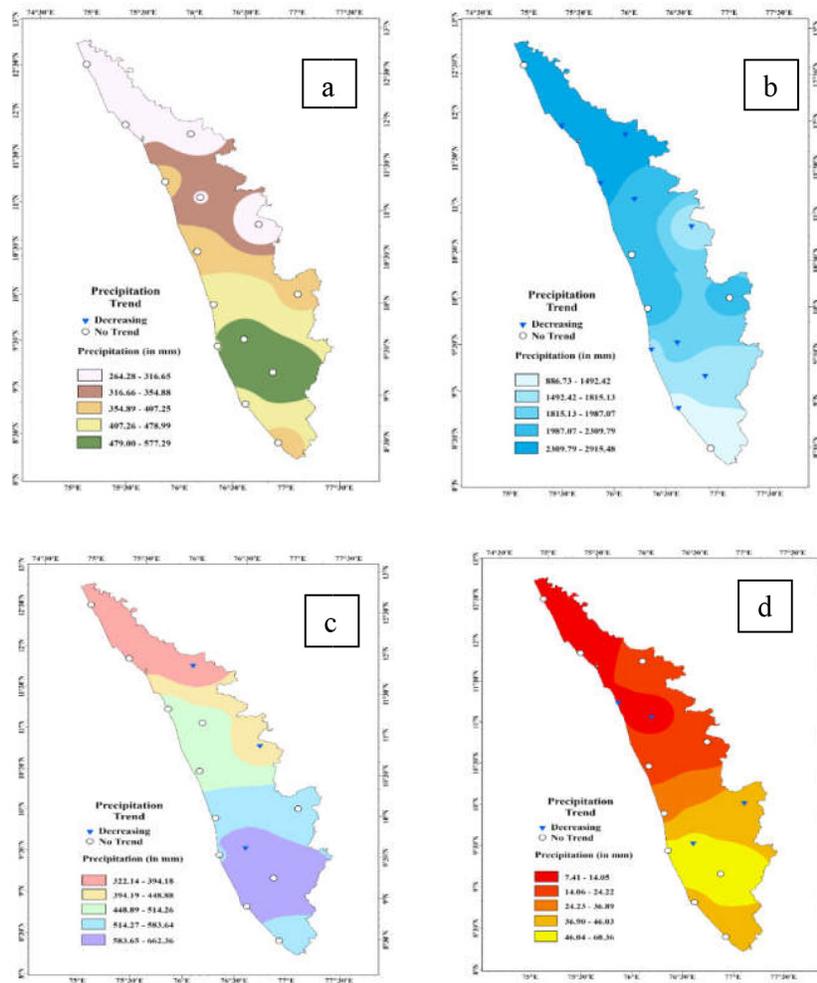


Fig. 5: The spatial variability and trend in rainfall during different seasons (a) summer (b) southwest (c) northeast (d) winter

trends given the data variability. The narrow magnitude of the slope, together with the confidence band encompassing near-zero change, indicates that the central tendency points towards an earlier onset as shown in Fig. 3. In contrast, the NEM onset exhibits a weakly increasing trend of 0.012 days per year (≈ 0.12 days per decade), pointing towards a marginal delay of just over one day across the past century.

Detecting shifts in rainfall patterns

The analysis of 124 years of annual rainfall indicates a decline across Kerala with a magnitude of 295 mm per decade. The minimum, maximum, and average rainfall are observed as 1870, 4258, and 2920 mm, respectively. The SWM and NEM rainfall trend analysis indicates a decline with magnitudes of 258 mm/decade and 35mm/decade, respectively. However, the summer rainfall analysis indicates a very small increase in its trend, with a magnitude of 9 mm/decade. The magnitudes of decadal changes are estimated using the least-squares regression method. The breakpoint analysis of annual, SWM, NEM, winter, and summer rainfall data to understand change detection points is analysed and presented in Fig. 4. The annual rainfall trend analysis reveals (Fig.4a) distinct temporal variations in rainfall patterns. During the early period (1950), rainfall showed

