LONG TERM CLIMATE VARIABILITY AND DROUGHT CHARACTERISTICS IN TROPICAL REGION OF INDIA

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Abstract

This work reports climate change signals and long-term trend analysis of climate variables, meteorological drought, and extreme climate indices over the tropical state of Kerala in India. The trend analysis reveals statistically significant decrease of annual and south-west monsoon rainfall (as much as 63 mm and 55 mm per decade respectively)**.** A decrease in number of annual rainy days (up to 2.8 days/decade) is also reported. Temperature trend analysis indicates an increasing trend with as high as 1.3°C/decade. The spatio-temporal variation of extreme climate indices across Kerala shows a decreasing trend of extreme precipitation indices and an increasing trend of extreme temperature indices. R95 and R95p decreased in northern and southern Kerala whereas R5 index increased in central and southern regions. Warm days have significantly increased whereas cold days exhibit a decreasing trend across the state. The increase in warmer nights is statistically significant whereas colder nights are decreasing in central and southern regions. Meteorological drought using Standardized Precipitation Index (SPI) reveals increasing occurrence of droughts in Kerala with higher frequencies over southern and central Kerala.

Keywords: Climate variability, Climate indices, Drought analysis, Kerala, Mann Kendall, Standardized Precipitation Index, Sen's Slope Estimator, Trend analysis

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Introduction

Climate scenario

India is highly dependent on monsoon rainfall for its agriculture (and allied sectors) which accounts for ~33% of India's Gross Domestic Product (GDP) making it the single largest contributor to the economy. Associated with global warming, there are indications of changes to regional and global climate and these changes directly impact the agrarian dependent economy of India. Several studies report the spatial and temporal variation of climatic variables worldwide (Burn and Elnur 2002; Zhang et al. 2007; Penalba and Robledo 2010; Chu et al. 2010; Alexander 2016). Investigations on the trend of climatic variables in India indicate a decreasing trend in monsoon rainfall and an increasing trend of temperature (Parthasarathy and Dhar 1974; Rao 1993; Guhathakurta and Rajeevan 2008; Goswami et al. 2006; Krishnakumar et al. 2009; Pal and Al-Tabbaa 2009; Kumar et al. 2010; Rana et al. 2012; Patra et al. 2012; Mondal et al. 2012). A decreasing trend in extreme rainfall events during monsoon will lead to higher water scarcity during the non-monsoon months and Kerala is highly susceptible to these changes (Pal and Al-Tabbaa 2009). Parthasarathy and Dhar (1974) observed an increasing trend of annual rainfall in Central India and a decreasing trend in parts of eastern India from 1901 to 1960. This highlights the high spatio-temporal variability of the Indian climate and the pressing need to carry out our present regional-scale study at different time steps.

The principal seasons for India are defined as south-west monsoon (June–September), north-east monsoon/post-monsoon (October–November), winter (December–February), and summer (March-May). From 1951 to 2000**,** central India has witnessed higher frequency and magnitude of extreme rainfall events and fewer variations in moderate events (Goswami et al. 2006). A significant decrease in monsoon rainfall over various parts of India is reportedly associated with more post-monsoon showers (Krishnakumar et al. 2009; Pal and Al-Tabbaa 2009; Jagadeesh and Anupama 2014; Babar and Ramesh 2014). Interestingly, long-term seasonal analysis over the 20^{th} century (1901 – 2003) indicates increasing trends in summer rainfall in southeast, north-east, and north-west India while a decreasing trend in the central region and the western coast (Varikoden et al. 2013). This paper, therefore, attempts to examine the variability of extreme events at different time steps over Kerala which is the entry point of south-west monsoon in the Indian subcontinent.

