Machine learning–based assessment of long-term climate variability of Kerala

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Machine learning–based assessment of long-term climate variability of Kerala

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Abstract Studies on historical patterns of climate variables and climate indices have attained significant importance because of the increasing frequency and severity of extreme events worldwide. While the recent events in the tropical state of Kerala (India) have drawn attention to the catastrophic impacts of extreme rainfall events leading to landslides and loss of human lives, a comprehensive and long-term spatiotemporal assessment of climate variables is still lacking. This study investigates the long-term trend analysis (119 years) of climate variables at 5% significance level over the state using gridded datasets of daily rainfall ($0.25° \times 0.25°$ spatial resolution) and temperature ($1° \times 1°$ spatial resolution) at annual and seasonal scales (south-west monsoon, north-east monsoon, winter and summer). Five trend analysis techniques including the Mann–Kendall test (MK), three modified Mann–Kendall tests and innovative trend analysis (ITA) test were performed in the study. It is evident from the trend analysis results that more than 83% of grid points were showing negative trends in annual and south-west monsoon season rainfall series (at a mean rate of 39.70 mm and 28.30 mm per decade respectively). All the trend analysis tests identified statistically significant increasing trends in mean and maximum temperature at annual and seasonal scales (0.10 to 0.20 °C/decade) for all grids. The K-means clustering algorithm delineated 59 grid points into five clusters for annual rainfall, illustrating a clear geographical pattern over the study area. There is a clear gradient in rainfall distribution and concentration inside the state at annual as well as seasonal scales. The majority of annual rainfall is concentrated in a few months of the year. That may lead the state vulnerable to water scarcity in non-rainy seasons.

Keywords Climate change · ITA · Mann–Kendall · K-means clustering · Principal component analysis · PCI · Seasonality index · Trend analysis

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Introduction

Indian economy and livelihood of people are highly dependent on monsoon rainfall. Accurate analysis of climatic variables is crucial because of the rain-fed agriculture, which contributes about 50% of the country's GDP. But global warming and urbanization led to the changes in regional and global climate which directly affect the agricultural sector of the country.

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The rapid growth of urbanization is one of the major causes of global warming which results in deterioration of ecological balance and human health (Adiguzel et al., 2020; Cetin, 2015a, 2020a, 2020b). Accurate analysis of climate variables is vital for regions like India, which is one of the most drought-prone areas in the world despite the fact that the county receives 1190 mm annually. Therefore, a better understanding of the trends and variability of the climate parameters is vital to measure climate-induced changes and solve the water management issues to a greater extent.

Studies around the world have reported the spatial and temporal variation of climatic variables (Alexander, 2016; Burn & Elnur, 2002; Caloiero et al., 2011; Martinez et al., 2012; Yang et al., 2017). The studies executed on climatic variables in India pointed out the reduction in monsoon rainfall (Ghosh et al., 2009; Goswami et al., 2006; Guhathakurta & Rajeevan, 2008; Guhathakurta et al., 2015; Jain & Kumar, 2012; Jain et al., 2013; Krishnamurthy & Shukla, 2000; Kumar et al., 2010; Mondal et al., 2015; Pal & Al-Tabbaa, 2009; Parthasarathy & Dhar, 1974; Rao, 1993), whereas an increasing trend in temperature (Hingane et al., 1985; Bhutiyani et al., 2007; Shafiq et al., 2019; Machiwal et al., 2019). Guhathakurta et al. (2015) conducted a study on the trend of south-west monsoon using 111 years of monthly rainfall data over India and revealed that decreasing trend in monsoon rainfall post-1950 period due to multidecadal epochal variability. The study also revealed the decreasing trend of frequencies of wet days and rainy days over most parts of the country. Dey and Mujumdar (2019) used relative entropy to examine the spatial variability and change in uniformity of rainfall distribution over India and observed a significant relationship between rainfall uniformity and low rainfall intensity. Variations in the onset and quantity of annual rainfall received can negatively impact the hydrological cycle and agricultural productivity. The characteristics of high-intensity rainfall events are affected by rising temperatures, thus altering the uniformity in rainfall distribution (Dey & Mujumdar, 2019).

Temperature is considered as a crucial climate variable that has a close relationship with other significant climate variables like atmospheric humidity and precipitation. The fifth assessment report of the Intergovernmental Panel on Climate Change reported the increase in surface air temperature by 0.87 °C during 1880–2012 (Myhre et al., 2013; Guo et al., 2020). In the view of above, many studies have attempted to analyse the pattern of temperature on the global scale (Ahmadi et al., 2018; Kruger & Shongwe, 2004; Saboohi et al., 2012; Tabari & Talaee, 2011) as well as national scale (Jhajharia & Singh, 2011; Kothawale et al., 2010; Pal & Al-Tabbaa, 2010). Pal and Al-Tabbaa (2010) analysed the long-term pattern of monthly and seasonal extreme temperatures over India from 1901 to 2003 and found out that minimum temperature changes were more variable, both spatially and temporally than the corresponding maximum temperature changes with results of lesser significance. The western Himalaya region is the most vulnerable area to climate change in India, with the highest variation and highest temperature increase, which most probably lead to the melting of glaciers in this region (Pal & Al-Tabbaa, 2010). Abrupt changes in climatic parameters like precipitation and temperature can impart a negative impact on human health and comfort (Cetin, 2015b, 2019a, 2019b; Kilicoglu et al., 2020; Gungor et al., 2021). Even though few studies are available showing the variability of rainfall over Kerala, there exists a lack of detailed research focusing on regional temperature trend patterns in the state.

Analysis of rainfall trend in Kerala indicated a decreasing trend in annual as well as south-west monsoon rainfall (Guhathakurta & Rajeevan, 2008; Nair et al., 2014; Nikhil Raj & Azeez, 2012; Singh et al., 1989; Soman et al., 1988) and an increasing trend in post-monsoon and winter rainfall (Adarsh & Janga Reddy, 2015; Krishnakumar et al., 2009; Thomas & Prasannakumar, 2016). Kerala receives more of the south-west monsoon in the northern parts of the state while the southern parts get more of the north-east monsoon (Nair et al., 2014). During the active spell of the south-west monsoon, north Kerala comes under the cyclonic shear area of the low-level jet, while south Kerala falls in the anticyclonic shear zone, which is the main reason for this asymmetry (Simon & Mohankumar, 2004). The increasing frequency of the dry days and a decreasing trend in extreme rainfall events during monsoon in Kerala point out the increasing probability of water scarcity during the non-monsoon season (Pal & Al-Tabbaa, 2009). The decreasing trend of the south-west monsoon rainfall leads to short-term meteorological droughts, which will directly affect the agricultural sector as well as water resources of the state (Thomas & Prasannakumar, 2016). The reduction of rainy days in central Kerala during the south-west monsoon is the main reason for higher intensities of rainfall over a shorter period, which contributed to the faster filling up of reservoirs and major landslides in Kerala over the recent years (Vijay et al., 2021).

Changes in rainfall concentration, as well as its seasonality, have been a subject of numerous studies during the past years across the world (De Luis et al., 2011; Feng et al., 2013; Kanellopoulou, 2002; Thomas & Prasannakumar, 2016; Tolika, 2019; Zamani et al., 2018; Zhang et al., 2009, 2019). Since rainfall and temperature are the major influence on characterizing the local climate over India, it is highly essential to determine whether the pattern and concentration of climatic variables are also changing in the context of climate change and urbanization. Various researchers have used PCI (precipitation concentration index) and seasonality index (SI) to identify temporal heterogeneity of rainfall distribution in many regions of the world. However, so far, there has been no detailed study of the influence of geographical parameters like latitude and longitude on these indices in India.

Nevertheless, very few studies were investigated about the regional scale rainfall as well as temperature trends in the state, even though it has a profound impact on its agriculture-based economy. Previous works addressing rainfall variability of Kerala have utilized either area-averaged or station data for the analysis, which will not give a clear representation of climate variability over a large area. Since the climate of the state is controlled by monsoon spells, it is essential to understand the variability of climate variables at seasonal scale and hence the detailed analysis of spatial and temporal patterns of climate variables and climate indices was carried out for different seasons also.

Considering the gap, the present study mainly focuses on trends and variability of rainfall and temperature over Kerala using high-resolution gridded data. The heterogeneity and complexity of the terrain in Kerala pose obstacles to study the climate in the state. Although there exist few reports of spatiotemporal variation of climate parameters, influences of complexity in topography on these parameters have never been investigated in Kerala. This study examines and documents the trends and variability of the rainfall and temperature, concentration and clustering of rainfall using daily data sets from 59 grids in Kerala from 1901 to 2019. Therefore, the main objectives of the present study are (1) to delineate rainfall clusters by K-means algorithm and identify the influence of geographical and statistical parameters of grids by principal component analysis (PCA); (2) to detect and quantify trends in annual as well as seasonal time series of rainfall, rainy days and temperature over Kerala using five trend analysis techniques; and (3) to analyse the concentration and seasonality of rainfall in various clusters.

Materials and methods

Study area

Kerala encompasses 38,863 km^2 area and is situated in the south-west portion of peninsular India (8° 15′ N to 12° 50′ N and 74° 50′ E to 77° 30′ E). The terrain of the state is very complex and heterogeneous as it is bounded by the Western Ghats in the east and the Arabian Sea in the west. Although the average width of the study area is 100 km, Kerala is tropically diverse, with varying land surface and land use land cover. Based on the altitude, the terrain of the state is divided into three distinguishable zones, namely low land (on the west side), midland (area between low land and high land) and high land (on the east side). The climate of the area is characterized as humid and tropical, which is highly influenced by the heavy seasonal rains of the south-west monsoon and north-east monsoon, winter and summer. Kerala is known as the entry point of the summer monsoon in the Indian continent (Fig. 1a).

Data and methodology

In this study, the long-term gridded rainfall data of 0.25°×0.25° spatial resolution (59 grid points) for the period from 1901 to 2019 and temperature gridded data of 1°×1° spatial resolution (from 1951 to 2019) for five grid points, located in the study area were gathered from the India Meteorological

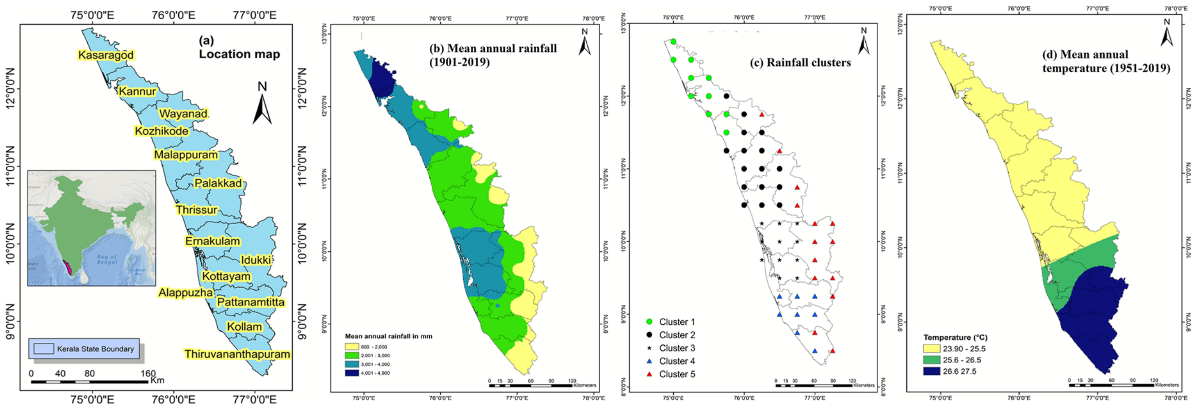

Fig. 1 Location map of study area showing (**a**) location map of Kerala, (**b**) spatial variation of mean annual rainfall, (**c**) location of rainfall clusters and (**d**) spatial variation of mean annual temperature

Department (IMD), Pune (Pai et al., 2014). The principal seasons in Kerala are south-west monsoon (June–September), north-east monsoon/post-monsoon (October–November), winter (December–February) and summer (March–May). The study utilized five non-parametric trend tests such as Mann–Kendall test (MK), modified Mann–Kendall test (MK-CF_1), modified Mann–Kendall test (MK-CF_2), pre-whitening Mann–Kendall test (PWMK) and innovative trend analysis (ITA). The methodology of the present investigation is illustrated in Fig. 2.

