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Climate Dynamics over Kerala, India: Insight from a Century-long Temperature and Rainfall Data Analysis

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Authors' contributions

This work was carried out in collaboration among all authors. This work was carried out in collaboration between all authors. Authors JA and NRK designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors AS, PKV, and GKJ managed literature searches and analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Historical climate data analysis is of great significance in climate change adaptation and mitigation planning at global as well as regional levels. This article attempted to study the long-term trends of temperature and rainfall across the districts in Kerala, India. CRU monthly time series data of

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rainfall and temperature data spanning from 1901-2022 were used for the analysis. Mann-Kendall test and Sen's Slop estimator were applied to detect the presence and magnitude of the trend, and Pettitt's homogeneity test was used to find the climate change point in temperature time series data. The analysis found a significant and positive temperature trend across all districts in Kerala, with temperature increases ranging from 0.0086°C/year to 0.0102°C/year. In terms of rainfall trends, June and January experienced a significant decrease, while July and September saw a significant increase over the years. The year 1976 was identified as the point of climate change. It was observed that there was an increase in the southwest and Northeast monsoons in the post-period, with higher variability in the latter. Winter rainfall notably decreased during the post-period. The variability in climate parameters identified in this study could impact crop cycles and agricultural productivity, requiring further investigation at a micro-level for effective adaptation and mitigation strategies for the state.

Keywords: Temperature; rainfall; mann-kendall test; sen's slop estimator.

1. INTRODUCTION

Climate change is one of the most widely discussed topics across the globe in the 21st century, and numerous studies are being conducted across various disciplines [1,2,3]. The Intergovernmental Panel on Climate Change (IPCC) defines "climate change" as "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and the variability of its properties, and that persists for an extended period, typically decades or longer" [4]. According to the United Nations Framework Convention on Climate Change (UNFCC), climate change can be attributed directly or indirectly to human activity that alters the composition of the global atmosphere, which is in addition to natural climate variability observed over comparable periods [5]. Over the past decades, there have been evident changes in global climate due to the intensified human activities that disrupted the earth's atmospheric composition [6]. On a global scale, the annual mean surface air temperature is projected to increase by up to 3.7°C by the end of this century [7]. It is also projected that the temperature of the earth's surface will increase by 4.4^{0}C by the end of the next century [8]. Further, The IPCC 2021 forwarded the starkest warning that the world is set to reach the 1.5^{0}c level in two decades down the line and emphasized that only immediate drastic cuts in carbon emissions would help prevent an environmental disaster [9]. The projected extent of heat-stressed areas in South Asia relative to the baseline (1950–2000) could increase by up to 12% in 2030 and 21% in 2050 [10]. Another study indicated that drier regions are forecasted to dry more, with severity as compared to humid regions. Sub-Saharan Africa's population poses more vulnerability in this situation [11].

In the Indian scenario, the increase in maximum temperature has exceeded that of minimum temperature, leading to an expansion of the diurnal temperature range across all seven contrasting temperature zones [12]. Consequently, the Indian subcontinent has experienced a warming of 0.56°C over the past century [13]. Monsoon seasons contribute 80% of the annual rainfall received over the Indian sub-continent [14]; hence, it is crucial for the performance of the overall economy, especially for the agricultural sector of the country [15]. Kerala, a state in southern India, receives the second-highest amount of monsoon among all the states. It often records an average annual rainfall above 3000mm, distributed over six months, with the highest rainfall occurring during June and July [16,17]. However, since 1965, there has been a significant declining trend in annual rainfall. Concurrently, maximum, minimum, and average temperatures in the state have been steadily increasing [18,19]. On the other hand, heavy rainfall events frequently became headlines, highlighting the natural hazards in different regions in Kerala [20]. Changes in the rainfall distribution pattern of seasonal rainfall and inter-annual variations were the driving forces for such hazardous rainfall events [21].

The aforementioned factors highlight the climate-sensitive nature of Kerala, and therefore, factoring climate information is crucial to delineate climate-proof development plans in Kerala. Climate data, especially rainfall and temperature, could serve as the basis for climate hazard mapping and risk assessment of various regions, sectors, and communities to ensure climate-proof development [22]. Numerous studies [23,24,25,26,27,28,29,30,31] have been conducted to analyze temperature and rainfall trends in various regions worldwide. A few studies also analyzed rainfall and temperature trends in Kerala using the non-parametric Mann-Kendall test and parametric regression test. For instance, Jan et al. [32] studied the centennial rainfall trend and variability in the Kuttanad region, while the rainfall trend in the Pattambi region was studied by Sai and Joseph [33]. Madhu et al. [34] analysed rainfall trends in different regions of the Wayanad district, and historical temperature and rainfall trends in the Bharathapuzha river basin were investigated by Varughese et al. [35]. Ajithkumar and Riya [36] examined the long-term trend of maximum temperature across various agro-climatic regions in Kerala. Nevertheless, there is no study specific to Kerala that identifies the climate change point using temperature time series data or explores how the rainfall distribution pattern varies during either period of the change point. With this backdrop, the present study aims to address the following research questions;