Temperature plays a key role in the moderation of Indian south-west monsoon as high temperatures in northern India during summer forms pressure gradient facilitating the entry of rain-bearing clouds in the Indian subcontinent during monsoon (Bhutiyani et al. 2007). The maximum, minimum, mean, and diurnal temperature ranges have been observed to increase over the north-western Himalayan region during the 20^{th} century (Bhutiyani et al. 2007). Also, the occurrence of hot days and hot nights shows a widespread increasing trend over the entire India and its seven homogeneous regions over the 20th century. However, this trend was found to be decreasing from 1970 to 2005 indicating temperature has higher temporal variability than spatial. Mean annual temperatures over most parts of India (west coast, interior peninsula, north-central and north-eastern regions) show an increase during the period 1901 to 1982 (Hingane et al. 1985; Rupa Kumar et al. 2002). Consequences of warming temperatures are on biodiversity, increase in precipitation extremes management of water resources (Paul et al, 2018; Mukherjee et al. 2018; Rajulapati et al., 2020). Owing to limited studies of such nature in Kerala, this work attempts a holistic approach and evaluates the long-term trend analysis of rainfall, temperature and drought indices over the region.

Climate change signals are quantified using long-term trends of extreme events that carry the fingerprint of climate change. The threshold values for detecting climate change signals are carefully chosen based on the objectives of the studies. 95th percentile values are usually adopted for upper thresholds and 5th percentile values are adopted for lower thresholds in climate change studies globally (Karl et al. 1999; Haylock and Nicholls 2000; Zhang et al. 2005 a, b; Smith 2011; Knapp et al. 2015; Alexander 2016; Kumar et al. 2020). The highlight of this study is an attempt to comprehensively fingerprint climate change signals using six thresholds for catering to a wide range of applications that readers deem appropriate. The extreme wet and warm years are quantified using 99th, 95^{th,} and 90th percentile values (as the higher threshold), and 1st, 5^{th,} and 10th percentile values are used for quantifying extreme dry and cold years (as the lower threshold).

Drought

The Intergovernmental Panel on Climate Change (IPCC) report on managing risks of extreme events and disasters parallels drought to natural disasters (IPCC 2012). India is considered to be one of the highly vulnerable drought-prone countries of the world (FAO 2017). This is owing to the fact that a drought event is reported at least once in three years during 1951-2000 and the frequency of droughts are increasing in recent times (Dash et al, 2007; Mishra and Singh 2010; Sharma and Mujumdar 2017). The analysis of drought concerning rainfall (i.e., meteorological drought) is thus crucial to the Indian subcontinent.

Although there are several categories of defining drought (such as meteorological, hydrological, climatic, agricultural, and economic), prolonged low moisture in a region is termed as drought (Palmer 1965; Wilhite and Glantz 1985; Dalezios et al. 1991). The intensity of drought is directly dependent on the intensity of rainfall and the number of rainy days. Additionally, an increasing temperature, lower relative humidity, changes in wind speed, and lag between rainy seasons also define the drought (Bordi et al. 2001). Several indices such as Palmer Drought Severity Index (PDSI), surface water supply index, crop moisture index, Standardized Precipitation Anomaly Index (SPAI), Standardized Precipitation Index (SPI) are used to detect drought conditions (Palmer 1965; Palmer 1968; Shafer and Dezman 1982; McKee et al. 1993; Chanda and Maity 2015). This paper adopts the SPI which examines the anomalies in regional dryness or wetness and is based on the depth of rainfall over temporal scale (Tsakiris and Vangelis 2004; Cancelliere et al. 2007; Mishra and Singh 2010; Thomas et al. 2015).

Several studies have reported the suitability of SPI for the Indian subcontinent. Pai et al. (2014) examine the district-wide drought climatology for the southwest monsoon over India and the results show that the Standardized Precipitation Index (SPI) is a better drought index than Percent of Normal Precipitation (PNP). Palchaudhuri and Biswas (2013) employ the SPI using daily gridded precipitation data generated by the India Meteorological Department to study severity and spatial pattern of meteorological drought in Puruliya district in West Bengal, India.