K-means clustering method

K-means clustering is one of the most common unsupervised techniques which is mainly used for segregation (MacQueen, 1967). The algorithm divides the dataset into user-defined groups that show similar patterns. This is also known as exclusive clustering since it groups data into pre-defined, non-overlapping clusters, where each point belongs only to the cluster. First of all, the algorithm identifies k number of centroids in the data series and assigns each point to

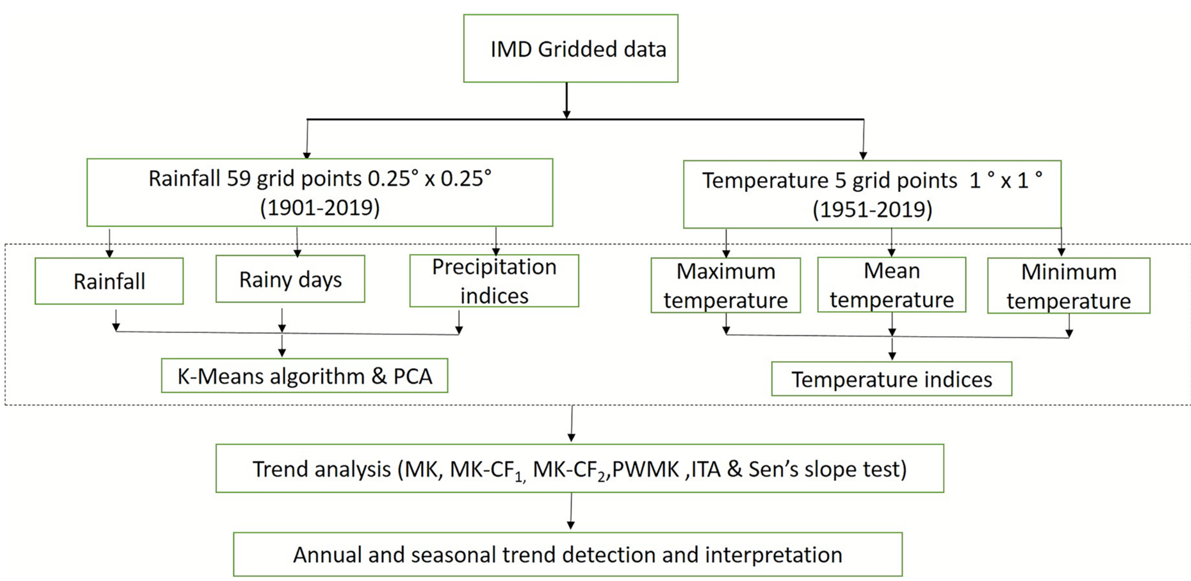

Fig. 2 Flow chart of methodology adopted

the nearest cluster. The value of k is obtained by the elbow curve. The algorithm calculates the Euclidean distance between each data point and the centroid of each cluster. Later, it allocates the data point into the cluster with minimum distance. Then, clusters with new centroid values are reassigned based on the average value of coordinates of data points. Repeat the previous two steps iteratively until the centroid of clusters stops changing their position. This step was carried out using scikit-learn, which implements many machine learning algorithms efficiently with the interface in python.

The principal component analysis (PCA) is a data pre-processing technique which mainly used to reduce the dimensionality of the data sets, without losing much information. This helps to identify the relevant patterns in a data set and highlight their similarities and differences. PCA is one of the most widely used machine learning techniques for predictive models.

Rainfall concentration and seasonality

The precipitation concentration (PCI; Oliver, 1980) is a tool for calculation of rainfall concentration (De Luis et al., 2000, 2011) on annual and seasonal scales and estimated using the following equation.

$$\mathrm{PCI}_{\mathrm{annual}} = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \tag{1}$$

where p_i is the rainfall for month i. The PCI at seasonal scales (i.e. south-west monsoon, north-east monsoon, winter and summer) was also calculated (De Luis et al., 2011). The PCI value below 10 refers to uniform monthly rainfall distribution throughout the year (same amount of rainfall in each month) as described by Oliver (1980) and Zamani et al. (2018). The values from 10 to 15 imply a moderate concentration of rainfall while the values between 16 and 20 indicate an irregular distribution; PCI values above 20 are the sign of strong irregularity in rainfall concentration. The PCI values above 15 show that total rainfall is concentrated in half of the year, and values above 25 indicated that total rainfall is reduced to one-third of the year (De Luis et al., 2011; Thomas & Prasannakumar, 2016).

Seasonality index (SI) is a powerful indicator for measuring the degree of variability of monthly rainfall (Guhathakurta & Saji, 2013; Nair et al., 2014; Walsh & Lawler, 1981). This index identifies the rainfall regime based on the monthly distribution of rainfall. Therefore, SI is computed by monthly and annual mean rainfall as Eq. 2.

$$\mathrm{SI} = \frac{1}{R} \sum_{i=1}^{12} \left| X_n - \frac{\overline{R}}{12} \right| \tag{2}$$

where X_n is the mean rainfall of month n and R is the mean annual rainfall. The classification of SI values according to Kanellopoulou (2002) is shown in Table 1.

Results

Rainfall characteristics

The statistics of annual, seasonal and monthly rainfall for the period of 1901 to 2019 over Kerala are estimated and are depicted in Table 2.

The normal annual rainfall of Kerala during the study period is 2666 mm with a standard deviation of 413.96 mm. The rainfall during the south-west monsoon accounts for 67.9% of the annual rainfall budget of Kerala, followed by the north-east monsoon (16.66%) and summer rainfall (12.43%). The coefficient of variation of annual rainfall (15.53%) shows the stability of rainfall over Kerala. The maximum and minimum ever recorded rainfalls were 3913.23 mm in 1961 and 1522.70 mm in 2005. The winter rainfall contributes only 3% of annual rainfall with a high coefficient of

Table 1 Classification of seasonality index (SI) (after Kanellopoulou, 2002)

SI	Rainfall behaviour
<0.19	Uniform rainfall throughout the year
0.20–0.39	Uniform rainfall but with a definite wetter season
0.40–0.59	Rather seasonal with a short drier season
0.60–0.79	Seasonal
0.80–0.99	Markedly seasonal with a long drier season
1.00–1.19	Most rain in 3 months or less
>1.20	Extreme, almost all rain in 1–2 months

Table 2 Monthly and seasonal distributions of rainfall for Kerala (1901–2019)

Season	Rainfall	% contribution	SD	CV	50% probability	75% probability	90% probability
January	15.75	0.60	19.18	121.70	7.86	2.81	0
February	16.69	0.62	17.34	103.9	9.17	5.12	1.09
March	38.38	1.44	31.50	82.05	29.66	18.69	12.22
April	102.76	3.85	41.18	40.07	99.90	71.78	52.00
May	190.08	7.13	117.06	61.58	154.31	112.00	83.21
June	538.44	20.20	162.52	30.18	507.60	431.37	334.41
July	632.9	23.74	210.05	33.18	637.12	500.17	353.97
August	409.23	15.35	157.26	38.42	375.22	303.21	249.08
September	229.70	8.62	106.88	46.53	210.72	143.09	90.584
October	277.60	10.42	80.72	29.07	267.86	220.30	175.09
November	166.65	6.25	85.24	51.15	153.42	96.00	68.00
December	47.31	1.78	39.97	84.48	35.99	14.83	7.20
Annual	2666.00	100.00	413.96	15.53	2681.70	2391.70	2208.80
S-w monsoon	1810.30	67.90	370.66	20.47	1783.20	1596.20	1434.61
N-e monsoon	444.24	16.66	118.04	26.57	441.86	441.86	296.13
Winter	79.76	3.00	43.73	54.83	75.07	45.40	29.03
Summer	331.24	12.43	121.69	36.73	666.80	246.07	265.52

variation (54.83%), which implies more variability of rainfall during this time. As depicted in Table 2, the south-west monsoon is the major rainy season in the state of which about 60% of the total rainfall contributed during June (20.20%), July (23.74%) and August (15.35%), which bring out the presence of a high concentration of rainfall. Rainfall during January and February is very negligible (0.6 and 0.62% of total rainfall respectively), and the coefficient of variation is also high during these months (CV > 100%), which clearly shows it is undependable. The dependable annual rainfalls at 50%, 75% and 90% probabilities over Kerala are observed as 2681.7 mm, 2391.8 mm and 2208.8 mm respectively. The dependable seasonal rainfalls at 75% for south-west monsoon, north-east monsoon, winter and summer seasons are 1596.2 mm, 441.8 mm, 45.4 mm and 246 mm respectively. It is noted that months and seasons receiving high mean rainfall show high standard deviation and less CV values compared to other months and seasons**.** The coefficient of variation of seasonal rainfall was highest in winter, followed by the summer rainfall, north-east monsoon and south-west monsoon. Figure 1b shows the spatial variation of annual rainfall from 1901 to 2019 over the state. The study is performed on 59 grid points inside the state, showing the spatial variability (800 to 4900 mm) and characteristic heterogeneity of rainfall.

Clustering

The K-means algorithm has established five homogeneous rainfall clusters of 59 grid points for the annual series, which are shown in Fig. 1c. The relative influence of geographical factors (latitude, longitude and altitude) and statistical parameters (mean, maximum and minimum rainfall, standard deviation (SD) and coefficient of variation (CV)) on mean rainfall was analysed using principal component analysis (PCA). These clusters show a clear geographical pattern, and the K-means has delineated nearby grids into different clusters because of the complexity of the terrain of the study area.

It is clear from Fig. 1c that cluster 1 and cluster 3 are characterized by the highest annual mean rainfall and located in low altitude areas, whereas CV of annual rainfall is moderate and low in the above-mentioned clusters respectively. However, the lowest annual rainfall was observed in cluster 5 with a high coefficient of variation. An in-depth examination revealed that grids of cluster 5 are mainly situated towards western parts of the state with high altitudes. Likewise, grids in cluster 2 are seen towards the northern side of Kerala with high rainfall, whereas cluster 4 is characterized by the moderate annual mean rainfall and is located in the region with low altitude.

Box–whisker plots are used as a better representation to compare different time-series data. Figure 3 depicts the temporal variation of the annual rainfall for 5 clusters. This gave a summary of five key statistics of the data distribution along with the outliers. The median of rainfall was highest in cluster 1 and lowest in cluster 5. Among all clusters, rainfall distribution is more uniform in cluster 3 as the outliers are few. It is observed from Fig. 3 that there is a clear spatial variation in the patterns of annual rainfall.

Overall, an increase in annual rainfall is observed when moving away from the high altitude of the study area to the coastal region. From Fig. 3, it is clear that annual rainfall is concentrated over a small range as the median of the annual rainfall data is above the middle of the box for most of the grids. The presence of outliers near the upper part of the box in all clusters is due to the occurrence of extreme events in the study area. The temporal variation of annual and seasonal rainfall for 5 clusters is presented using scatter plots in Fig. 4.

It is seen from Fig. 4 that annual as well as other seasonal rainfalls (except for summer) are decreasing in all clusters. The average rate of decrease of annual as well as south-west monsoon rainfalls in cluster 1 (-4.26 and -3.49 mm/year) and cluster 2 (-5.55 and -4.73 mm/year) is more compared to other clusters. It is worth mentioning that the summer rainfall, which accounts for more than 20% of annual rainfall in clusters 4 and 5, is slightly increasing in the above-mentioned region.

Like rainfall series, the rainy days (rainfall ≥ 2.5 mm/day) also decrease in all clusters (Fig. 5). The rainy days have a significant role in runoff generation and other components of the hydrological cycle. The annual average rainy days over Kerala vary from 56 to 180 show the heterogeneity and irregularity in rainy day distribution. The highest number of rainy days is experienced by clusters 1 and 3 (131 to 180), followed by clusters 2 and 4 (101 to 130). The rate of decrease of rainy days is more in cluster 3 and cluster 4 than other clusters even though annual rainfall does not show a noticeable reduction. This will lead to high-intensity rainfall for a short duration in the above-mentioned regions. It is observed that all clusters experience the maximum number of reduction in rainy days during the south-west monsoon.