a) What is the trend of mean temperature across districts in Kerala?
b) What is the climate change point year based on temperature time series data?
c) What is the monthly, seasonal, and annual rainfall trend over Kerala?
d) How does the rainfall distribution vary between the pre- and post-period of climate change point?

2. METHODOLOGY

2.1 Data and Study Location

The present study used recent release version 4.07 of the CRU TS (Climatic Research Unit gridded Time Series) dataset, which contains monthly time series data on various climatic variables such as rainfall, temperature, wet days, cloud cover, vapour pressure, frost days and potential evapotranspiration, spanning from 1901 to 2022 (122 years). This is an open source dataset widely used in climate change research which covers a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica [37]. Historical data on rainfall and temperature were then extracted from the CRU TS using R-studio software. The data was first downloaded as nc.gz files, then converted into .nc files, and finally extracted using the “remotes” package available in R-studio.

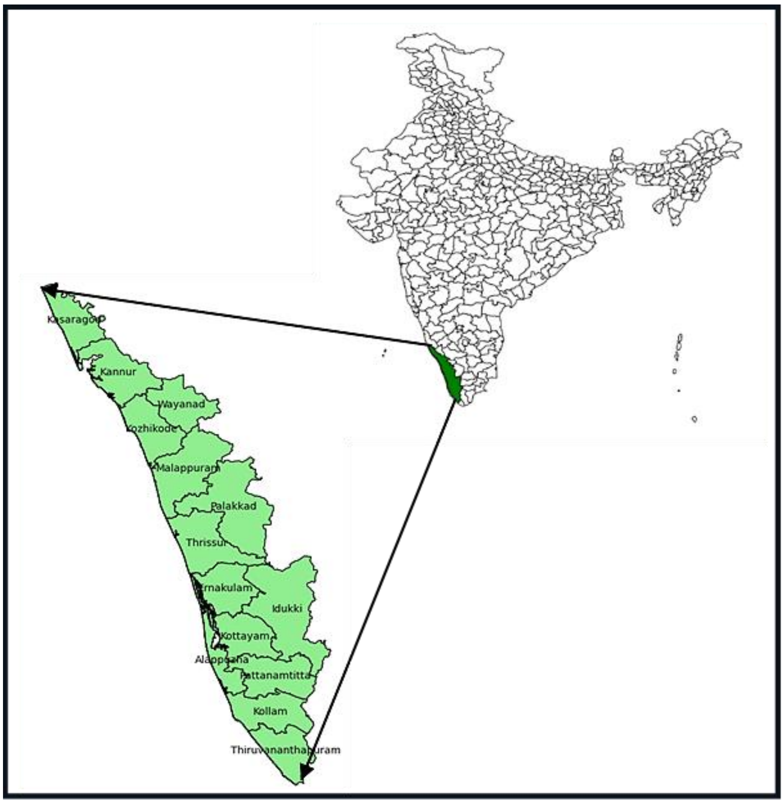


Fig. 1. Map of the study area: The state of Kerala

Table 1. Geographical coordinates of locations chosen for the study

S.N.	Locations	Latitude(^{0}N)	Longitude(^{0}E)
1	Kasargod	12.4997	74.9870
2	Kannur	11.8745	75.3704
3	Wayanad	11.6362	76.0175
4	Kozhikode	11.2588	75.7804
5	Malappuram	11.0510	76.0711
6	Palakkad	10.7867	76.6548
7	Thrissur	10.5276	76.2144
8	Ernakulam	9.9816	76.2999
9	Idukki	9.9189	77.1025
10	Kottayam	9.5916	76.5222
11	Alappuzha	9.4981	76.3388
12	Pathanamthitta	9.2648	76.7870
13	Kollam	8.8932	76.6141
14	Thiruvananthapuram	8.5241	76.9366

The southern Indian state, Kerala (Fig. 1), was chosen as the study area because of its climate-sensitive nature [22], being highly vulnerable to various extreme climate events like floods, drought, and landslides. Fourteen locations, corresponding to the fourteen districts in Kerala (Table 1), were identified to extract rainfall and temperature data. The CRU data validated with India Meteorological Department (IMD) station observatory data provided the best fit for different locations in Kerala [32]. Further, as per IMD, the entire state is classified as one meteorological sub-division for climatological purposes, and the whole year is divided into four seasons, viz. South-west monsoon (June to September), Northeast Monsoon (October to December), Winter (January-February), and Summer (March to May).