Mundetia and Sharma (2015) obtain the rainfall indices and SPI for the state of Rajasthan, reporting a noticeable increase in the frequency of severe droughts on a longer time scale. SPI has been used in the drought analysis of Parambikulam-Aliyar basin, Tamil Nadu. There are recent instances where the India Meteorological Department (IMD) has declared drought in several districts of Kerala and this work analyzes the drought occurrence in detail. Based on the stable performance across various parts of India, the present study employs the SPI for analysis of drought. Based on the review of literature, the objectives of the present study are thus defined as: (1) to evaluate the long-term trend analysis of rainfall, temperature and drought indices over the tropical state of Kerala; (2) to examine the variability of extreme climate events at different time steps; (3) to analyse the intensity and frequency of drought in the region.

Regional setting of the study area

Kerala is located along the western portion of peninsular India (8° 15' N to 12° 50' N and 74° 50' E to 77° 30' E) with a total area of 38,863 sq. km. Geographically, the state is divided into three distinct regions which include the eastern highlands, the central midlands, and the western lowlands. Considering the natural climatic zones (variability of rainfall and temperature), this paper categorizes Kerala into three regions as northern Kerala (districts of Kasaragod, Kannur, Wayanad, Kozhikode, and Malappuram), central Kerala (districts of Palakkad, Thrissur, Ernakulam, Idukki and Kottayam districts) and southern Kerala (districts of Thiruvananthapuram, Kollam, Alappuzha and Pathanamthitta districts) for the analysis [Figure 1 (a)].

Data sources and methodology

Daily gridded rainfall data of 0.25° x 0.25° spatial resolution (65 grid points) for the period from 1901 to 2018 and temperature data of 1° x 1° spatial resolution (5 points) for the period from 1951 to 2018 were procured from the IMD, Pune (Pai et al. 2014). The scatter plots were prepared by averaging all the grid points in each region (24, 27 and 14 grid points for north, central and south zones respectively) of Kerala for annual and seasonal time steps. The spatial variation of the rainfall characteistics within each zone is neglected. The temperature data was not regridded (2, 2 and 1 for north, central and south zones respectively) as the spatial variation of temperature within each zone of Kerala was not significant. The trend was detected at 5% significance level using the Mann-Kendall trend test and the magnitude of the trend was quantified using the Sen's Slope estimator. The long-term trends of seasonal and annual climate (rainfall, temperature) for the three zones of Kerala were generated using daily recorded values of climatic variables for robustness.

In this study, 24 climate indices were evaluated on an annual basis based on daily climate variables for the base period 1901-2018 to detect climate change signals and suit a wide range of applications such as periods of dryness, wetness, heat or cold, periods of mildness as in the case of the growing season. The climate indices were calculated following the guidelines provided by the World Climate Research Programme (ETCCDI 2021). The thresholds for extreme climate indices were chosen to indicate the number of days exceeding percentile thresholds and are more meaningful since they are evenly distributed in space and time. These thresholds were set such that the frequency of threshold crossing the base period is fixed. 90th, 95^{th,} and 99th percentile values were used to obtain the number of days having precipitation more than the upper limit threshold and these indices are denoted as R90, R95, and R99 respectively. Precipitation contribution from these days in each year was denoted as R90p, R95p, and R99p. Similarly, the number of days having precipitation less than the lower limit threshold (1st, 5th, and 10th) for each year was calculated (R1, R5, and R10) and precipitation contribution from these days in each year (R1p, R5p, and R10p) was also determined.

Twelve extreme indices for temperature were adopted to understand the variation of temperature indices among extreme and average years as per ETCCDI guidelines. TX90, TX95, and TX99 (denoting warm days) were evaluated for the number of days having a maximum temperature greater than the threshold value of 90^{th}, 95th, and 99^{th} percentile of daily time series. Similarly, TX1, TX5, and TX10 (denoting cold days) were evaluated for the number of days in each year when daily maximum temperature was less than 1^{st}, $5^{th,}$ and 10^{th} percentile of daily time series. TN1, TN5, and TN10 were denoted for cold nights having daily minimum temperature below 1^{st},5^{th} and 10^{th} percentile, and TN90, TN95, and TN99 were the warmer nights having a daily minimum temperature greater than the threshold (90^{th}, $95^{th,}$ and 99^{th}). The list of indices used in this study and their definitions are available elsewhere (ETCCDI 2021).