a marginal increasing trend ($y = 1.4452x + 258.65$), suggesting relatively stable or slightly wetter conditions. However, in the later period (1951–2020), the trend reversed, indicating a gradual decline in annual rainfall ($y = -3.7924x + 4758$). The breakpoint is observed around 1930 in the case of the SWM, with a decline in the slope value from 3.008 to -0.823 (Fig. 4b). Compared to the annual and SWM rainfalls, the breakpoint for NEM rainfall is observed in a recent year, and it is around 2020, with a considerable increase in the slope from -0.527 to 23.048. However, such breakpoints and trends are not observed in the case of the winter and summer rainfall. Aligning with the findings, in recent years, the NE monsoon in Kerala has shown considerable variability, and it can be largely influenced by changing ocean-atmosphere interactions and broader climate variability (Fig. 4c). These shifts are particularly critical for Kerala, where the NE monsoon plays an essential role in post-monsoon agricultural activities and groundwater recharge. There are no such breakpoints observed in case of the winter and summer rains (Fig. 4 d & e).

A spatial perspective on seasonal rainfall variability

The spatial visualization helps to identify rainfall hotspots, regional disparities, and potential water-stressed zones. Fig. 5b

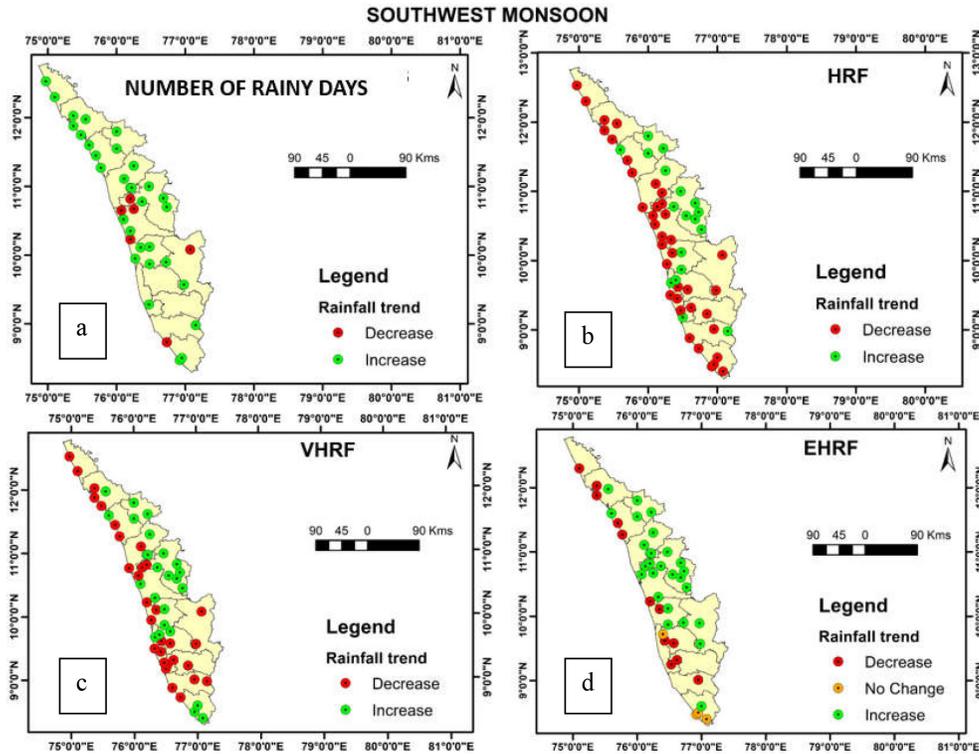


Fig. 6: The trends in a) number of rainy days, frequency of b) HRF, c) VHRF, and d) EHRF during the SW monsoon