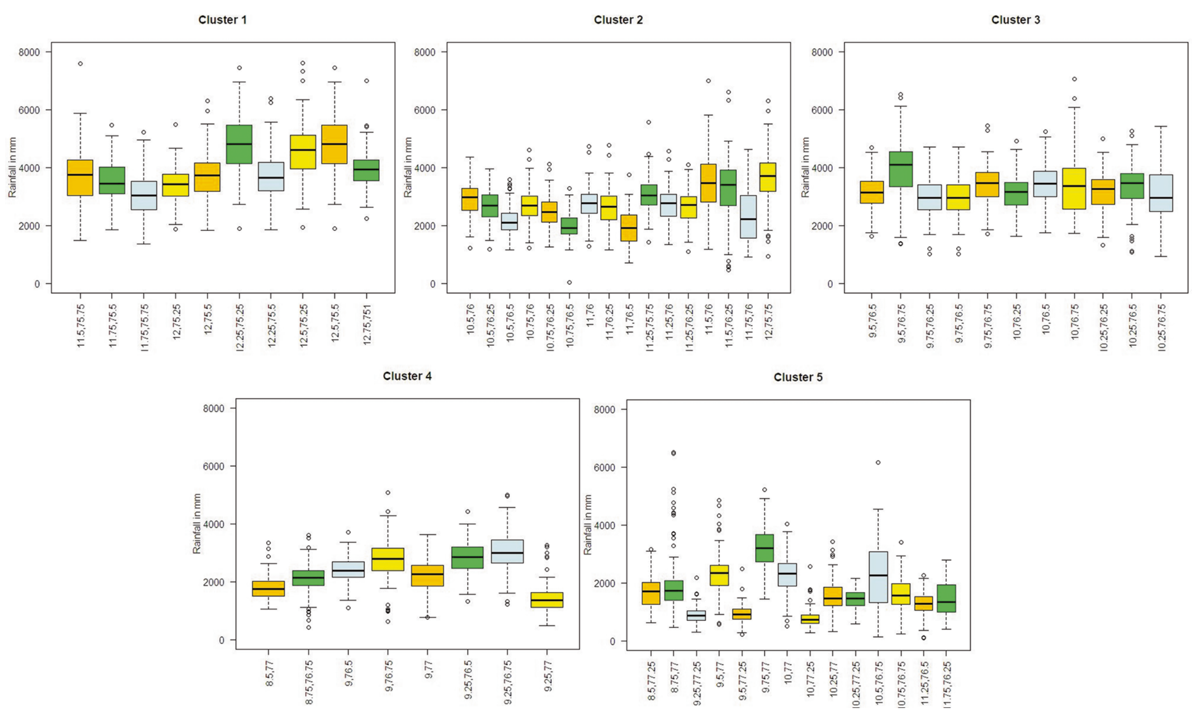

Fig. 3 Box–whisker plots of annual rainfall for 5 clusters

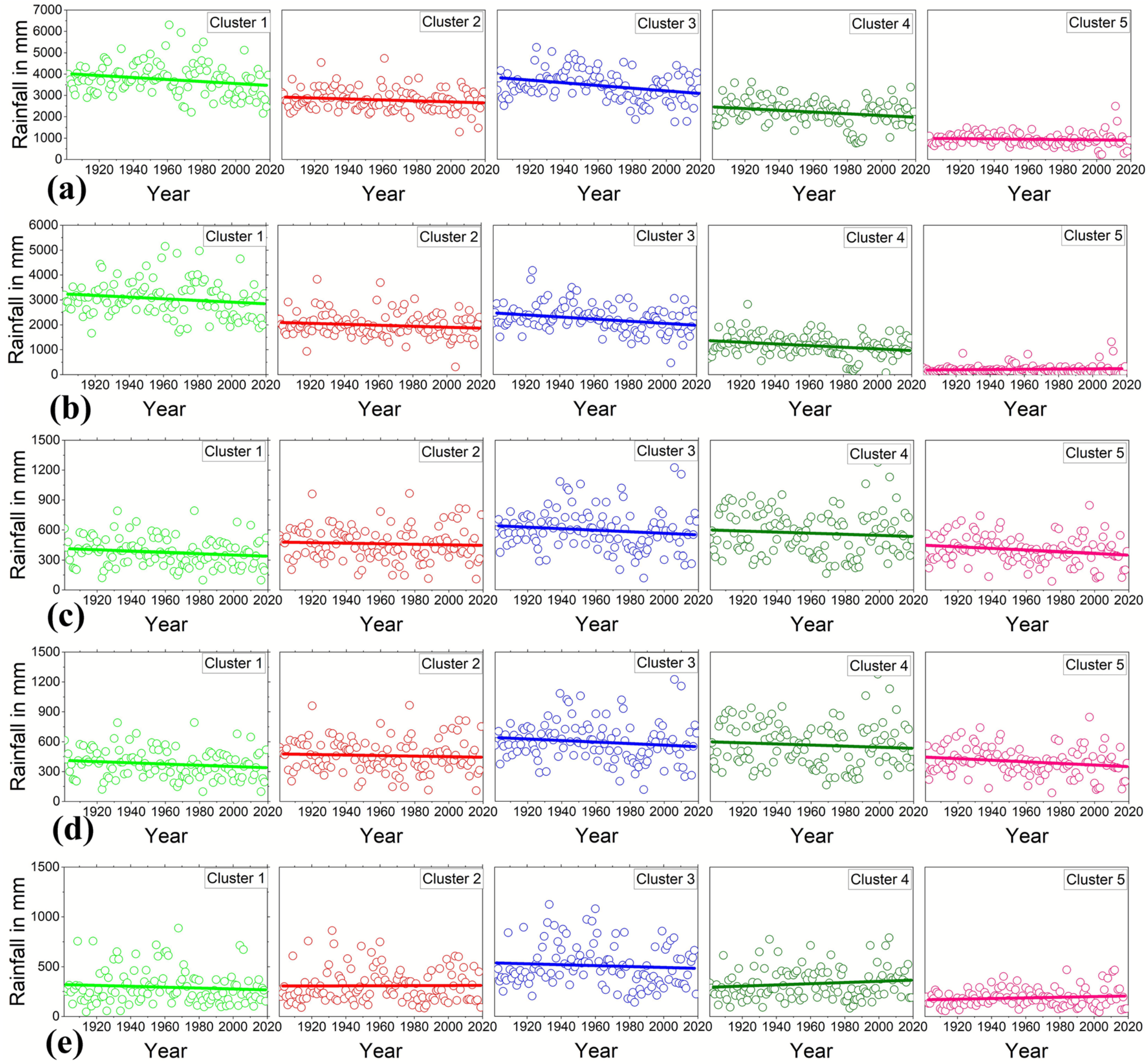

Fig. 4 Scatter plots of long-term rainfall for (**a**) annual, (**b**) south-west monsoon, (**c**) north-east monsoon, (**d**) winter rainfall and (**e**) summer rainfalls

This will lead to high intensity rainfall events during the south-west monsoon despite the reduction in rainy days. This is evident in the state of Kerala, which has been witnessing subsequent major flood events during 2018, 2019 and 2020 August month. The number of rainy days experienced by the state during 2018, 2019 and 2020 south-west monsoon was considerably less when compared to a long-term record. These extreme events resulted in the large surface runoff, which triggered an increase in natural disasters. Interestingly, summer rainy days are increasing in clusters 3 and 4.

Long-term trend of annual and seasonal rainfalls

The results of five trend analysis tests for annual and seasonal rainfall are shown in Fig. 6. It can be observed that trends discovered by the Mann–Kendall test showed some resemblance with the findings of MK-CF_1 and MK-PW test for all grid points and seasons. The MK-CF_2 and the ITA test exhibit more or less similar results in all the time series. Most of the grid points are showing negative trends, whether significant or non-significant, in all the time series.

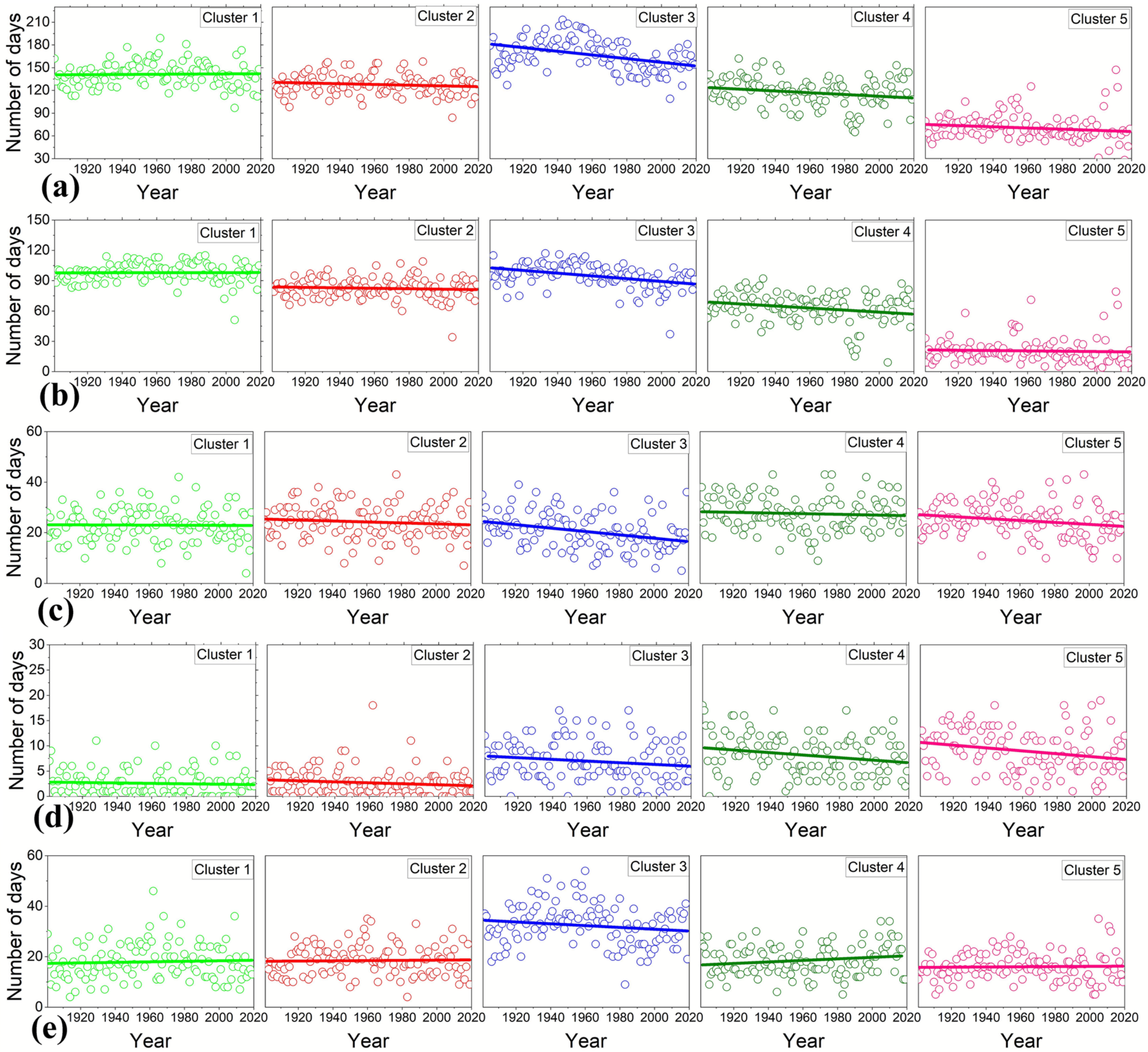

Fig. 5 Scatter plots of rainy days for (**a**) annual, (**b**) south-west monsoon, (**c**) north-east monsoon, (**d**) winter and (**e**) summer

It is seen from Fig. 6 that the Mann–Kendall test found a significant decreasing trend of annual rainfall at 31 grid points (53%) of total 59 grids, whereas MK-CF_1 and MK-PW revealed 28 (47%) statistically significant decreasing grid points. However, the MK-CF_2 and the ITA test detected a statistically decreasing trend of annual rainfall at 40 (68%) and 44 (75%) grid points. In the south-west monsoon rainfall series, MK-CF_2 and ITA tests found statistically significant decreasing trends for 37 (63%) and 43 (73%) grids, whereas Mann–Kendall test, MK-CF_1 and PWMK tests revealed a significant trend only at 32 (54%), 30 (51%) and 27 (46%) grid points respectively. Likewise, the statistical decreasing trends at 5% significance level in the north-east monsoon rainfall are unveiled for 43 (73%), 40 (68%), 23 (39%), 17 (29%) and 14 (24%) grids from the results of the ITA, MK-CF2, MK-CF1, Mann–Kendall and PWMK respectively. In the winter rainfall time series, the significant decreasing trends at 5% significance level are evident for 50 (85%), 47 (80%), 30 (51%), 28 (47%) and 26 (44%) grids from the results of the MK-CF_2, ITA, MK-CF_1, Mann–Kendall and PWMK respectively.