The Standardized Precipitation Index (SPI) used for quantifying meteorological drought in this study was evaluated using long-term precipitation data for 118 years (1901-2018). For the computation of SPI values, daily gridded rainfall data was integrated in to monthly scale and each grid point is considered as a station. The precipitation data were fit into gamma distribution and later transformed to normal distribution to ensure SPI for the desired location and period is zero (Edwards and McKee 1997). A unix - style filter was used for the calculation of SPI values at different time scales in the present study. This enabled SPI calculation for six-time scales at a given time and location. To quantify the intensity of drought, consecutive negative SPI values up to -1 or less were considered as the occurrence of a drought event. Droughts were further classified as Mild Drought (SPI of -0.5 to -0.99), Moderate Drought (-1.0 to -1.49), Severe Drought (-1.50 to -1.99) and Extreme Drought (<-2) (McKee et al. 1993). The nonparametric Mann-Kendall test used by many researchers (Taylor and Loftis 1989; Burn 1994; Burn et al. 2004; Thomas et al. 2015) was applied to identify the trends in the SPI time series. The methodology of the present investigation is shown in Figure 2.

Results and Discussion

Trend Analysis

Rainfall

The statistics for zonal average rainfall were obtained from the daily gridded data for the period 1901 to 2018 and are presented in Table 1. It is evident that the annual average rainfall in northern Kerala (3211mm) is more than the other two zones and the southern districts of Kerala receive the least rainfall (2308mm). The north-east monsoon, winter and summer rainfall increase towards the south in Kerala. The spatial distribution of rainfall showed a strong gradient in the rainfall received by the three zones [Figure 1(b)] from the sea coast to the Western Ghats. The immediate windward side of the Western Ghats receives less rainfall due to the higher altitude. Thus, topography plays an important role in the distribution of precipitation over the region. The temporal distribution indicates that southern Kerala receives more rainfall during winter and summer seasons as compared to the other two zones. But the coefficient of variation was highest in winter followed by the summer rainfall (Table 1). The topography of the Western Ghats plays a role in intercepting rainfall and studies report the maximum rainfall occurs at a certain distance on the windward side from the crest of the Western Ghats (fig. 1b) and depends on the mountain barrier followed by the steepness of windward side slope and altitude of the mountain (Mudbhatkal and Mahesha, 2018; Tawde and Singh 2015). Since the Western Ghats do not extend up to the southern end, there could be the least interference on the north-east monsoon for southern Kerala.