2.2 Analytical Methods

2.2.1 Mann-kendall test

The non-parametric Mann-Kendall test is a widely employed technique to detect monotonic trends in environmental and hydro-meteorological time series of data [38,39,40,41]. The null hypothesis, H_0, is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_A, is that the data follow a monotonic trend. The Mann-Kendall test statistic "S" is calculated using the formula given under [42,43]:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sign}(x_j - x_k) \qquad (2.1)$$

With

$$\text{Sign}(x_j - x_k) = \begin{cases} 1 & \text{if} \quad x_j - x_k > 0 \\ 0 & \text{if} \quad x_j - x_k = 0 \\ -1 & \text{if} \quad x_j - x_k < 0 \end{cases} \qquad (2.2)$$

The mean of S is E[S] = 0 and the variance of S, Var(S), is calculated as:

$$\text{Var}(S) = \frac{\left\{n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j-1)(2t_j+5)\right\}}{18} \qquad (2.3)$$

where p is the number of the tied groups in the data set, and tj is the number of data points in the jth tied group.

The statistic S is closely related to Kendall's τ as given by:

$$\tau = \frac{S}{D} \qquad (2.4)$$

Where,

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j(t_j-1)\right]^{1/2}\left[\frac{1}{2}n(n-1)\right]^{1/2} \qquad ---------- (2.5)$$

The statistic S is approximately normally distributed provided that the following Z-transformation is employed:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}; & \text{if} \quad S > 0 \\ 0 \;; & \text{if} \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}; & \text{if} \quad S > 0 \end{cases} \qquad --------------------- (2.6)$$

The positive and negative values of Z statistic represent increasing and decreasing trends in the time series data, respectively. Further, the null hypothesis (H_0) can be either accepted or rejected based on the set probability level, thereby facilitating the interpretation of the presence of significant trends in the data [44].

2.2.2 Sen's slope estimator

This test computes both the slope (i.e. linear rate of change) and intercept according to Sen's method [45]. Sen's slope estimator is used to determine the magnitude of trend in rainfall and temperature time series data that has been identified through the Mann-Kendall test [46,47,48,49]. The slope β (Sen's slope estimator) can be calculated from N pairs of data as follows:

$$β_i = \frac{x_k - x_j}{k-j}, i = 1,2,3, \cdots\cdots N, k > j \qquad ------------ (2.7)$$

Where,
x_k and x_j denotes values of data at k and j times, and $β_i$ is the median slope.

2.2.3 Pettitt's homogeneity test

The approach after Pettit [50] is widely applied to detect a single change-point or abrupt shift in hydrological series or climate time series data [51,52]. The Pettitt test is an approximation for a sequence of random variables of the non-parametric method [48]. It tests the H_0: The T variables follow one or more distributions that have the same location parameter (no change) against the alternative H_A: a change point exists. The non-parametric statistic is defined as follows:

$$K_T = max\left|U_{t,T}\right| \qquad ------------ (2.8)$$

Where,

$$U_{t,T} = \sum_{i=1}^{t}\sum_{j=t+1}^{T} \text{sign}(x_i - x_j) \qquad -------- \;\; -(2.9)$$

The change-point of the series is located at K_T, provided that the statistic is significant. The significance probability of K_T is approximated for p ≤ 0.05 with

$$p \simeq 2\exp\left(\frac{-6K_T^2}{T^3+T^2}\right) \qquad -------------- (2.10)$$

2.2.4 Box-and-whisker plot

A Box and Whisker Plot (or Box Plot) is a standardized way of visually displaying the data distribution through their quartiles [53, 54]. Box plot summarizes the data on a five-point basis, viz. minimum or Lower extreme value limit, first quartile (Q_1), median(Q_2), third quartile (Q_3), and maximum or upper extreme value limit [55]. The plot will also display the outliers that go beyond either side of minimum or maximum limits. Since the plot did not make any assumption about the underlying statistical distribution, it is non-parametric. This tool helps depict the degree of dispersion in related groups of time series datasets. Therefore, it has been used to compare the quantity and dispersion of monthly and seasonal rainfall between pre- and post-periods of climate change points [48,56].