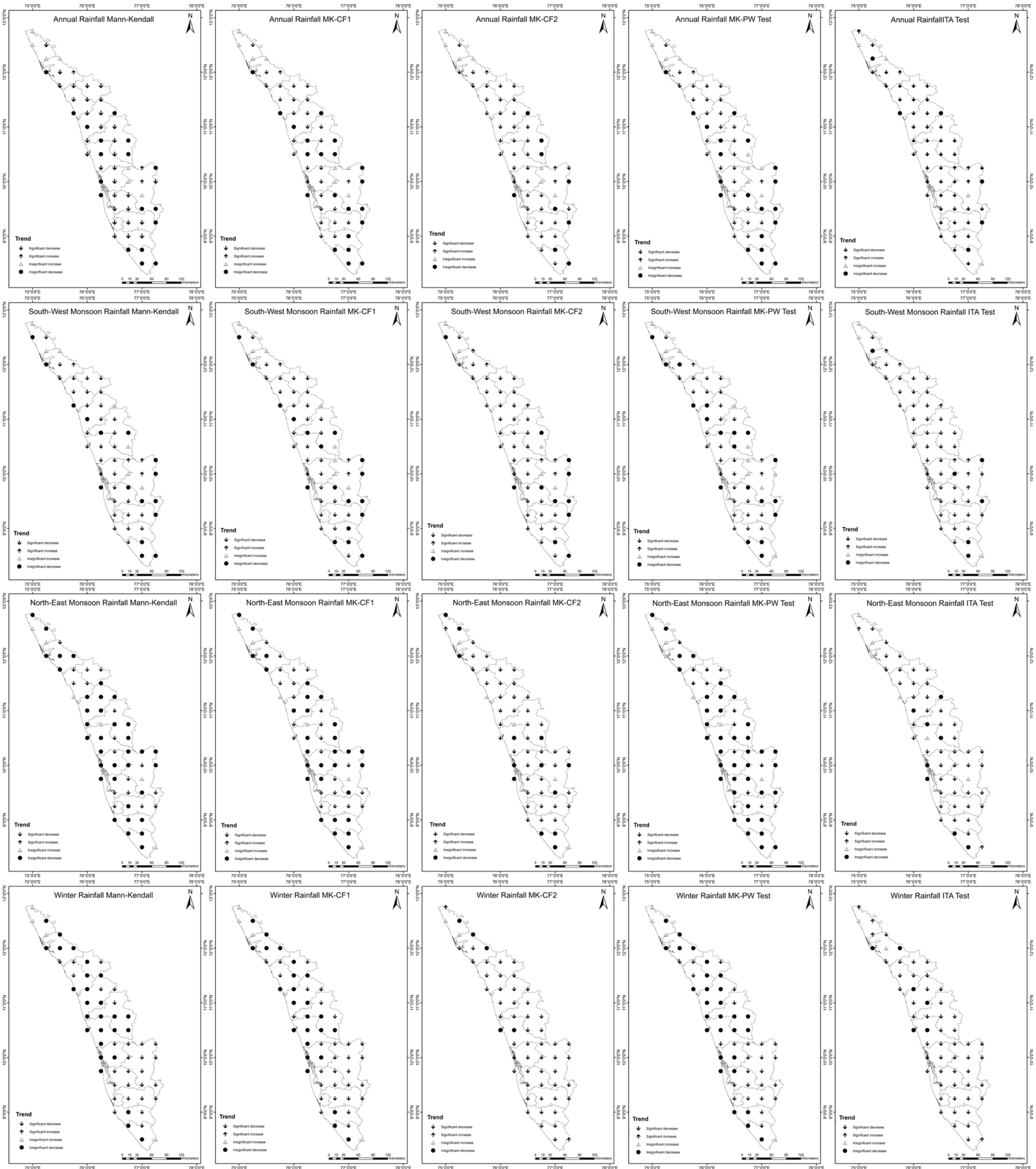

Fig. 6 Results of five trend analysis tests of annual and seasonal rainfalls

In the summer rainfall series, the Mann–Kendall test, MK-CF_1 and PWMK found statistically significant decreasing trends for 9, 8 and 7 grids respectively. On the contrary, the ITA and MK-CF_2 resulted in statistically significant decreasing trends for 39 and 17 grid points.

However, the annual rainfall is having statistically significant increasing trends at 3 (5%) grids as revealed by both the Mann–Kendall test and MK-CF_2. Both MK-CF_1 and PWMK tests identified a statistically significant increasing trend at 2 (3%) grids, whereas the ITA test suggested a significant increasing trend for 5 grids. Likewise, the statistical increasing trends at 5% significance level in the south-west monsoon rainfall are unveiled for 7 (12%), 6 (10%), 4 (7%), 3 (5%) and 3 (5%) grids from the results of the ITA, MK-CF$_2$, Mann–Kendall test, MK-CF$_1$ and PWMK respectively. Mann–Kendall test, MK-CF$_1$ and PWMK could not find any statistically significant increasing trend during the north-east monsoon and winter season. However, the ITA test and MK-CF$_2$ detected a statistically significant increasing trend for 2 (3%) and 1 (2%) grids during the north-east monsoon. In the winter season, increasing trends for 4 (7%) and 2 (3%) grids were statistically significant as revealed by the ITA test and MK-CF$_2$ respectively. In the summer rainfall series, the Mann–Kendall test and PWMK identified statistically significant increasing trends for one grid. On the contrary, both the ITA and MK-CF$_2$ found statistically significant increasing trends for four grid points, whereas MK-CF$_1$ discovered a significant trend only for one grid.

It is seen that more than 83% of grid points are showing negative trends whether significant or non-significant in annual and south-west monsoon rainfall series. However, in the case of north-east monsoon and winter rainfall, more than 90% of the grid points are showing a negative trend (both significant and non-significant), making it a subject of concern. On the contrary, when compared to other seasons, the grid points (69%) corresponding to the decreased rainfall in summer are fewer. More than 30% of the grid points are showing increasing rainfall during the summer season.

Trends in annual and seasonal rainy days

Results of five trend analysis techniques indicating a significant and non-significant trend in annual and seasonal rainy days are depicted in Fig. 7. In the annual rainy days series, the significantly decreasing trends at 5% significance level are identified for 44 (75%), 36 (61%), 31 (53%), 42 (71%) and 47 (80%) grids from the results of Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA test respectively. However, at $\alpha = 5\%$, 4 (7%) and 3 (5%) grids were having significantly increasing trends based on the results of the Mann–Kendall test and ITA test, whereas the significantly increasing trend at 2 grids (3%) was detected by MK-CF$_1$, PWMK and MK-CF$_2$.

Likewise, the statistically significant decreasing trends in the south-west monsoon rainy days are unveiled for 35 (59%), 34 (58%), 29 (49%), 37 (63%) and 45 (76%) grids from the results of the Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA tests respectively. The statistically significant rising trends of rainy days in south-west monsoon are perceived from the results of the Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA tests for 4 (7%), 2 (3%), 3 (5%), 3 (5%) and 4 (7%) grids respectively.

Similarly, in north-east rainy days, a significantly decreasing trend is evident for 29 (49%), 33 (56%), 26 (44%), 42 (71%) and 48 (81%) grids from the results of the Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA tests respectively. The Mann–Kendall test, MK-CF$_1$ and PWMK identified a statistically significant increasing trend in north-east rainy days at 1 (2%) grid, whereas both MK-CF$_2$ and ITA tests unveiled the trend at 2 (3%) grids. In winter rainy days, the Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA tests discovered a statistically significant decreasing trend for 34 (58%), 34 (58%), 24 (41%), 43 (73%) and 42 (71%) grids respectively at $\alpha = 0.05$. However, the Mann–Kendall test, MK-CF$_1$ and PWMK could not find any significant increasing trend, whereas MK-CF$_2$ and ITA tests confirmed statistically significant increasing trends for 1 (2%) and 4 (7%) grids at a similar significance level.

The rainy days in the summer season were found to be significantly decreasing for 17 (29%), 16 (27%), 16 (27%), 20 (34%) and 39 (66%) grids by Mann–Kendall test, MK-CF$_1$, PWMK, MK-CF$_2$ and ITA tests at 5% significance level. The Mann–Kendall test, MK-CF$_1$ and PWMK identified a statistically significant increasing trend in summer rainy days at 2 (3%) grid, whereas both MK-CF$_1$ and ITA tests unveiled the trend at 6 (10%) grids.

It is apparent from the above results that more than 88% of grid points are showing negative trends, whether significant or non-significant, in annual and south-west monsoon rainy days series. However, more than 90% of the grid points are showing a negative trend (both significant and non-significant) in the north-east monsoon and winter rainy days. Contrariwise, when compared to other seasons, the grid points (75%) corresponding to the summer season rainy days show a decreasing trend, whereas the increasing trends are evident for more than 25% of the grid points.

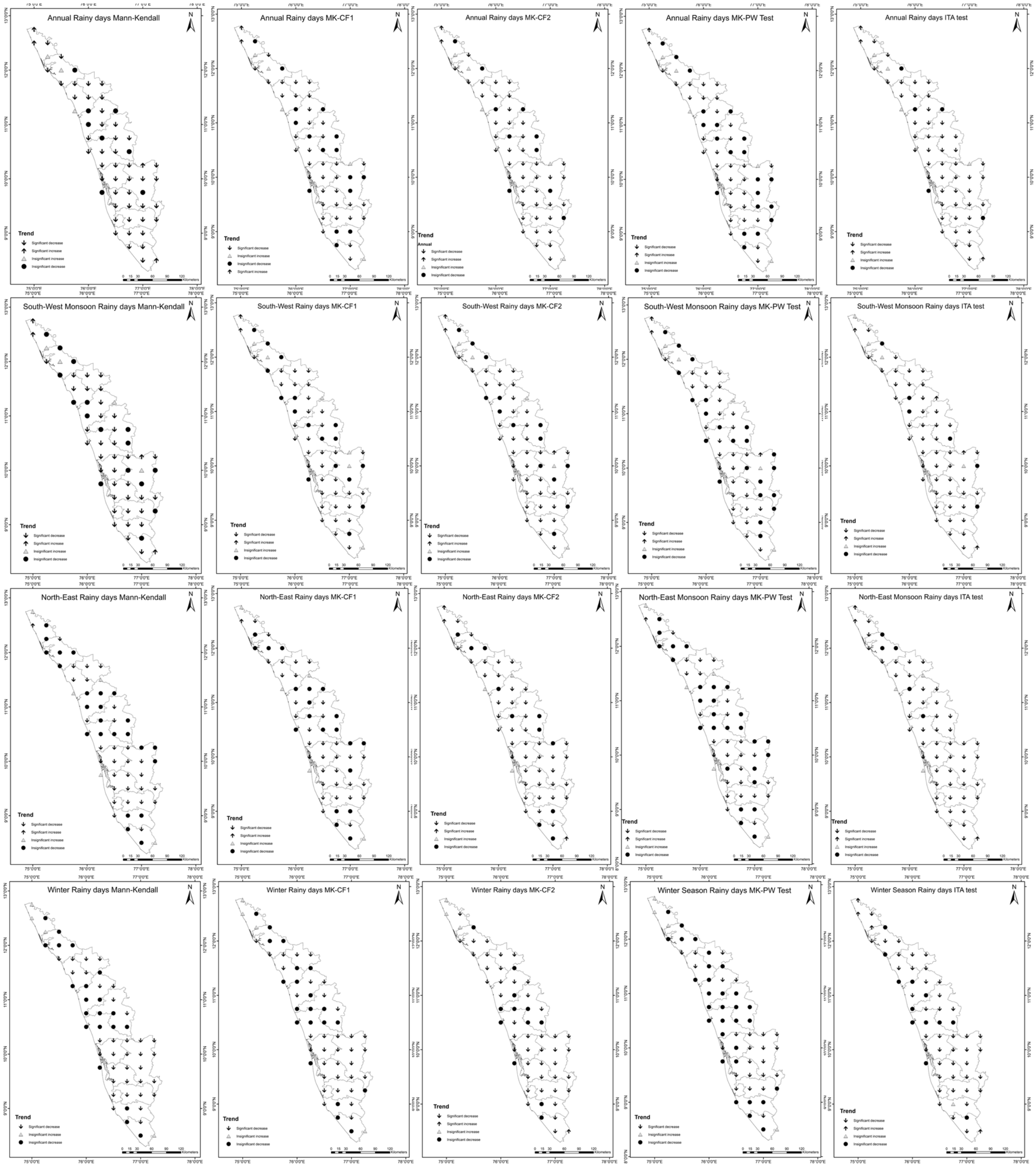

Fig. 7 Results of five trend analysis tests of annual and seasonal rainy days

The magnitude of rainfall and rainy days' trend

Table 3 shows the magnitude of the increasing and decreasing trend in annual and 4 seasonal time series of rainfall and rainy days calculated using Sen's slope test for 59 grids. It is seen from Table 3 that annual rainfall is varying at a range from − 17.38 to 7.6 mm/year with a mean value of − 3.97 mm/year.