The trend of rainfall over 118-years was analyzed on an annual and seasonal basis and these trends are illustrated using scatter plots. From Figure 3 (a-e), it may be observed that rainfall over all three regions of Kerala has been decreasing over time. The interannual/decadal variations from the average rainfall exist but there is no clear evidence to suggest that the strength and variability of the monsoon rainfall are dependent either on global warming or El Nino- Southern Oscillation (ENSO) phenomenon during the study period as was confirmed earlier (Kripalani et al. 2003; Sameer et al. 2020). There was no change in the trend during the 1990s which was the warmest decade of the previous century. A decreasing trend was observed for annual and seasonal time steps and the magnitude of decrease in northern Kerala was more pronounced compared to central and southern regions. The results of the Mann-Kendall trend test and Sen's slope estimator are presented in Table 2. The decrease in annual rainfall is more in northern Kerala compared to the other two regions. The magnitude of decrease in annual and south-west monsoon rainfall northern Kerala was found to be 5 mm/year and 6 mm/year (at 5% significance level) respectively. The south-west monsoon also shows a decrease of 3.36 mm/year in southern Kerala. Results for central Kerala show a decrease but were found not to be significant statistically. The study on subdivisions of India reported that annual rainfall in Kerala is decreasing at the rate of 1.3% of mean/100 years (Kumar et al. 2010). North-east monsoon rains contribute to mean rainfall of 385 mm to 530 mm/year and a statistically significant decrease was found in northern Kerala and central Kerala (1 mm/year). However, southern Kerala did not portray a significant trend which could be due to the absence of Western Ghats barrier against the north-easterly winds. The winter rainfall was found to decrease in all three zones with high statistical significance. It may be noted that the mean rainfall during winter ranges from 36 mm/year (northern Kerala) to 94 mm/year (southern Kerala). The summer rainfall of 293 mm/year (north Kerala) to 442 mm/year (south Kerala) which is crucial in moderation of temperature in hot summer months did not exhibit a significant decrease across the state. These findings were justified with earlier studies on the analysis of monsoon rainfall with the ENSO phenomenon and Darwin Pressure Tendency (DPT) (an index of ENSO) indicating that the relationship has changed sign around 1990 and showed maximum positive relationship during the 1990s (Kripalani et al., 2003, Reddy and Ganguly, 2012).

The trend of rainy days (rainfall >2.5 mm/year) was further evaluated and a general decrease in rainy days was observed [Figure 4 (a-e)]. The number of rainy days signifies the intensity of rainfall and is a vital factor in runoff generation, deep percolation, and other aspects of the hydrological cycle. The annual average rainy days experienced byg northern Kerala, central Kerala, and southern Kerala are 170, 180, and 180 days respectively. The results of the trend analysis of rainy days across various seasons are presented in Table 3. The results show that the number of annual rainy days is decreasing across all the three zones of Kerala but, the decrease was significant in central and southern Kerala (2.8 days/decade). In the case of northern Kerala, the decrease in the rainy days during the winter season was statically significant. All the seasons in central Kerala show a significant decrease in rainy days especially during south-west monsoon (1 day/decade) and north-east monsoon (0.7 days/decade). The decreasing rainy days in southern Kerala during all the seasons except summer is significant. Extended dry spells and a decline of agricultural production in Kerala have been reported in recent times (Guhathakurta and Rajeevan 2008; Pal and Al-Tabbaa 2009). The study carried out on increasing temperatures and precipitation extremes (Mukherjee et al., 2018) indicated that anthropogenic warming contributes to an increase in the frequency of precipitation extremes and may have implications on infrastructure, agriculture, and water resources in India.

It is interesting to note that the decrease in rainy days is more pronounced in central and southern regions of Kerala although total rainfall does not indicate a more pronounced decrease. This leads to an inference that although there is a decrease in rainy days, central and southern Kerala are receiving higher intensity of rainfall for shorter durations. This is in agreement that extreme heavy events (>95th percentile) are increasing in intensity and/or frequency across peninsular India (Bisht et al., 2018; Dash et al., 2009, 2011; Goswami, et al., 2006; Krishnamurthy et al., 2009; Malik et al., 2016; Mukherjee et al., 2018; Rajeevan et al., 2008; Roy & Balling, 2004; Vittal et al., 2013). These increasing extremes are dominated by an increase in short duration (≤4 days) but intense (>99th percentile) rainfall spells (Dash et al., 2011; Vinnarasi and Dhanya, 2016) since longer duration events are decreasing. A direct consequence of a high-intensity rainfall for shorter durations is abnormal rainfall to runoff conversion triggering an increase in natural disasters such as landslides. This is because high-intensity rainfall saturates soil on the slopes and soils with higher clay content having more water retention capacity and low drainage result in high pore pressure along the slopes. This is evident in the state of Kerala which has been witnessing major monsoon–related landslides during the years 2018, 2019, and 2020 (NRDF 2019) which experienced heavy rainfall (up to 164% excess of monthly average) occurred over a few days during August. The issue is exacerbated by heavy loading on the slopes by buildings on the cut-and-fill ground (usually without adequate protective measures on the uphill and downhill sides) which may generally be observed in Kerala. It is also a general practice in Kerala to create small pits (makeshift reservoirs) by altering hillslopes to store water for irrigation by obstructing natural drainage. These reservoirs lead to increased infiltration and super saturation of soil along hillslopes (Wadhawan et al. 2020).