3. RESULTS AND DISCUSSION

3.1 Long-term Temperature Trend and the Year of Abrupt Shift

The analysis of long-term temperature across the districts (Table 2) indicated that Thrissur had the highest mean temperature (27.28°C) with a CV value of 1.57%. All districts, except Wayanad and Idukki, had a mean temperature of over 25°C during the considered period. The highest CV values were observed in Wayanad and Idukki at 1.88% and 1.87%, respectively. The Man-Kendall test indicated a positive and highly significant (<1%) value of z-statistic in all the districts, which suggests a significant increasing trend in the historical data of mean temperature across the districts. Ajithkumar and Riya [36] also reported a significant increasing trend in the maximum temperature across all districts of Kerala from 1983 to 2020. The average surface air temperature in Kerala increased by 0.65 °C from 1956 to 2014, and in the Idukki district, the maximum temperature is increasing, and the minimum temperature is declining, resulting in a widening of temperature ranges [57]. Mann-Kendall rank statistics provided a statistically significant increasing trend of temporal and seasonal temperature in the Pattambi region, which is located in the Palakkad district of Kerala, from 1950 to 2018 [58]. The southern districts of Kerala, including Kottayam, Alappuzha, Pathanamthitta, Kollam, and Thiruvananthapuram, showed an increase in mean temperature at the rate of 0.01°C/annum. In contrast, the northern districts showed an increase of 0.009°C/annum or less. As revealed by Sreeraj et al. [59], pre-monsoon temperature changes in the Kottayam district from 1991 to 2014 indicated a decrease in maximum temperatures and an increase in minimum temperatures, which in turn resulted in the rise in the number of hot days in the region.

The next stage of the study involved using Pettitt's test on the district-wise mean temperature data to identify the shift or abrupt change point in the time series data. The K-statistic of the test showed a highly significant value with less than 0.01 probability values in all districts. The test successfully identified the change points in all districts (Fig. 2) and found that 1976 was the climate change point in all districts, except for Malappuram, where it was 1975. Hence, we selected 1976 as the year of climate change in Kerala in our subsequent analyses as well. Similar findings were reported in literature dealing with multifractal fingerprinting of fine-resolution daily gridded rainfall of Kerala meteorological subdivision [60]. The study mentioned a global climatic shift that occurred in 1976/77, which they used as a reference point for splitting the time series into two periods. George and Athira [61] reported a significant change in the climatic pattern in the Bharathapuzha river basin (which covers three districts) in Kerala after the 1980s. They identified 1980 as a significant change point in the rainfall time series data.

3.2 Rainfall Trend and Distribution over Kerala

The state of Kerala has an average annual rainfall of 2770 mm with a coefficient of variation (CV) of 13.29% (Table 3). The South-west monsoon contributes more (68%) to the annual rainfall, followed by the North-east monsoon (27%), which means that both monsoons together contribute 86% of the annual rainfall over Kerala. Among the months, July receives the highest rainfall (24%), followed by June (20%), while the CV is highest in January (105%).

Month-wise rainfall trend analysis indicated that June had experienced a significant (1% level) decreasing trend over the years, with a magnitude of decrease of 1.18 mm/year. January also showed a decreasing trend of rainfall (0.045 mm/year), which was significant at the 10% level. However, July and September showed a positively significant trend of z-statistic, with a magnitude of increase in rainfall equivalent to 0.88 and 0.62 mm/year, respectively. Among the different seasons, only the winter season showed a significant decreasing trend of rainfall (0.092 mm/year). The rest of the seasons and annual rainfall did not show any significant trend over the years. A study by Vijay et al. [62] revealed a declining trend of annual and seasonal rainfall for the entire state of Kerala over 118 years ending in 2018. Adarsh and Janga Reddy [63] indicated that the annual rainfall in the Kerala meteorological sub-division shows a significant decreasing trend, along with a similar decreasing trend in Jun rainfall as well. Further, they found a significantly decreasing trend of post-monsoon rainfall, which includes the months of October and November.

The Box plots depicted in Fig. 3 show the monthly rainfall distribution over two distinct periods: the first period runs from 1901 to 1976, while the second period is from 1977 to 2022. A comparison between these two periods reveals changes in rainfall patterns over time, with fluctuations in average rainfall and variability observed across different months.