The rainfall during the south-west monsoon, north-east monsoon, winter and summer season is changing at rates varying from − 15.3 to 8.0, − 7.0 to 0.48, − 1.16 to 0.39, − 1.74 to 0.7 mm/year respectively with the

Table 3 Trend magnitude in rainfall and rainy days at 59 grid points (1901–2019)

Grids	Annual		South-west monsoon		North-East monsoon		Winter		Summer	
	Rain	R.D	Rain	RD	Rain	RD	Rain	RD	Rain	RD
1	−1.45	−0.10	−1.10	−0.07	−0.10	−0.01	−0.21	−0.01	0.13	0
2	−0.72	0.16	−0.16	0.10	0.17	0.04	0.39	0.01	−0.47	−0.02
3	−2.06	−0.10	−2.29	−0.11	−0.26	−0.01	−0.17	0	0.34	0
4	−2.07	−0.19	−0.79	−0.08	−0.66	−0.04	−0.72	−0.06	0.03	−0.01
5	−3.90	−0.28	−2.74	−0.13	−0.60	−0.06	−0.28	−0.02	−0.24	−0.05
6	−6.24	−0.11	−4.43	−0.10	−1.16	−0.02	−0.24	0	−0.55	0
7	−3.10	−0.11	−2.82	−0.06	−0.84	−0.02	−0.61	−0.03	0.50	0.01
8	−6.80	−0.34	−4.30	−0.15	−1.09	−0.07	−0.49	−0.04	−0.89	−0.07
9	−6.13	−0.41	−4.13	−0.17	−0.96	−0.08	−0.49	−0.04	−1.04	−0.11
10	−4.54	−0.33	−2.20	−0.17	−1.49	−0.06	−0.89	−0.05	−0.27	−0.03
11	−0.94	−0.08	−0.08	0	−0.83	−0.03	−0.87	−0.02	0.17	0
12	−7.66	−0.39	−4.52	−0.15	−1.42	−0.08	−0.64	−0.05	−1.02	−0.10
13	−15.48	−0.60	−11.80	−0.21	−2.25	−0.12	−0.82	−0.08	−1.74	−0.17
14	−3.09	−0.19	−2.37	−0.12	−0.47	−0.04	−0.80	−0.04	−0.08	0
15	−1.29	−0.10	−0.20	−0.05	−0.77	−0.04	−0.77	−0.03	0.02	0
16	−1.43	−0.05	−1.07	−0.04	−0.18	0	−0.10	0	0.59	0.02
17	−6.43	−0.31	−4.95	−0.16	−0.74	−0.04	−0.37	−0.02	−0.73	−0.08
18	−4.73	−0.44	−1.98	−0.14	−1.28	−0.10	−0.83	−0.07	−1.03	−0.12
19	2.13	−0.07	1.71	−0.01	0.15	−0.04	−0.58	−0.05	0.51	0
20	−2.88	−0.30	−2.44	−0.14	−0.26	−0.05	−0.15	−0.03	−0.53	−0.06
21	−5.76	−0.25	−3.92	−0.12	−0.88	−0.05	−0.27	−0.02	−0.36	−0.03
22	0.83	−0.19	2.82	−0.04	−0.81	−0.07	−0.57	−0.05	−0.32	−0.03
23	4.54	−0.13	6.20	0.04	−0.98	−0.07	−0.81	−0.07	0.18	−0.01
24	−1.28	−0.13	−0.04	−0.02	−0.29	−0.03	−0.58	−0.03	−0.26	−0.02
25	−6.07	−0.32	−4.42	−0.16	−0.75	−0.06	−0.20	−0.02	−1.17	−0.08
26	−7.14	−0.28	−3.90	−0.13	−1.98	−0.08	−0.10	−0.02	−1.61	−0.06
27	4.14	−0.39	5.38	−0.11	−1.01	−0.13	−0.41	−0.04	−0.32	−0.09
28	3.87	0.31	5.12	0.30	−0.78	−0.04	−0.67	−0.04	0.05	0.03
29	−1.33	−0.16	−0.43	−0.06	−0.34	−0.03	−0.89	−0.05	−0.43	−0.02
30	−4.29	−0.10	−3.70	−0.06	−0.77	−0.02	−0.02	0	−0.08	−0.01
31	−2.47	−0.16	−2.63	−0.08	−0.24	−0.03	−0.04	0	0.18	−0.04
32	−3.36	−0.11	−2.42	−0.07	−0.65	−0.03	−0.09	0	−0.10	0
33	−0.89	−0.06	0.50	0	−0.33	−0.03	−0.17	−0.01	−0.08	0
34	−3.87	−0.20	−2.94	−0.10	−0.63	−0.05	−0.08	0	−0.49	−0.05
35	−1.89	−0.04	−1.63	−0.02	0.01	0	−0.06	0	−0.06	0
36	−3.25	−0.15	−2.60	−0.10	−6.99	−0.05	−0.09	0	0.07	0
37	−2.47	−0.16	−1.44	−0.07	−0.55	−0.04	−0.15	−0.01	−0.24	0
38	−1.76	−0.04	−1.82	0	−0.54	−0.02	−0.08	0	0.15	0
39	−5.63	−0.11	−4.81	−0.07	−0.73	−0.02	−0.07	0	−0.36	−0.01
40	−10.20	−0.29	−8.18	−0.17	−1.20	−0.06	−0.17	−0.01	−0.60	−0.04
41	−1.21	0	−1.54	−0.01	0.19	0	−0.10	0	0.21	0.03
42	−3.43	0	−2.61	−0.02	−0.60	0	−0.08	0	0.06	0.01
43	−6.51	−0.15	−5.42	−0.11	−0.63	−0.02	−0.21	−0.03	−0.16	0
44	−0.66	−0.07	1.01	0.03	−0.48	−0.03	−1.16	−0.05	−0.30	−0.01
45	−15.16	−0.22	−12.62	−0.09	−1.58	−0.07	−0.24	−0.02	−0.46	−0.05
46	−17.38	−0.19	−15.30	−0.14	−1.23	−0.04	−0.11	0	−0.34	−0.01
47	−14.97	−0.18	−13.54	−0.15	−0.55	0	−0.12	0	−0.59	0
48	−5.62	−0.12	−3.98	−0.03	−0.67	−0.03	−0.17	−0.01	−0.45	−0.03
49	−12.17	−0.22	−9.28	−0.08	−1.88	−0.09	−0.23	−0.02	−0.83	−0.04
50	−16.19	−0.23	−14.75	−0.15	−0.94	−0.05	−0.08	−0.01	−0.30	−0.01
51	−12.02	−0.60	−10.44	−0.48	−1.00	−0.07	−0.16	−0.02	−0.41	−0.03
52	−2.28	−0.10	−2.17	−0.05	−0.04	−0.01	−0.03	0	−0.21	−0.02
53	−4.97	0.01	−4.06	0.02	−0.70	0	−0.04	0	−0.42	0
54	7.60	−0.01	7.99	0	−0.46	−0.01	−0.01	0	−0.18	0.03
55	1.68	0	1.46	0	0.20	0	0.02	0	0.26	0
56	2.87	−0.10	3.90	−0.02	−0.95	−0.05	−0.04	0	−0.20	0
57	−8.46	0.24	−7.84	0.08	−0.45	0	−0.01	0	−0.22	0.07
58	0.59	−0.08	−0.37	−0.02	0.48	−0.03	0.01	0	0.37	−0.03
59	0.90	0.16	0.05	0.04	−0.02	0.03	0.02	0	0.70	0.08

mean values of − 2.83, − 0.79, − 0.31 and − 0.26 mm/year respectively.

Moreover, the annual rainy days is found to be varying at a range from − 0.6 to 0.31 days/year with the mean value of − 0.15 days/year. Similarly, the rainy days during the south-west monsoon, north-east monsoon, winter and summer season are altering within − 0.48 to 0.3, − 0.13 to 0.04, − 0.08 to 0.01 and − 0.17 to 0.08 days/year respectively with the mean rates of − 0.07, − 0.04, − 0.02 and − 0.02 days/year respectively.

Temperature characteristics

The summary statistics of monthly, seasonal and annual temperatures (mean temperature, maximum temperature and minimum temperature) for the period 1951 to 2019 are presented in Table 4.

At the annual scale, the average values of mean, maximum and minimum temperatures ($T_{mean,}$ T_{max} and T_{min}) for 69 years were 24.7 °C, 28.8 °C and 20.4 °C respectively. The ever recorded maximum temperature is 37.6 °C which was measured in 2016, whereas 20.8° C (1956) is the lowest temperature measured from 1951 to 2019. According to IMD, 2016 was the warmest year on the record since 1901. The annual mean temperature over India for the year 2016 was 0.87 °C above the 1971–2000 average followed by 2009 (0.85° C). From Fig. 1c, it is evident that there is a strong gradient in mean temperature over Kerala from 1951 to 2019.

Trends in annual and seasonal temperature

From Fig. 8, it is evident that annual and seasonal mean temperatures are increasing in all 5 grids. Compared to other grids, the mean temperature is high in grids 4 and 5, which is mainly situated towards southern parts of the state. The temperature is the least in grid 3, which is located in the central part of the state. There is an overall increase in mean temperature observed when moving from the northern to the southern part of the study area.

Results of 5 trend tests for the mean temperature of annual and seasonal time series in the study are presented in Fig. 9. It is seen that in annual as well as 4 seasonal (south-west monsoon, north-east monsoon, winter and summer) mean temperature series, Mann–Kendall test, MK-CF_1, PWMK, MK-CF_2 and ITA tests at 5% significance level identified statistically significant increasing trends for all 5 grids.

Likewise, in the case of annual and 4 seasons, the Mann–Kendall test, MK-CF_1, PWMK, MK-CF_2 and ITA tests evidenced the statistical significant increasing trends in the maximum temperature series of all 5 (100%) grids at $\alpha = 5\%$ (Fig. S1). It is seen that the minimum temperature in annual, south-west monsoon and north-east monsoon was found to be significantly increased for all grids by the Mann–Kendall test, MK-CF_1, PWMK, MK-CF_2 and ITA tests at $\alpha = 5\%$ (Fig. S2).

The Mann–Kendall test, MK-CF_2 and ITA tests identified a statistically significant increasing trend in winter season minimum temperature at 4 (80%) grids, whereas PWMK discovered a significant trend at 2 (40%) grid only. Likewise, the MK-CF_1 unveiled a statistically significant increasing trend at one grid (5% significance level).

The summer season minimum temperature is having a significantly increasing trend at all 5 grids (100%) as revealed by MK-CF_2 and ITA tests at $\alpha = 5\%$. On the contrary, MK-CF_1 and PWMK resulted statistically significant increasing trends for 2 (40%) grids, whereas the Mann–Kendall test discovered a significant trend at 3 grids at a similar significance level.

Magnitude of the temperature trend

The magnitude of increasing trends in annual and seasonal time series of mean temperature, maximum temperature and minimum temperature that was quantified by the Sen slope test is summarized for 5 grids in Table 5. It is seen from the table that annual as well as seasonal mean temperatures are increasing at a rate ranging from 0.1 to 0.2 °C/decade. Likewise, the maximum temperature in annual, south-west monsoon, north-east monsoon, winter and summer seasons is increasing at a rate of 0.2 °C/decade.