Temperature

The spatial variation of mean annual temperature over Kerala is shown in Figure 1 (c) and mean temperatures are higher towards the south. This study analyzed the mean, maximum, and minimum temperature over Kerala on an annual and seasonal basis to evaluate climate change signals and its effects in moderation of long-term climate. The scatter plots for long-term variation of mean temperature for annual, south-west monsoon, north-east monsoon, winter, and summer seasons are presented in Figure 5 (a-e). A continual rise in mean temperatures over time may be observed across all the time steps. The increase in temperature was further quantified and the results are shown in Table 4. Results indicate a higher rate of warming in northern Kerala at the rate of 0.13°C/decade (statistically significant at 5%) and 0.12°C/decade in central and southern Kerala. Increasing mean temperatures during south-west and north-east monsoon over the entire state indicate overall warming. A recent study of borehole temperature profiles and surface air temperature (SAT) profiles (Jha et al. 2020) over the Western Ghats of India also reports warming of 0.8 ± 0.2 °C over the past 100 years in the region.

The rate of increase in annual maximum temperature was highest in southern Kerala (0.21°C/decade), 0.20°C/decade in northern Kerala, and 0.18°C/decade in central Kerala (Table S2). The results also reveal an increase in maximum temperature during south-west monsoon over all the three zones (0.20, 0.20, 0.22°C/decade for northern Kerala, central Kerala and southern Kerala respectively). The south-west monsoon season being the principal crop season of Kerala, the increased temperature may implications on crop behavior and yield. The rate of increase in minimum temperature is shown in Table S3. The increase of annual minimum temperature per decade in northern, central, and southern Kerala was found to be 0.05°C, 0.06°C, and 0.06°C respectively. Also, the minimum temperature during south-west monsoon and north-east monsoon across Kerala were seen to increase. An increase in maximum and minimum temperatures at such high rates is a cause of serious concern as it can be inferred as a 1°C rise in future temperature within less than five decades. Studies have reported that increasing temperatures could lead to an increase in the frequency of precipitation extremes especially in southern India (Mukherjee et al. 2018) and this is observed from the present study over Kerala which could be due to anthropogenic warming and an increase in extreme precipitation over last few years.

Extreme climate indices

Precipitation Indices

The extreme precipitation indices were computed at the annual scale and results of trend analysis of indices are presented in Table 5. The results suggest that trend of analysis of extreme indices is not uniform over the entire state (Figure S1). It may be seen that dry days are increasing at an alarming rate in all three regions of Kerala. The trend analysis was also carried out for a higher threshold (90^{th} and 99^{th} percentile) and a significant reduction was observed over northern and southern Kerala. R99 index was significant only in northern Kerala indicating a decrease in extreme wet days [Figure S1 (a-b)]. The central region did not portray statistically significant changes in high precipitation indices. The Mann-Kendall trend test and Sen's slope estimator suggest that R95 and R95p [Figure S1 (c-d)] over northern Kerala and southern Kerala show a strong and significant decreasing trend whereas the negative trend of R95 in central Kerala was not statistically significant in central Kerala. Temporal variations in R95p were observed in northern Kerala (decreasing from 1246 mm in 1901 to 120 mm in 2016). It may be observed that the R5 index has increased all over Kerala [Figure S1 (g)] indicating the number of days where the precipitation depth is less than the 5^{th} percentile is increasing across Kerala. The increasing trend in R5 was found to be significant over central and southern Kerala (55 to 103 days). At the same time, R5 showed a weak and insignificant increase over northern Kerala but statistically significant in central and southern Kerala.