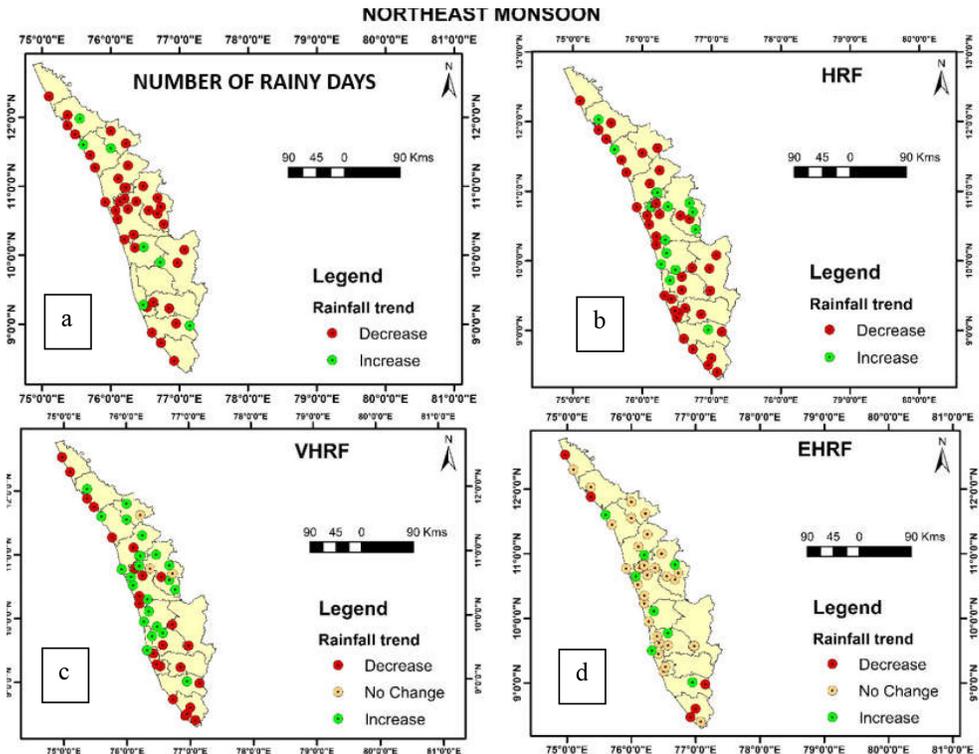


Fig. 7: The trends in a) number of rainy days, frequency of b) HRF, c) VHRF, and d) EHRF during NE

illustrates the spatial variability of rainfall during the southwest monsoon across Kerala. The highest rainfall is concentrated in the northern region, with amounts ranging from 2300 to 3000 mm. A gradual decrease in rainfall is observed toward the central part of the state, while the southern region records the lowest values,

with magnitudes below 1500 mm. The downward-pointing blue triangles represent a declining trend in rainfall distribution across Kerala. Fig. 5c illustrates the spatial variability of rainfall during the northeast monsoon, which follows a pattern like the summer rainfall distribution. Higher rainfall magnitudes, exceeding 500

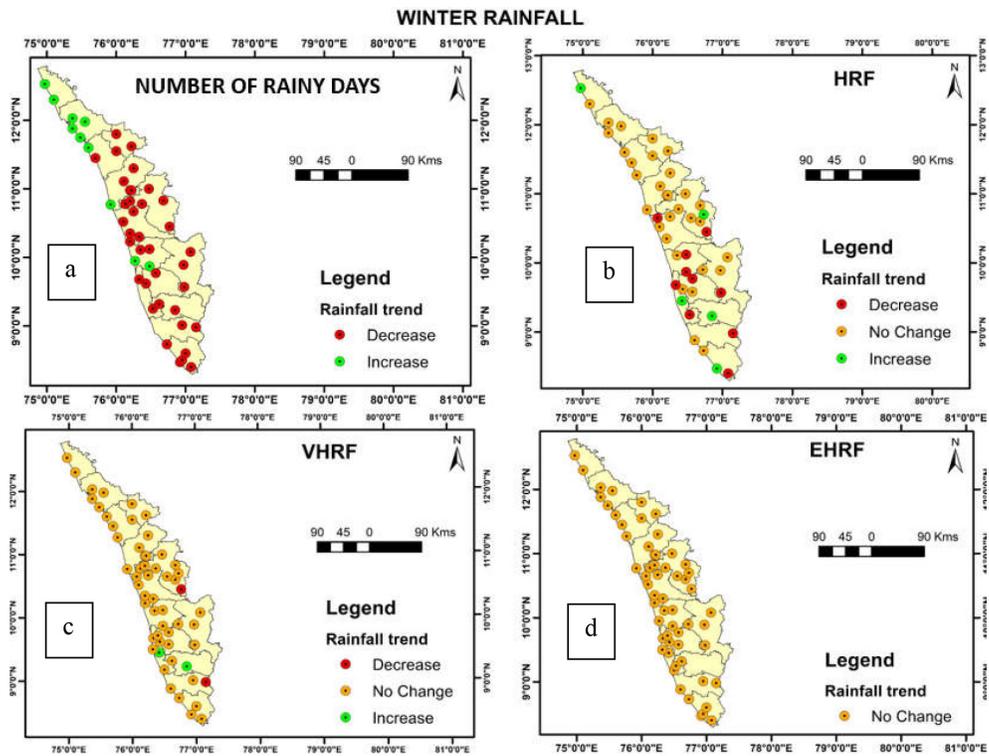


Fig. 8: The trends in a) number of rainy days, frequency of b) HRF, c) VHRF, and d) EHRF during winter monsoon