Similarly, the magnitude of minimum temperature is found to be increasing in the annual, south-west monsoon, north-east monsoon, winter and summer seasons at a magnitude of 0.1 °C/decade. However, the winter as well as summer minimum temperatures at 1 of 5 grid points have no change.

Table 4 Monthly and seasonal means of temperature (°C) over Kerala for 69 years (1951–2019)

Seasons	Mean (°C)			Maximum (°C)			Minimum (°C)		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
January	25.3	23.0	24.2	30.8	28.5	29.7	20.1	17.1	18.6
February	26.5	24.3	25.3	32.3	29.6	31.0	20.8	18.0	19.6
March	28.4	25.5	26.8	34.1	30.5	32.4	22.7	20.0	21.2
April	29.6	26.6	27.7	35.0	31.0	32.7	24.3	21.6	22.6
May	28.8	25.7	27.4	33.7	29.7	32.0	24.0	21.7	22.8
June	27.1	24.2	25.5	31.1	27.3	29.2	23.0	21.0	21.8
July	26.1	23.7	24.8	30.1	26.6	28.2	22.2	20.7	21.4
August	26.2	24.2	24.8	30.1	27.1	28.3	22.2	20.8	21.4
September	26.3	24.3	25.3	30.6	27.6	29.1	22.2	20.8	21.3
October	26.1	24.2	25.2	30.6	27.5	29.3	22.0	20.3	21.2
November	25.8	23.8	24.7	30.6	27.3	29.1	21.5	18.7	20.4
December	25.5	23.2	24.3	30.4	27.7	29.2	21.2	17.5	19.3
Annual	26.5	24.7	25.5	31.2	28.8	30.1	21.7	20.4	21.0
S-w	26.1	24.2	25.1	30.1	27.2	28.7	22.3	21.0	21.5
North-east	25.8	24.2	25.0	30.6	27.7	29.2	21.6	19.7	20.8
Winter	25.6	23.9	24.6	31.1	28.9	30.0	21.1	18.1	19.2
Summer	28.7	26.3	27.3	34.0	31.0	32.3	23.4	21.4	22.2

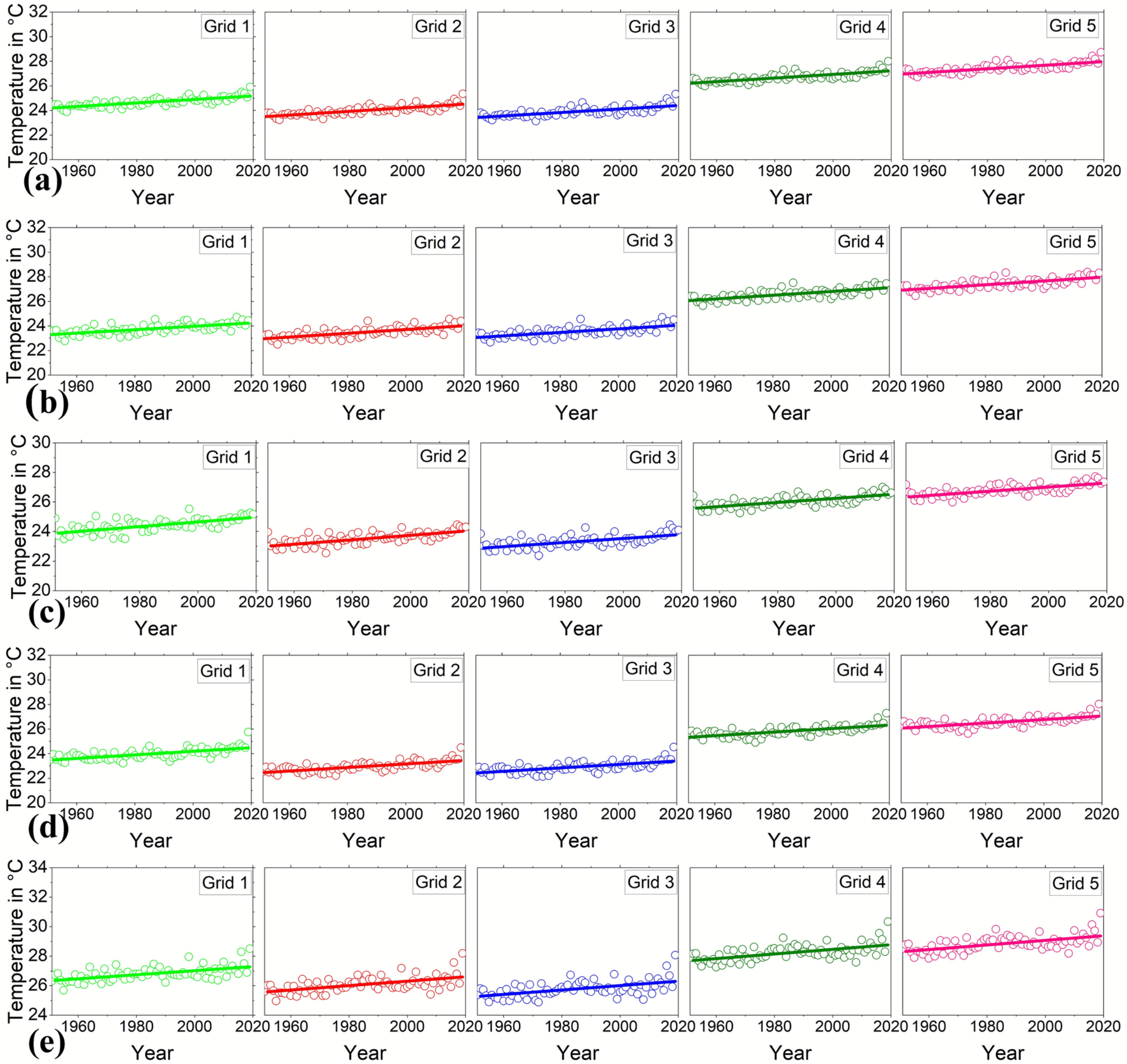

Fig. 8 Scatter plots of long-term mean temperature for (**a**) annual, (**b**) south-west monsoon, (**c**) north-east monsoon, (**d**) winter and (**e**) summer

Rainfall concentration and pattern change

The annual scale of precipitation concentration index (PCI) calculated for 5 clusters in the study area varies from a minimum of 13 (moderate concentration) in cluster 4 to a maximum of 28 (high concentration) in cluster 1, which indicates that PCI distribution is not uniform over the state (Fig. 10a). In general, if the PCI value is less than 10, it represents the uniform distribution of rainfall in all months, whereas if the PCI values vary from 11 to 20, it indicates the seasonality of rainfall distribution and values above 20 indicates strong irregularity in rainfall distribution (De Luis et al., 2011; Thomas & Prasannakumar, 2016; Zhang et al., 2019).

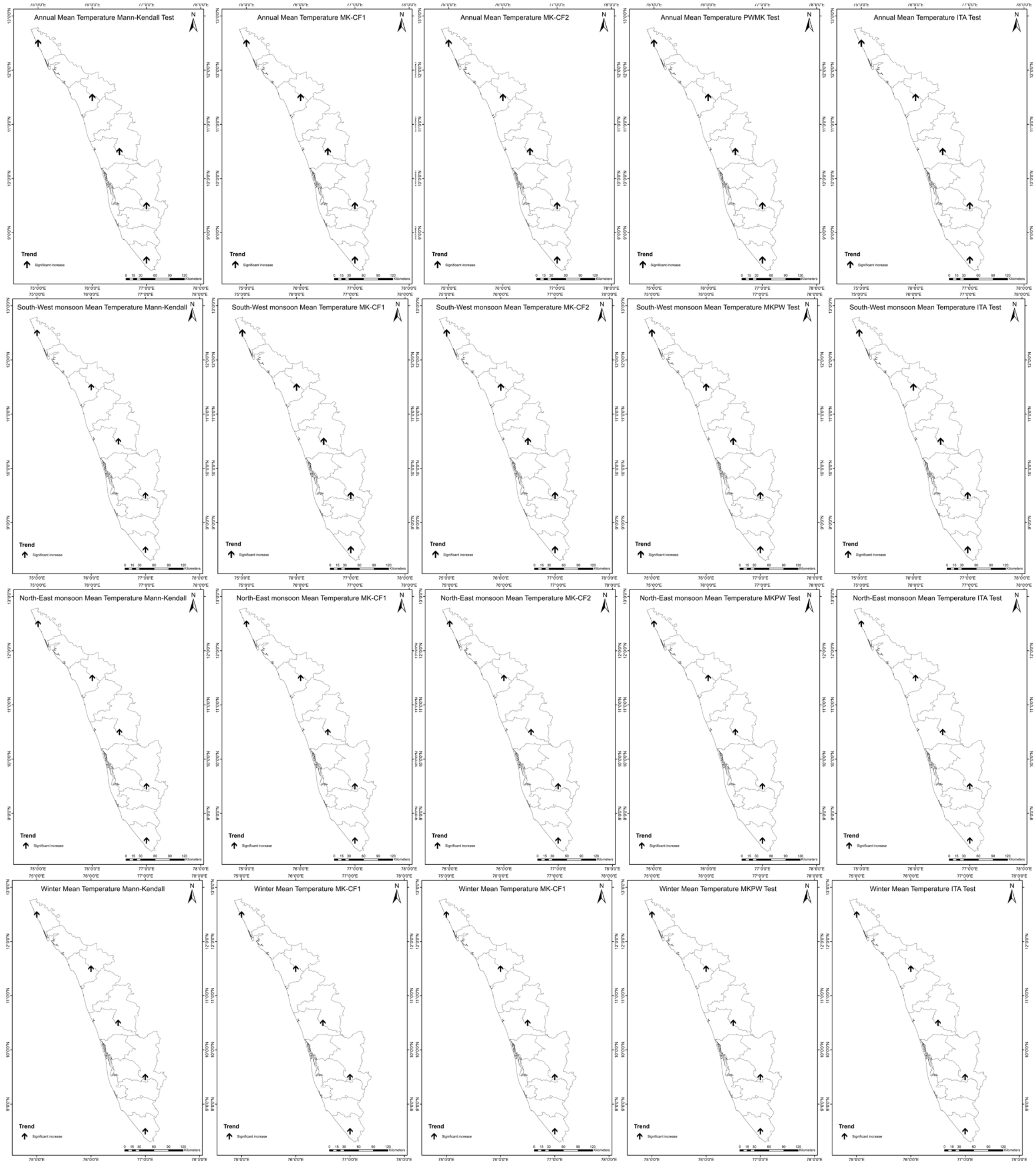

Fig. 9 Results of five trend analysis tests of annual and seasonal mean temperatures

It is noted that, in general, higher values of PCI are observed in clusters 1, 2 and 5 while lower values are detected in cluster 3 and cluster 4. There is a significant variation in PCI values noticed in clusters 1, 2 and 5. A clear gradient of change in the PCI values as moving from southern Kerala to northern Kerala (Fig. 10a) is noted. It is evident that mean PCI (21–23) values in northern parts of the state are higher than the southern and central parts of the state (13.7 to 20). The high value of PCI in northern parts

Table 5 Trend magnitude in temperature at 5 grid points (1951–2019)

Grids	Annual			SW			NE			Winter			Summer		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
1	0.01	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
2	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
3	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
4	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01
5	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01

of the state indicates that the majority of the annual rainfall occurs in a few months of the year, and it will lead to an increase in dry days, leaving the area vulnerable to the scarcity of water in non-rainy seasons. It is interesting to note that there is an abnormal increase in PCI values in all clusters after 2016**.**

The PCI values were calculated seasonal wise to know the pattern of seasonal rainfall distribution in these periods (Fig. 11). On the seasonal scale, the south-west monsoon shows the least variability compared to other seasons. In all 5 clusters, the PCI value was less than 12 during the study period (range: 8.3 to 12). This indicates that rainfall concentration is uniform during the south-west monsoon in all 5 clusters. But PCI values of north-east monsoon, winter season and summer vary from 8.3 to 25 in all clusters. This gives an insight into the highly irregular pattern of rainfall during the season.