Maximum Temperature Indices

The long-term scatter graphs of maximum temperature indices over Kerala are presented in Figure S2. A dominant increasing trend of hot days over the entire state is indicated from the analysis of temperature indices. TX95 which is a measure of hot days increased from 0 days in 1951 to 73 days in 2016 in northern Kerala which is a matter of concern. Also, in southern Kerala, TX95 was found to have a prominent increasing trend (4.4 days/decade) compared to other parts of the state. Figure S2 (e) depicts TX5 (lowest daytime temperature or cold days) trend over Kerala which indicates a significant decreasing trend over the state. The TX5 index value was 15 in 1951 for northern Kerala and it has decreased to 3 in 2017. This reduction in the number of cold days in northern Kerala is very alarming. The trend analysis results of maximum temperature indices are tabulated in Table S3. The trend analysis was also carried out for other thresholds of extremes of daily maximum temperature (90^{th} and 99^{th} percentile for higher threshold and 1^{st} and 10^{th} percentile for the lower threshold).

Minimum Temperature Indices

Figure S3 shows the trends of minimum temperature indices over Kerala and results are tabulated in Table S4. The results indicated a significant increase in TN95 throughout the state except for southern Kerala and the number of warm nights has increased from 14 (1951) to 56 (2017) in northern Kerala. The value of TN95 has increased to a maximum of 1.6 days/decade in north Kerala. The trend analysis was also carried out for 90^{th} and 99^{th} percentiles of daily minimum temperature. It was found that TN90 is significantly increasing over the entire state whereas no trend for TN99. Figure S2 (e) presents the trend of TN5 over Kerala which is a measure of coldest nights. TN5 exhibited a significant decreasing trend over central and southern Kerala. TN5 index for central and southern Kerala exhibits a significant decreasing trend. The number of cold nights (TN5) has decreased from 12 (1951) to 0 (2016) in southern Kerala. The value of TN5 has decreased by 1.3 days/decade in southern Kerala which is higher compared to other parts of the state.

Drought analysis

In this study, SPI was calculated at 1-, 3-, 6- and 12-month time scales (SPI1, SPI3, SPI6, and SPI12) for 65 grid points in Kerala to assess the anomalies of total rainfall over 1901 to 2018. Shorter time steps (SPI1 and SPI3) reflect short-term conditions and immediate impacts such as soil moisture and streamflow in small streams. SPI3 is effective in highlighting available moisture conditions in primary agricultural regions such as India. Medium accumulation period (SPI6) reflects changes to streamflow, reservoir levels, and is also effective in reflecting rainfall over distinct seasons (seasonal estimation of precipitation). Longer accumulation period (SPI12) reflects changes to groundwater recharge and reservoir storage and streamflow in rivers (WMO 2012). Kumar et al. 2010 suggest interpreting SPI with caution while assessing the intensity of drought and therefore the results of SPI in this study were interpreted by comparing with trend analysis of rainfall to ensure the correctness of the interpretation of SPI values.

Using the calculated SPI values, drought frequency was calculated as number of drought events in each category over 1901-2018. The drought frequency expressed in terms of percentage of occurrence was calculated for all 65 rainfall grid points and for the four time scales adopted in this study (SPI1, SPI3, SPI6, and SPI12). The percentage of occurrence for all 65 rainfall grid points was then interpolated to determine the spatial variation of drought frequency in each category of drought. Figure 6 presents the maps of Kerala showing the frequency of three drought categories (moderate, severe and extreme) for SPI1, SPI3, SPI6, and SPI12. It may be observed from Figure 6 that the frequency/percentage of occurence of moderate drought over the study area was 9.62% and higher in the southern and central parts of Kerala for 1- month time step. But, in 3-, 6- and 12- month time scales, the occurrence of moderate drought was higher in central and northern Kerala. The percentage of occurrence of moderate drought in a 12-month time scale was 15.3%. Severe droughts occur more in southern and central regions of Kerala as compared to the north. Severe drought occurrence is higher on a 12-month time scale and the percentage drought occurrence was found to be 8.02%. The frequency of extreme drought is low in the study area as compared to moderate and severe droughts. The occurrence of extreme drought is more in the southern and central part of Kerala.