It is worth noting that the average rainfall in January decreased from 14.20 mm to 9.84 mm, while slight increases in average rainfall were observed in July, August, September, October, and November. Interestingly, June and July maintain high average rainfall values in both periods, albeit with a decrease in average rainfall in June during the second period (587 mm to 505 mm). The findings of Madhu et al. [34] indicated an asymmetric change in rainfall over Wayanad district in Kerala from 1999-2014, with an increase in September rainfall and a decrease in other months, indicating a shift in the distribution pattern. It can also be noted that a greater number of outliers were observed in the June and July months in both periods, indicating extreme rainfall events or fluctuations from the normal trend. The frequency of such outliers is more in number during the first period, particularly in June. These findings align with the observations of Pal & Al-Tabbaa [64], who reported a significant decrease in monsoon rainfall extremes in Kerala, which could affect the overall tendency of change in seasonal total rainfall.

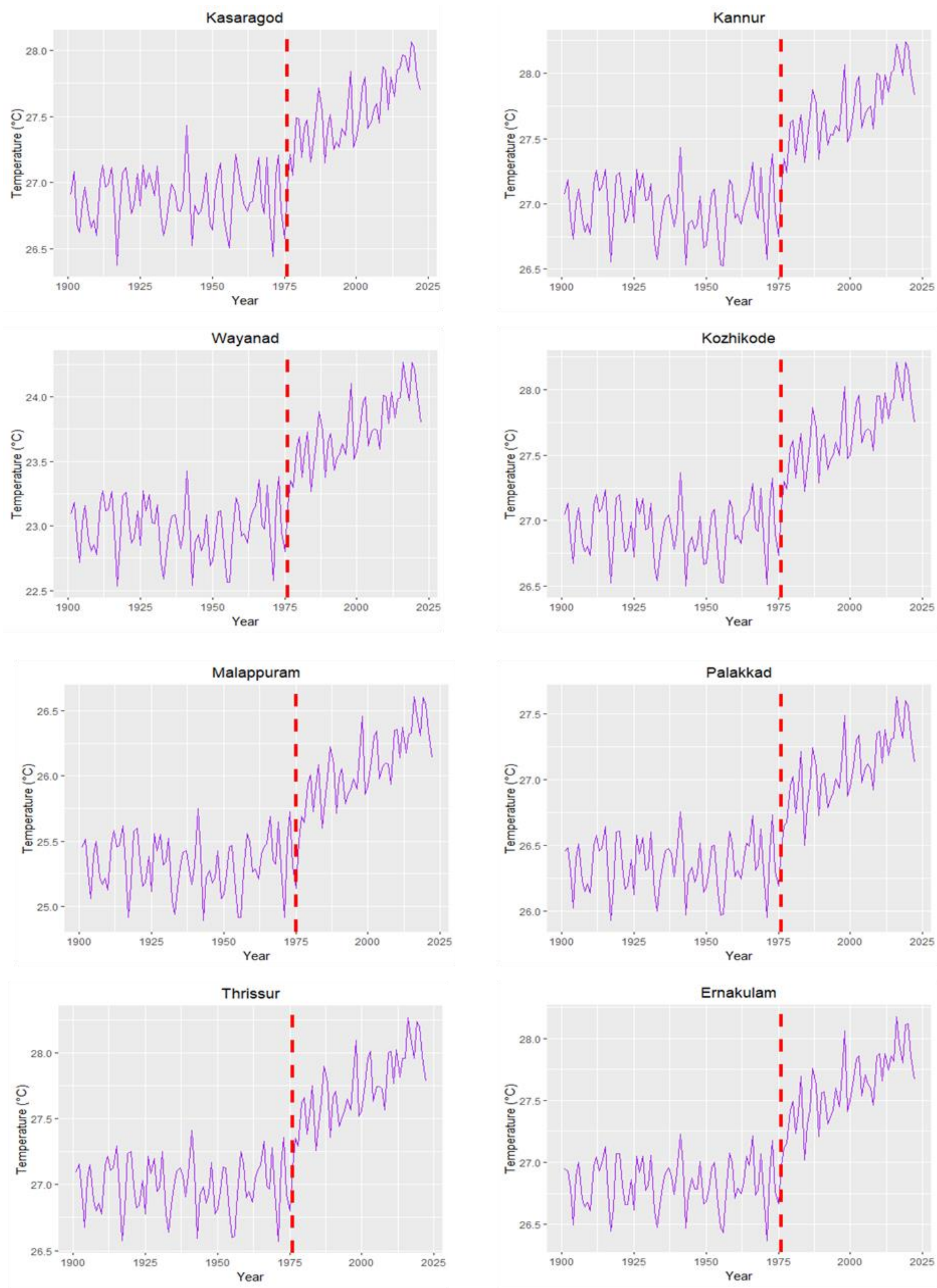
In the second period, certain months show noticeable increases in CV values compared to the first period, indicating increased variability. For example, January, February, and October showed a high increase in CV values, suggesting greater variability in rainfall during the second period. However, the June and November months showed a decrease in CV (42% to 32% and 50% to 49%), implying lower variability of rainfall in June during the second period.