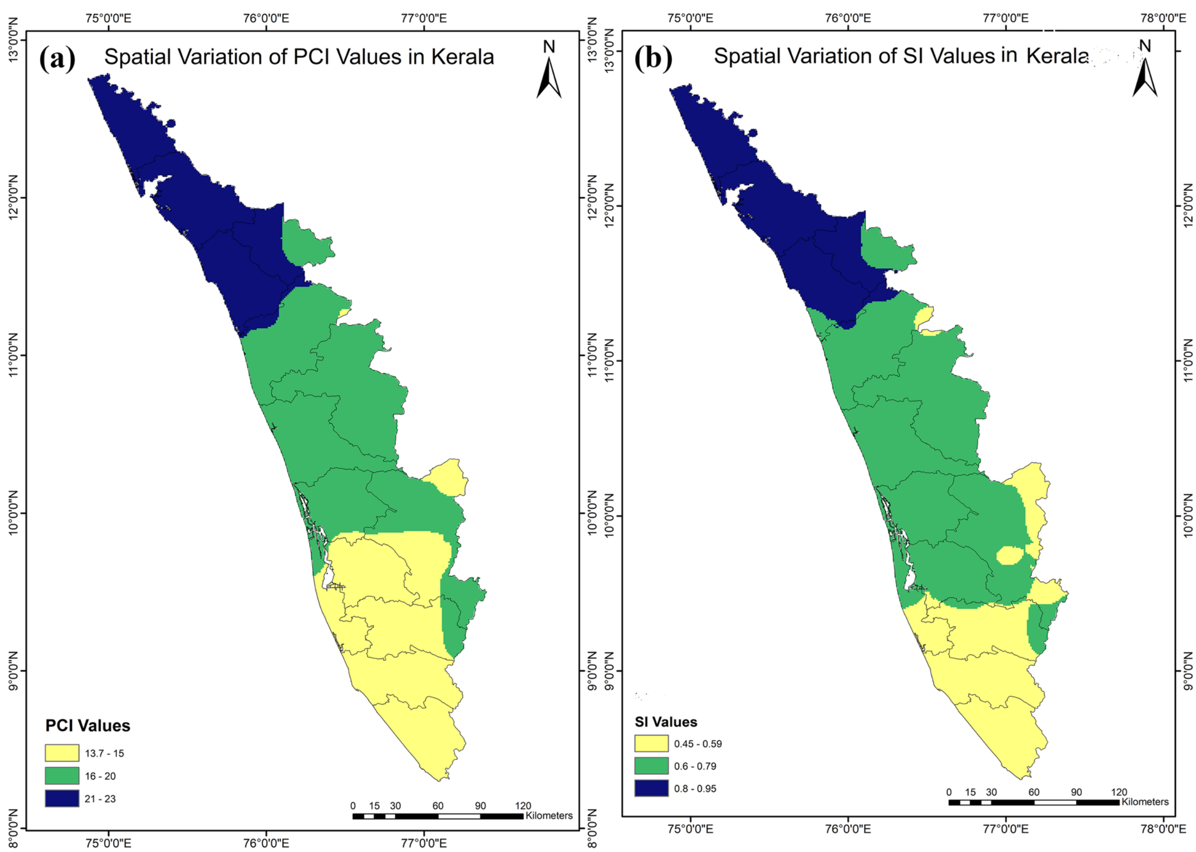

Fig. 10 (**a**) Spatial variation of mean PCI values. (**b**) Spatial variation of SI values over Kerala

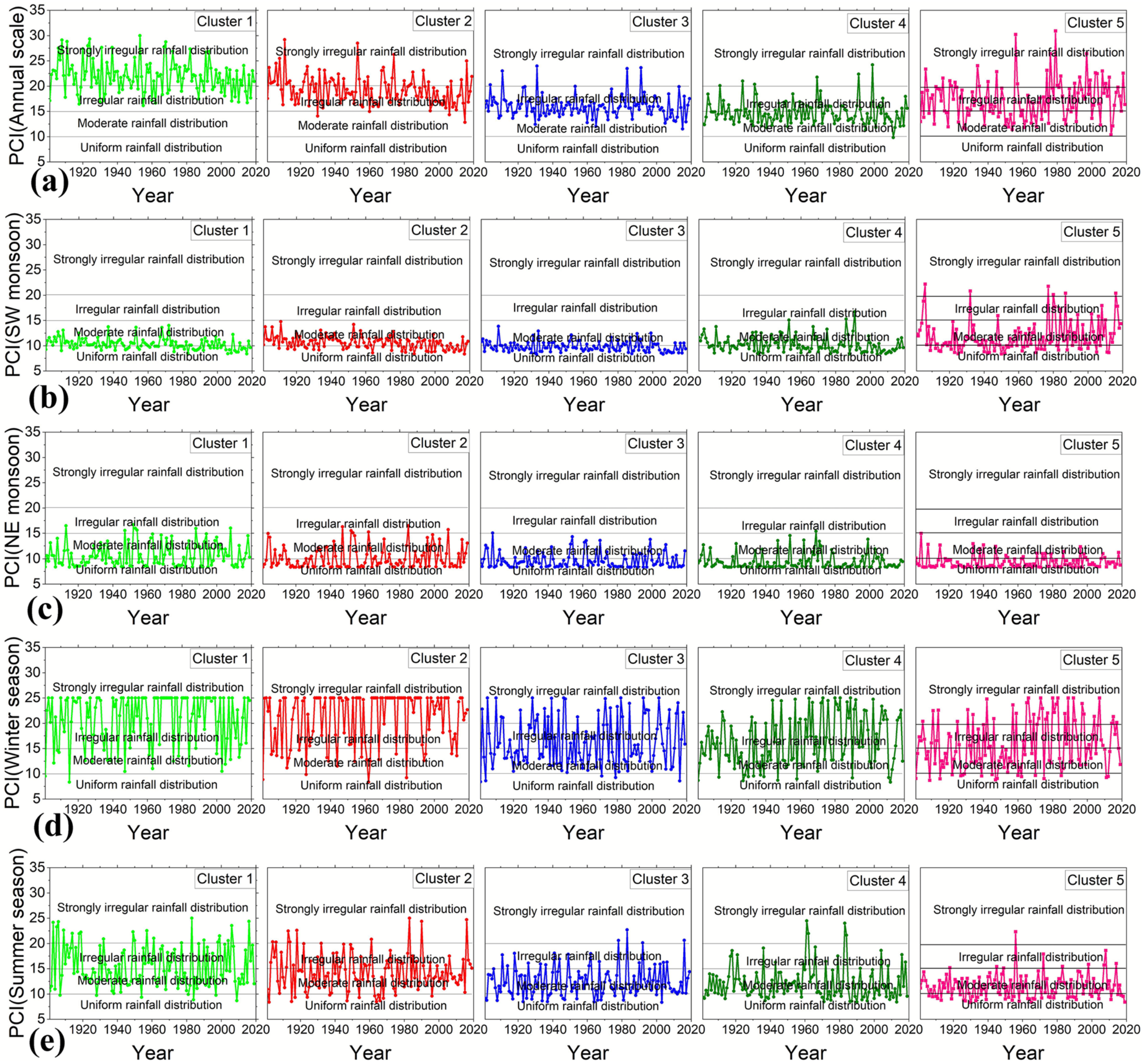

Fig. 11 Temporal variation of precipitation concentration index (PCI) of (**a**) annual rainfall, (**b**) south-west monsoon, (**c**) north-east monsoon, (**d**) winter and (**e**) summer

Seasonality index

The degree of variability in monthly rainfall can also be estimated using the seasonality index. Figure 10b presents the spatial variation of SI values over Kerala from 1901 to 2019, which depicts the substantial variation in the distribution of rainfall throughout the year.

The value of SI ranges from a minimum of 0.45 in the southern part of Kerala (short dry seasons) to a maximum of 0.95 in the northern parts of the state (long dry season). The lower value of the SI indicates a better distribution of rainfall. These findings support the spatial variation of PCI over the state.

Discussion

The study on long-term trends of climate variables and indices of Kerala was carried out considering the geographical features of the state as well as its dependency on the monsoon. The annual average rainfall over Kerala from 1901 to 2019 is 2666 mm of which 67.9% share of rainfall was received during the south-west monsoon. The coefficient of variation of annual rainfall and south-west monsoon shows the stability of rainfall in the state as the coefficient of variation is low. At the same time, rainfall during winter and summer is not dependable as the value of the coefficient of variation is very high. Even though the contribution of the north-east monsoon to the annual rainfall budget is 16.66%, it has got a signifiycant role in the agricultural sector of the state.

The spatial variation of annual rainfall over the state is depicted in Fig. 1b. Most of the previous studies have used area-averaged rainfall data for trend detection (Krishnakumar et al., 2009; Nair et al., 2014; Simon & Mohankumar, 2004; Thomas & Prasannakumar, 2016), which only represents an average variation of rainfall over the state. The high-resolution gridded data used in the present study has demonstrated the heterogeneity of rainfall, which varies from 800 to 4900 mm. The K-means clustering algorithm grouped the 59 grid points in the state based on geographical factors and statistical parameters into 5 rainfall clusters. It is observed that grid points in clusters 1 and 3 are characterized by the highest annual rainfall and are located in low altitude areas. The lowest annual rainfall was noticed in cluster 5 with a high coefficient of variation. The grids with high altitude situated in the western parts of the state constitute the cluster 5. The topography of the Western Ghats plays an important role in rainfall distribution over the state. Studies reported that the maximum intensity of rainfall is not at the crest of the Western Ghats but at a distance from the crest on the windward side. Rainfall distribution also depends on the mountain barrier, steepness of windward side slope and altitude of the mountain (Mudbhatkal & Amai, 2018; Tawde & Singh, 2015).

The annual rainfall showed a significant increase when moving from the southern to northern sides of the state. More than 70% of annual rainfall is contributed by the south-west monsoon in cluster 1 and cluster 2, whereas the south-west monsoon only accounts for 40 to 50% of annual rainfall in clusters 4 and 5. It is observed that grids in cluster 3 receive more than 65% of the annual rainfall during south-west monsoon, whereas the contribution of north-east monsoon to the annual rainfall budget is more than 15%. On the contrary, the contribution of north-east monsoon (24 to 28%), winter (5 to 8%) and summer (16 to 18%) rainfalls is more in clusters 4 and 5. This is due to the absence of Western Ghats in the southern end; there could be the least influence of the north-east monsoon in clusters 4 and 5. The grids in cluster 1, 2 and 3 receive more than 85% of annual rainfall during June to November (south-west monsoon and north-east monsoon), which shows a strong irregularity in annual rainfall distribution in these clusters. It is noted that less than 10% of annual rainfall is contributed by winter as well as summer season together in clusters 1 and 2, which leads to short-term drought in these areas.

The temporal variation of annual as well as other seasonal rainfalls in 5 clusters indicated (Fig. 4) that the magnitude of trend is not uniform throughout the state. It is interesting to note that summer rainfall is increasing in clusters 4 and 5, whereas annual as well as other seasonal rainfalls are decreasing in all clusters. The rate of decrease of annual as well as south-west monsoon rainfalls is more in cluster 1 and cluster 2, and these grids are situated in the northern parts of the state. It is worth mentioning that the contribution of south-west monsoon as well as summer rainfalls to the annual rainfall budget is increasing. In contrast, the share of winter rainfall is considerably decreasing in all clusters. The significant reduction in the contribution of the north-east monsoon in clusters 1 and 2 is also evident. On the contrary, the influence of the north-east monsoon in clusters 4 and 5 is stable because of the absence of the Western Ghats barrier against the north-easterly winds. These findings were justified with earlier studies on the analysis of monsoon rainfall of the state (Nair et al., 2014; Vijay et al., 2021).