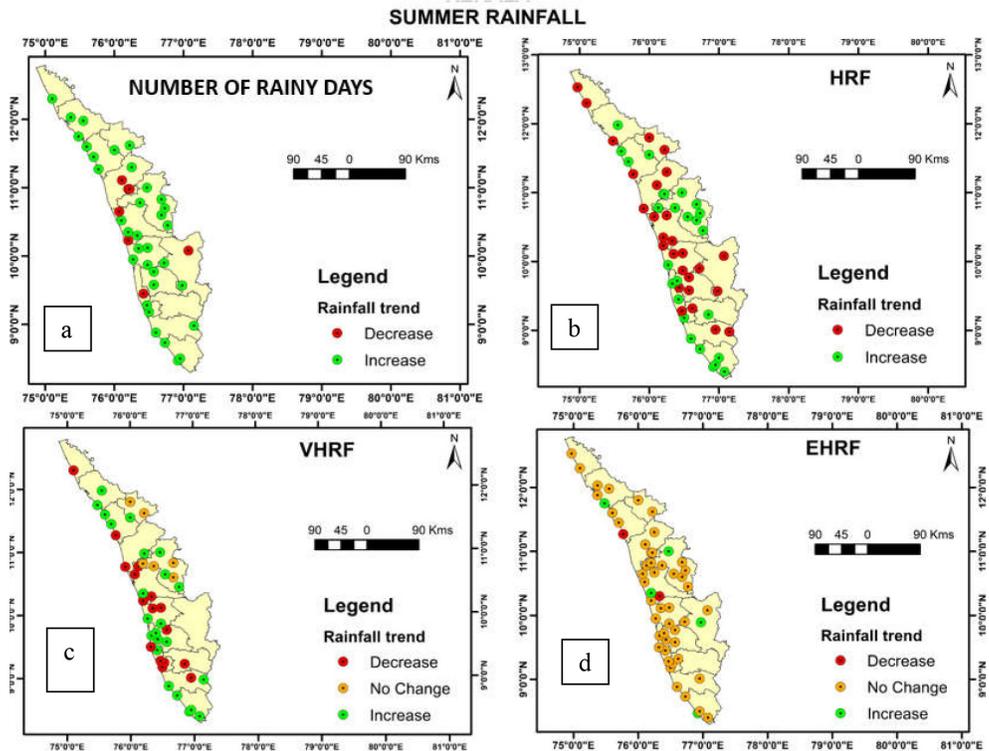


Fig. 9: The trends in a) number of rainy days, frequency of b) HRF, c) VHRF, and d) EHRF during the summer monsoon

mm, are predominantly observed in the southern part of Kerala. Overall, no significant trend is evident across the region, except for a declining trend observed at three specific locations. Fig. 5d depicts the spatial variability of winter rainfall, which also mirrors the patterns observed during the summer and northeast monsoons.

Rainfall is higher in the southern regions and decreases towards the northern parts of Kerala. A predominantly decreasing trend in rainfall magnitudes is observed during this season. Fig. 5a illustrates that although no distinct trend is observed in summer rainfall across Kerala, the highest values (higher than 400 mm) are concentrated