The box plots in Fig. 4 provide a comparison between the distribution of seasonal and annual rainfall data for two periods. The average annual rainfall was relatively consistent between the two periods, with only minor variation: 2770.81 mm in the first period and 2767.74 mm in the second period. During the South-west monsoon season, there was a slight increase in mean rainfall from the first period (1882.27 mm) to the second period (1902.06 mm). The decrease in the coefficient of variation (from 19% to 17%) indicates a reduction in variability, which suggests a more consistent dispersion of South-west monsoon rainfall in the second period. Jagadeesh and Anupama [65] observed an increasing trend of south-west monsoon rainfall during 1976-2008 in the Bharathapuzha river basin areas.

Table 2. Trend analysis of district-wise mean temperature (1901-2022): Mann-Kendall and Sen's slope estimation

District	Mean	CV (%)	MK Tau	Z-statistic	Sen's Slope (°C/annum)
Kasaragod	27.14	1.46	0.5480	8.9426***	0.0086
Kannur	27.26	1.61	0.5323	8.6902***	0.0096
Wayanad	23.27	1.88	0.5462	8.9117***	0.0097
Kozhikode	27.22	1.61	0.5436	8.8675***	0.0098
Malappuram	25.61	1.71	0.5507	8.9826***	0.0098
Palakkad	26.63	1.61	0.5565	9.0820***	0.0096
Thrissur	27.28	1.57	0.5525	9.0156***	0.0096
Ernakulam	27.13	1.65	0.5553	9.0600***	0.0101
Idukki	23.46	1.87	0.5626	9.1773***	0.0099
Kottayam	26.19	1.69	0.5577	9.0998***	0.0100
Alappuzha	27.24	1.65	0.5573	9.0952***	0.0102
Pathanamthitta	27.04	1.65	0.5569	9.0886***	0.0101
Kollam	27.19	1.65	0.5623	9.1771***	0.0102
Thiruvananthapuram	27.20	1.65	0.5573	9.0931***	0.0101

****Significant at 1% level*


Kasaragod
Kannur
Wayanad
Kozhikode
Malappuram
Palakkad
Thrissur
Ernakulam
Temperature (°C)
Year
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1925
1950
1975
2000
2025