In the case of annual as well as south-west monsoon rainfall time series, more than 83% of grid points had a negative trend based on the results from five non-parametric tests. The decreasing trend of annual and south-west monsoon rainfall was reported by various researchers (Krishnakumar et al., 2009; Nair et al., 2014; Thomas & Prasannakumar, 2016; Vijay et al., 2021). During the north-east monsoon and winter season, the rainfall was found to be decreasing at more than 90% of the grid points. It is apparent from the results that there exists a clear pattern of rainfall trend across the study area. It is interesting to note that annual rainfall was found to be significantly decreasing for more than 70% of the grid points in clusters 2, 3 and

4. Most of these points are located along the coastal region and midland, whereas some of the grid points in cluster 5 show an increasing trend in annual rainfall. On the other hand, 11 grids were having increasing trend in south-west monsoon which are located near the Western Ghats. The annual rainfall is varying at a range from − 15.16 to 2.87 mm/year with a mean value of − 4.26 mm/year in cluster 1, whereas it is changing from − 17.38 to 7.60 mm/year with a mean value of − 5.55 mm/year in cluster 2. Likewise, south-west monsoon rainfall is found to be deviating at a mean rate of − 12.62 to 3.90 mm/year with a mean value of − 3.49 mm/year in cluster 1, whereas it is varying at a range from − 15.30 to 7.99 mm/year with a mean value of − 4.74 mm/year in cluster 2. The decrease in annual as well as south-west monsoon rainfalls is more in clusters 1 and 2, whereas reduction in north-east monsoon rainfall is found to be high in clusters 2 and 3 compared to the other clusters. The average magnitude of decrease in north-east monsoon rainfall over clusters 2 and 3 was found to be 0.99 and 1.05 mm/year respectively. Likewise, the mean value of winter and summer rainfall is observed to be decreasing in cluster 3 (− 0.40 mm/year and − 0.74 mm/year respectively) and cluster 4 (− 0.74 mm/year and − 0.25 mm/year respectively), which is higher compared to other clusters. These findings are consistent with previous studies done in the study area (Simon & Mohankumar, 2004; Vijay et al., 2021).

The spatial variation of rainy days (56 to 180 days) over the state gives a clear indication of asymmetry in distribution of rainy days. Although the highest number of rainy days is experienced by clusters 1 and 3, there is a considerable reduction in the number of rainy days that occurred from 1901 to 2019. It is interesting to note that number of rainy days during winter as well as the north-east monsoon has considerably decreased in all 5 clusters. The reduction in annual as well as seasonal rainy days is more in clusters 3 and 4 compared to the other clusters. The annual rainy days are decreasing at a mean value of 3.20 days/decade and 2.20 days/decade in cluster 3 and cluster 4 respectively. Likewise, rain days of the south-west monsoon were declining at a rate of 1.20 days/decade in clusters 3 and 4. Even though there is a reduction in the rainy days in cluster 3, annual rainfall does not show a profound reduction. This is an indicator of the possible occurrence of high-intensity rainfall for a short duration in the above-mentioned regions. The increase in the frequency of climate extremes across peninsular India was reported by various researchers (Goswami et al., 2006; Dash et al., 2009; Malik et al., 2016; Mukherjee et al., 2018). These results can be validated with 2018, 2019 and 2020 Kerala floods which occurred over a few days.

The years 1901 to 2019 experience considerable increase in the number of dry days with highest number recorded in clusters 4 and 5 (Fig. S3). The rate of increase of annual dry days is more in cluster 3 (from 137 days in 1901 to 173 days in 2019) and 4 (from 134 days in 1901 to 210 days in 2019) compared to the other clusters (Fig. S4). The number of dry days has considerably increased in all clusters especially during the south-west monsoon and north-east monsoon which have significant implications on the different types of water sources of the state. Increasing frequency of dry days during non-rainy seasons led to the severe water scarcity and dropping of groundwater levels because of the uneven distribution of rainfall. The majority of rain water discharges to the Arabian Sea within 48 to 72 h of the occurrence due to the complexity in the topography of the state (Dash et al., 2018).

The spatial variation of mean temperature is well illustrated in Fig. 1d and magnitude steps down from southern part to northern part of the state. Figure 8 depicts the temporal variation of mean temperature from 1951 to 2019, and a continual rise in mean temperatures over time is noted. The highest and lowest temperature was observed in the southern part (grids 4 and 5) and central part (grid 3) of the state respectively. It is seen from Table 5 that annual as well as seasonal mean temperatures are increasing at a rate of 0.1 to 0.2 °C/decade (statistically significant at 5%). Increasing mean temperatures during the south-west monsoon at a rate of 0.2 °C/decade over most of the grids signals overall warming. It is noteworthy that a significant study done by Ross et al. (2018) also indicated that no cooling was observed during the south-west monsoon. A uniform increase in maximum temperature at a rate of 0.2 °C/decade over 5 grids is observed, which is statistically significant at 5% (Fig. S5). The increase of annual as well as seasonal minimum temperature per decade in all grids was found to be 0.1 °C/decade (Fig. S6). This study revealed a rapid increase in maximum and mean temperatures which indicates a serious concern that possibly impact the paddy cultivation of the state which is the backbone of Kerala's economy. Studies pointed out that warming climate causes an increasing tendency of extreme precipitation indices as well as the quantum of precipitation, implying an increase in the frequency of high-intensity rainfall events (Mukherjee et al., 2018; Rao et al., 2020; Wang et al., 2020). The results of the current study can be correlated with the recent Kerala floods.

Temporal variation of PCI of annual as well as seasonal rainfall from 1901 to 2019 is illustrated in Fig. 11. It is noted that in cluster 1 and cluster 2, very strong irregularity in rainfall distribution was detected in 46 and 85 years respectively, mostly between 1910–1930 and 1985–2000. The irregularity in rainfall concentration is associated with a high contribution of the south-west monsoon rainfall (Thomas & Prasannakumar, 2016). In the case of cluster 1, years show very strong irregularity in rainfall concentration, and it has received more than 75% of the annual rainfall during the south-west monsoon (mean = 70.6%, range = 24 to 86%). In cluster 1, none of the PCI values falls below 15 (moderate precipitation concentration) during the study period.

But among the study time, 85 years in cluster 2, which has shown strong irregularity, has also received nearly 83% annual rainfall during south-west monsoon (mean = 80%, range = 45.6 to 93%). It is noted that in both clusters, more than 70% of the annual rainfall is received during the south-west monsoon, and it indicates the concentration of the majority of the annual rainfall falls in a few months of the year. The rainy season in clusters 1 and 2 is very short, and heavy rainfall is confined in the quarter part of the year. This clearly indicates that economy of Kerala largely depends upon the monsoon driven climate.

But as we go to clusters 3 and 4, an extreme irregularity was identified only in 5 and 6 years respectively. In cluster 3, the contribution of south-west monsoon to the annual rainfall budget is in the range of 70 to 85% during the years where PCI value is more than 20 (mean = 65%, range = 26 to 85%), whereas, in the case of cluster 4, a substantial irregularity was found only in 6 years in which the contribution of the south-west monsoon was more than 60% (mean = 50%). The contribution of the north-east monsoon to annual rainfall in grids of cluster 5 is more than 45%. There are 25 years that shows strong irregularity in rainfall in cluster 5, mostly between 1915–1945 and 1975–2018. It is worth mentioning that in these 25 years, the contribution of the north-east monsoon was more than 55%. This could be due to the absence of the Western Ghats barrier against the north-easterly winds.

The seasonality of rainfall has a vital role in deciding the calendar of agricultural activities. There is a necessity in the calculation of seasonality of rainfall as it has a direct impact on extreme events like floods and drought. In the southern part of the state, SI value ranges from 0.4 to 0.59, which indicates seasonal rainfall with short dry seasons. In the case of southern parts of Kerala, the contribution of the south-west monsoon rainfall to the annual rainfall budget is near 50 to 55% only. So the north-east monsoon and summer rainfall has a significant influence on the southern part of the state. In the central part of the state, the value ranges from 0.6 to 0.79, indicating that rainfall distribution is seasonal, where the rainfall contribution from the south-west monsoon is in the range of 60 to 70%. Moreover, the SI values of the northern part of Kerala vary from 0.8 to 0.95, reflecting the rainfall distribution in these areas are seasonal with long and drier seasons. This is mainly because more than 75% of annual rainfall is contributed by the south-west monsoon and the rest of the seasons have minimal impact on the northern part of the state. This explains the increasing rate of dry days in other seasons. These findings support the spatial variation of PCI over the state.

Conclusions

Recent events in the topical state of Kerala in India have drawn attention to the catastrophic impacts of extreme rainfall events leading to landslides and loss of human lives. In the present study, performance evaluation of various statistical tests for analysing the trends of climate variables for the state of Kerala, India, was demonstrated at annual and seasonal time using long-term data for 119 years (1901 to 2019). The spatial pattern of annual as well as seasonal rainfall was analysed by delineating 59 grid point into five clusters through K-means algorithm and identified the influence of geographical and statistical parameters on this clusters by PCA. It is observed that annual mean rainfall is highest in cluster 1 and cluster 3 (located in low altitude areas), whereas it remains lowest in cluster 5 (high altitude areas) with a high coefficient of variation. Likewise, grids in cluster 2 are mainly situated towards the northern side of Kerala with high rainfall, whereas cluster 4 is characterized by the moderate annual mean rainfall and is located in the region with low altitude. The declining trend of annual as well as seasonal rainfalls was observed for the entire study area with highest in cluster 1 (−4.26 and −3.49 mm/year) and cluster 2 (−5.55 and −4.73 mm/year). The decrease in north-east monsoon rainfall is more in cluster 2 (0.99 mm/year) and 3 (1.05 mm/year), whereas reduction in winter and summer rainfalls is found to be high in cluster 3 (0.40 mm/year and 0.74 mm/year respectively) and 4 (0.74 mm/year and 0.25 mm/year respectively) compared to the other clusters.

Five trend analysis techniques, including Mann–Kendall test, three modified Mann–Kendall tests and ITA test were used in the study. The trend analysis results pointed that more than 83% of the grid points were showing decreasing trends (significant and non-significant) in annual and south-west monsoon rainfall series. However, rainfall during north-east monsoon and winter was found to be decreasing at more than 90% of the grid points making it a subject of concern. On the contrary, when compared to other seasons, the grid points (69%) corresponding to the decreased rainfall in summer are fewer. More than 30% of the grid points are showing increasing trend in rainfall during the summer season.

The highest annual average rainy days obtained in the state are in clusters 1 and 3 (131 to 180), followed by clusters 2 and 4 (101 to 130). The annual rainy days are predominantly decreasing in cluster 3 (3.20 days/decade) and 4 (2.20 days/decade) compared to other clusters even though annual rainfall does not show a noticeable reduction in above-mentioned regions. Results show that more than 88% of grid points are showing negative trends, whether significant or non-significant, in annual and south-west monsoon rainy day series. However, in case of north-east monsoon and winter rainy days, more than 90% of the grid points are showing a negative trend (both significant and non-significant). On the contrary, the grid points (75%) corresponding to the summer season rainy days show a decreasing trend, whereas the increasing trends are evident for more than 25% of the grid points. These findings clearly indicate the possible occurrence of high-intensity rainfall for a short duration in the clusters 3 and 4. The results of the present study can be correlated to the recent occurrence of extreme rainfall events happened in the study area.

There is a significant increase in the number of dry days in all clusters with highest in clusters 3 (from 137 days in 1901 to 173 days in 2019) and 4 (from 134 days in 1901 to 210 days in 2019). Increase in the dry days during the south-west monsoon and north-east monsoon has serious implication on the agricultural sector of the state as it will lead to water stress and crop failure.

All of the trend analysis tests discovered a statistical significant increasing trend in mean and maximum temperature at annual and seasonal scales for all grids. The trend magnitudes in the mean temperature range from 0.1 to 0.2 °C/decade for annual and other seasons, whereas the maximum temperature is increasing at a rate of 0.2 °C/decade. Similarly, the magnitude of minimum temperature is found to be rising in the annual, south-west monsoon, north-east monsoon, winter and summer seasons at an extent of 0.1 °C/decade. It is evident from the above results that climate of the state is significantly changing which can have major impacts on human health and water resources of the state.

The annual scale of PCI calculated for the state varies from a minimum of 13 (moderate concentration) in the southern part of the state to a maximum of 28 (high concentration) in the northern part of the state, which indicates that PCI distribution is not uniform over the state. On a seasonal scale, south-west monsoon shows the most minor variability compared to other seasons. But PCI values of north-east monsoon, winter season and summer vary from 8.3 to 25 in all clusters. This gives an insight into the highly irregular pattern of rainfall during the season. The value of SI ranges from a minimum of 0.45 in the southern part of Kerala (short dry seasons) to a maximum of 0.95 in northern parts of the state (long dry season). The rainfall in clusters 1, 2 and 3 is irregular, and total rainfall is concentrated in half of the year. The increasing number of dry days during the south-west monsoon as well as the north-east monsoon adversely affects the paddy cultivation in Kerala.

Therefore, this study concluded with an effort to study the rainfall and temperature pattern of Kerala and connected various indices for a better understanding of the several environmental issues in the state. It is anticipated that the outcome of this work will be highly beneficial to sustainable regional planning and disaster risk management strategies.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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