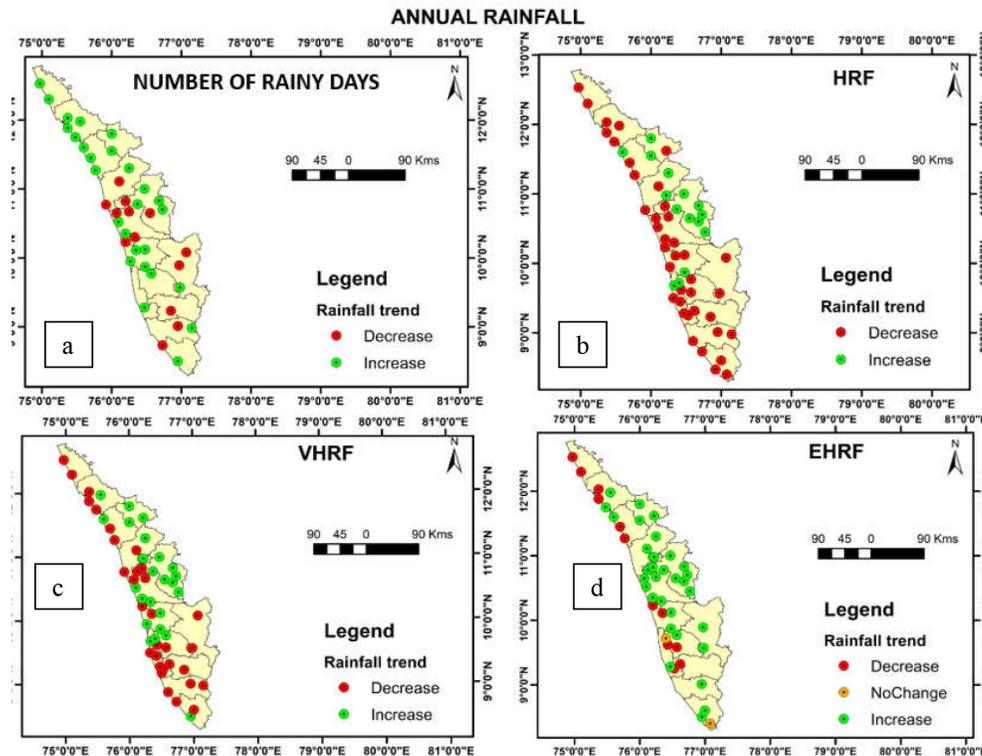


Fig. 10: The trends in a) number of rainy days, frequency of b) HRF, c) VHRF, and d) EHRF for annual rainfall

in the southern regions, with lower rainfall amounts found in the northern parts of the state.

Frequency of extreme rainfall events

An analysis of the frequency of HRF, VHRF, and EHRF events across Kerala reveals spatial variability in their trends, with certain regions experiencing an increase while others show a decline (Fig. 6 to 11). An analysis of the total number of rainy days during the SWM season reveals an increasing trend across most locations in Kerala (Fig. 6a). However, this increase in rainy days is accompanied by a notable decline in the frequency of HRF and VHRF events, particularly across the coastal regions (Fig. 6b and 6c). This suggests a shift toward more frequent but less intense rainfall events in these areas. In contrast, EHRF events show an increasing trend across many locations, with a pronounced intensification observed in the central part of the state (Fig. 6d).

In contrast to the monsoon season, the post-monsoon period exhibits a decreasing trend in the number of rainy days across most locations (Fig. 7a). A similar declining trend is observed in the frequency of HRF events at many point locations (Fig. 7b). Interestingly, the VHRF events show an increasing trend, indicating a shift toward more intense but less frequent rainfall occurrences during this season (Fig. 7c). In the case of EHRF, however, no significant change is observed, suggesting relative stability in the extreme tail of the rainfall intensity distribution (Fig. 7d). Fig. 8 illustrates the spatial variability in the trends of the number of rainy days and the frequency of HRF, VHRF, and EHRF events during the winter season. Overall, there is a declining trend in the number of rainy days across most parts of Kerala, except for a few isolated locations in the northern region, which show a slight increase (Fig.

8a). In terms of rainfall intensity, no statistically significant trends are observed in the frequency of HRF, VHRF, or EHRF across the state (Fig. 8b, 8c, and 8d). However, a few locations in the central and southern parts of Kerala exhibit a marginal decline in the occurrence of these high-intensity rainfall events.

Fig. 9 presents the spatial trends in rainfall characteristics during the pre-monsoon season across Kerala. The number of rainy days shows an overall increasing trend across the northern part of the state (Fig. 9a), with a decline towards the central and southern regions. The frequency of Heavy Rainfall (HRF) and Very Heavy Rainfall (VHRF) events exhibits spatial variability, with both increasing and decreasing trends observed at different locations (Fig. 9b and 9c). However, in the case of Extremely Heavy Rainfall (EHRF) events, no trends are observed. The number of rainy days shows a mixed trend (Fig. 10 a), with several stations in central and southern Kerala exhibiting a decline, while parts of the northern region indicate an increase. Heavy rainfall frequency (HRF) displays a widespread decreasing trend (Fig. 10b), particularly along the coastal and midland regions, suggesting a weakening of high-intensity rainfall events. Very heavy rainfall frequency (VHRF) also shows predominantly negative trends across most stations (Fig. 10c), emphasizing a reduction in extreme rainfall occurrences. Conversely, extremely heavy rainfall frequency (EHRF) reveals an increasing trend at numerous stations in northern and central Kerala, indicating localized intensification of extreme precipitation (Fig. 10d).