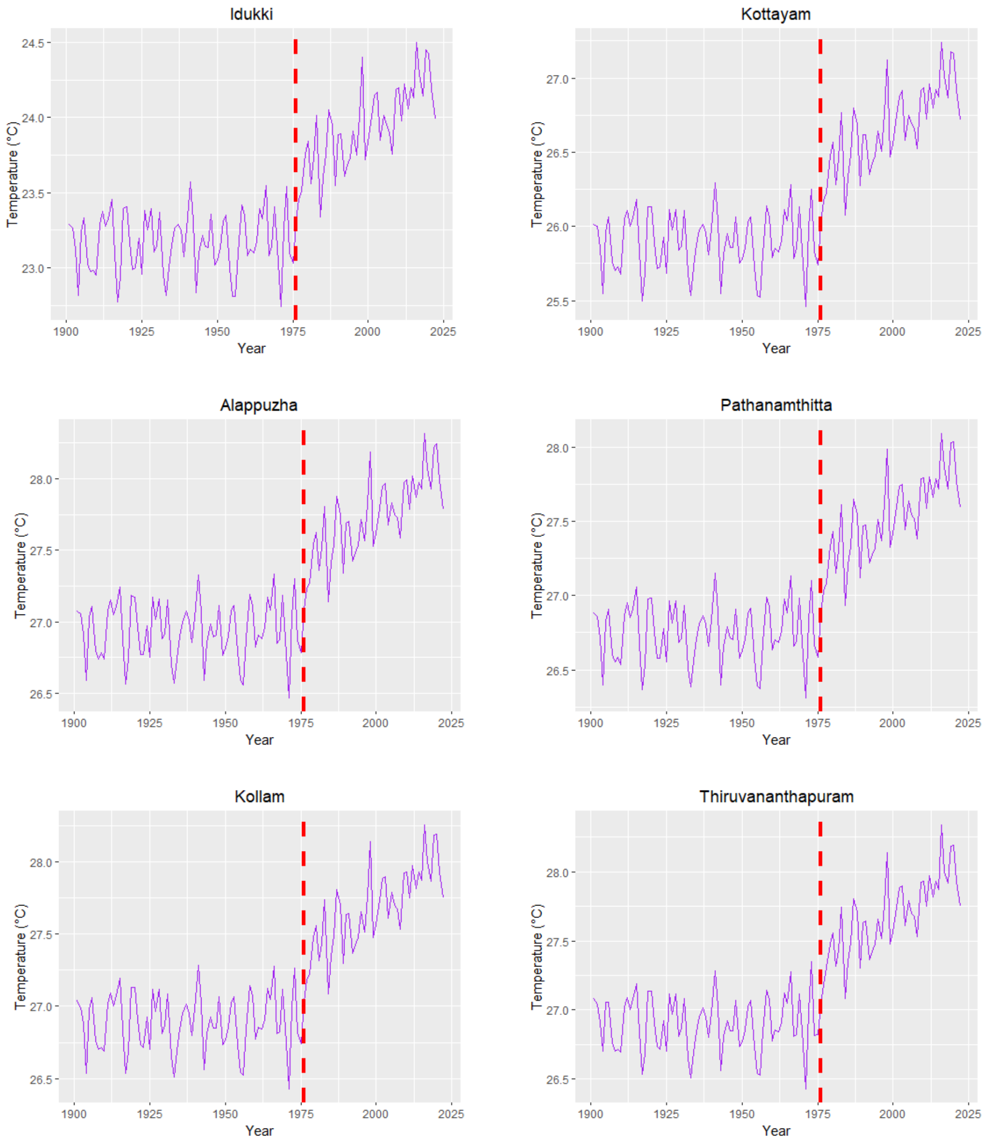

Fig. 2. Pettitt's test plots of district-wise mean temperature indicating the change point

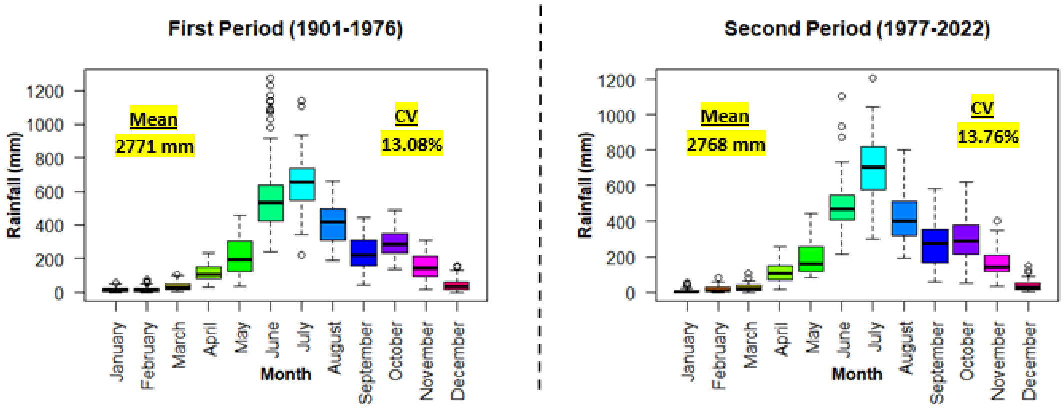

Fig. 3. Monthly rainfall over Kerala: Comparison of First (1901-1967) and second periods (1977-2022)

Table 3. Trend analysis of monthly and seasonal rainfall (mm) over Kerala during 1901-2022

Month/Season	Mean	CV (%)	% Contribution to annual rainfall	MK Tau	z-statistic	Sen's Slope (mm/year)
January	12.55	105.18	0.45	-0.1189	-1.9407*	-0.0451
February	17.27	101.19	0.62	-0.0256	-0.4138	-0.012
March	33.25	75.02	1.20	-0.0976	-1.5933	-0.0845
April	112.51	43.60	4.06	0.0637	1.0356	0.1407
May	208.08	49.54	7.51	-0.0597	-0.9737	-0.2368
June	556.25	39.87	20.08	-0.1875	-3.0582***	-1.1889
July	674.41	25.47	24.35	0.1256	2.0492**	0.8884
August	413.36	30.26	14.92	0.057	0.9294	0.3113
September	245.71	45.40	8.87	0.1259	2.0536**	0.6172
October	293.78	33.21	10.61	-0.006	-0.0974	-0.0286
November	160.52	50.03	5.80	-0.0061	-0.0974	-0.0144
December	41.96	83.15	1.52	-0.0263	-0.4293	-0.0279
SW monsoon	1889.73	18.58	68.23	0.031	0.5045	0.4421
NE monsoon	496.25	27.57	17.92	-0.0251	-0.4072	-0.1417
Winter	29.83	75.07	1.08	-0.1168	-1.9031*	-0.0919
Summer	353.84	32.43	12.78	-0.031	-0.5045	-0.1479
Annual	2769.66	13.29	100.00	0.0175	0.2833	0.2550

**Significant at 10% level, **significant at 5% level, ***Significant at 1% level.*

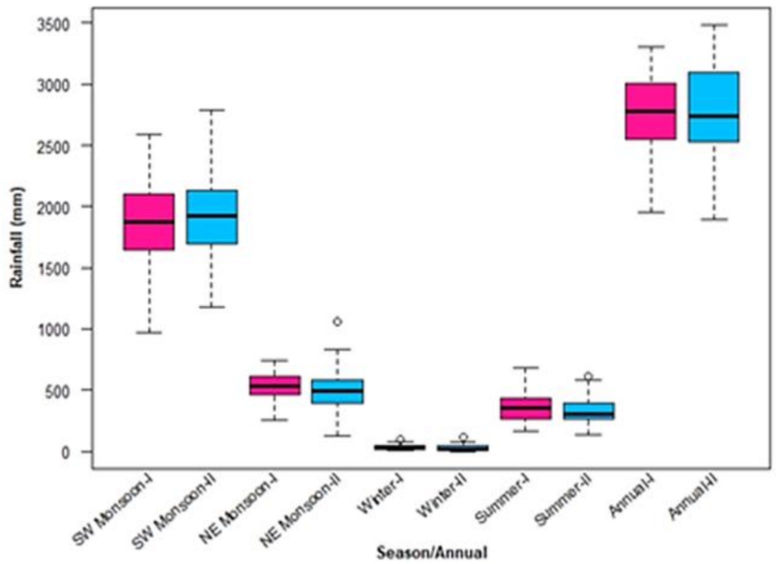

Fig. 4. Seasonal and annual rainfall in Kerala: Comparison of first (1901-1967) and second periods (1977-2022)

Similarly, the average rainfall during the North-east monsoon increased from the first period (490.46 mm) to the second period (505.83 mm). However, there was a significant increase in the coefficient of variation, indicating higher variability in Northeast monsoon rainfall during the second period. Among these two monsoon seasons that contribute to the lion's share of rainfall over Kerala, the North-east monsoon has depicted higher variability over the years, particularly after the climate change point (1976). Archana et al. [60] highlighted a change in the pattern of rainfall within the Kerala metrological subdivision after 1977.

The average winter rainfall decreased notably from the first period (31.63 mm) to the second period (26.84 mm). Additionally, there was a substantial increase in the coefficient of variation, suggesting much higher variability in winter rainfall during the second period. The average summer rainfall also decreased from the first period (366.45 mm) to the second period (333.01 mm), albeit with less variability than in winter.

4. CONCLUSIONS

Historical climate trend analysis across the districts in Kerala revealed important insights. Every district marked a significant increase in mean temperature over the years, with southern districts recording high rates of temperature rise as compared to northern districts. The year 1976 was identified as the point that signifies an abrupt shift in temperature pattern. The rainfall analysis indicated a decreasing trend in January and June and an increasing trend during July and September. Furthermore, winter rainfall showed a significantly decreasing trend over the years. Comparison of rainfall distribution between pre and post-periods of climate change year pointed to a high degree of variability in rainfall in the post-period, particularly for January, February, and April. In contrast, the months of June and November exhibited a decline in rainfall variability. Notably, during the South-west monsoon rainfall, there was a slight increase in average rainfall from the first to the second period with a decline in variability even though North-east monsoon recorded a modest increase in average rainfall in the second period, but with a much higher variability. However, average annual rainfall remained relatively consistent between the two periods, with minor variability. The changes in temperature and rainfall distribution, particularly monsoon rainfall across most of the districts, render the state of Kerala highly vulnerable. This may affect the crop cycle, crop rotation, and, ultimately, the productivity of the overall agricultural system. However, this study does not cover other critical climatic parameters like relative humidity, sunshine, wind patterns, etc. We suggest undertaking in-depth studies on these aspects to explore their individual and combined effects on the state's climate. Yet, our findings are crucial, mainly because they help underscore the dynamic nature of major climatic variables in Kerala. Further, these findings can be used as indicators for effective adaptation and mitigation planning in the state.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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