Precipitation concentration index (PCI)

The Precipitation Concentration Index (PCI) reveals an increasing trend across Kerala (Fig. 11), with a notable rise

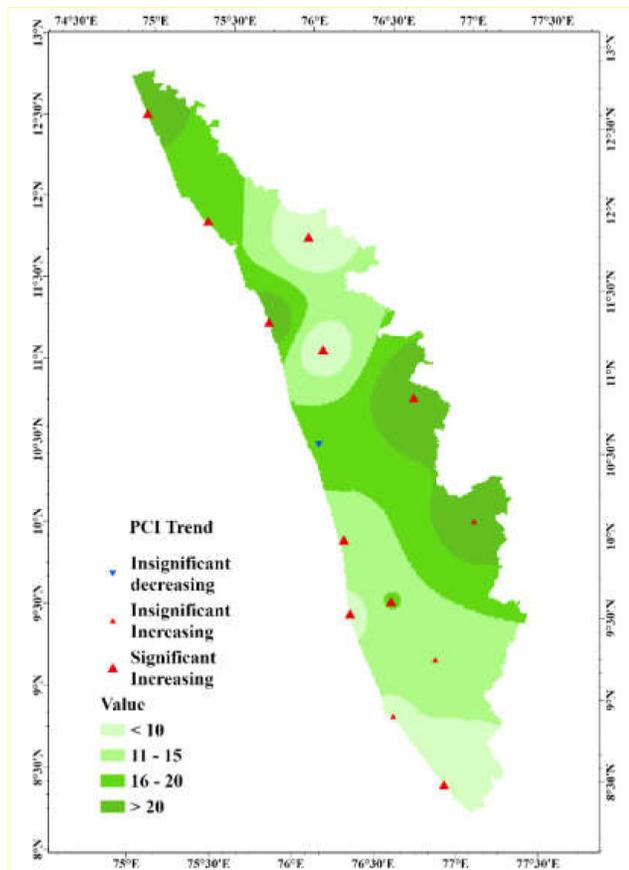


Fig. 11: Precipitation concentration index across Kerala

in the northern and coastal regions. Throughout the state, PCI values consistently exceed 10, signifying moderate to highly irregular rainfall distribution. Particularly elevated PCI values are observed in the northern districts and along the Western Ghats, highlighting regions where rainfall events are increasingly uneven and concentrated. This growing irregularity in precipitation patterns underscores the heightened vulnerability of these areas to extreme weather events, such as floods and droughts. Consequently, the findings emphasize the urgent need for localized adaptation strategies, including climate-resilient agricultural practices, improved water resource management, and early warning systems, to mitigate the adverse impacts of such climatic variability.

CONCLUSIONS

The study analysed 124 years of rainfall data across Kerala to assess spatial and seasonal variability, identify breakpoints, and evaluate the Precipitation Concentration Index (PCI). The onset analysis reveals a shift in the southwest monsoon towards May and the northeast monsoon towards the end of October. This temporal shift is critical for planning cropping seasons and mitigating water scarcity issues. The spatial variability of seasonal rainfall shows a general decline across Kerala. Except for the southwest monsoon, most seasons exhibit a consistent pattern of higher rainfall in the southern regions, whereas the southwest monsoon shows greater rainfall concentrations in the northern regions. Furthermore, the study highlights a significant increase in rainfall irregularity, as indicated by the rising PCI values, emphasizing the urgency for

effective adaptation and mitigation strategies across sectors like disaster management, agriculture, and rural livelihoods. The study emphasizes the urgent need to focus on micro-level adaptation strategies, tailored to the place-to-place variability in extreme rainfall events across Kerala. Overall, the findings reinforce the importance of integrating rainfall variability into early warning systems and long-term planning for climate resilience.

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Data availability: The data is available and will share on request

Authors contribution: BPS-Data analysis and drafting the manuscript; RP-Supervising and reviewing the manuscript; RT-Methodology and reviewing the manuscript; VB and HP-Visualization of data; GK and DM-Reviewing the manuscript

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