Detailed analysis of SPI3

SPI3 was used to indicate the soil moisture availability during cropping season in Kerala and long-term temporal variation of SPI3 was analyzed for all the grid points in the study area. The trend analysis of SPI3 was carried out for June, July, August, and September for all the grid points in the 14 districts of Kerala. Most of the stations indicate a significant falling trend at a 5% level. The recent severmost drought was in the year 2015 followed by in 2016. A drought severity map for SPI3 corresponding to August 2005 [Figure 1 (d)] shows most of Kerala is subjected to extreme drought (SPI<-2) during August 2005. The drought severity map for other duration SPI are shown in Fig. S4. The areal extent of doesn't show much difference with variation of SPI duration and as duration SPI increased, the southern and south-eastern part of Kerala got relieved from drought. The severity of drought for SPI3 on station-basis in August 2005 showed an SPI value of -3.23. In Thiruvananthapuram district of south Kerala, the maximum SPI value (-4.53) occurred during April 1983 (summer). In Kollam, Pathanamthitta, Alappuzha and Kottayam districts, the highest severity of drought occurred in August 2005 at station 5 (-5.07), station 8 (-4.24), station 14 (-4.61) and station 17 (-4.11) respectively. In Idukki district, maximum SPI3 value was found in station 24 in August 1987 (-3.55). The results of SPI3 reveal that all other districts in Kerala experienced extreme drought in August 2005 indicating a likely water-deficit in the state of Kerala.

Conclusions

The investigations on trends of climate variables for the state of Kerala, India were carried out considering its dependency on the monsoon rains. The declining trend of annual and seasonal rainfall was detected for the entire state based on the long-term data for 118 years (1901 – 2018). The south-west monsoon rainfall is predominantly decreasing in north Kerala compared to the other two regions of the state. The declining trend of annual and south-west monsoon in northern Kerala (63 mm/decade and 55 mm/decade) and southern Kerala (34 mm/decade and 24 mm/decade) were found to be significant. The monsoon rains being the major source of water, the quantum of decrease would play a major in assessing the water availability for the entire year.

The average annual rainy days experienced by the northern, central, and southern Kerala were 170 days, 180 days, and 180 days respectively. The results of the trend analysis of annual and seasonal rainy days showed a decreasing trend for all the three regions of Kerala. The Mann-Kendall analysis for the number of rainy days showed a declining trend of annual rainy days (2.76 and 2.76 days/decade), south-west monsoon (1.1 and 1.3 days/decade), north-east monsoon (0.7 and 0.5 days/decade) and winter (0.4 days/decade and 0.3 days/decade) in central and southern Kerala. The decrease of annual and seasonal rainy days (except for winter) in northern Kerala has no significance. Compared to the other zones, central Kerala experienced a maximum decrease in the number of rainy days (annual). The decrease in rainy days is more during the south-west monsoon all over the state. It is important to note that the implications of higher intensities of rainfall over a shorter period (fewer rain days) are leading to faster filling up of makeshift reservoirs/pits and major landslides in Kerala affecting human lives which were reported over the recent years in central Kerala.

The average annual mean temperature during 1901-2018 for northern, central, and southern Kerala was 24.3, 23.9, and 27 °C respectively. The temperature of central Kerala is comparatively lesser than the other two regions with southern Kerala being the hottest region. The results indicate that northern Kerala and southern Kerala have the highest rate of temperature rise. The increase of annual mean temperature in northern Kerala is 0.13°C/decade and 0.12°C/decade in central and southern Kerala. The regression and Sen’s slope analysis for mean, minimum, and maximum temperature shows an annual and seasonal increase for all three regions of Kerala. The increase of annual, south-west, and north-east minimum temperature is statistically significant in all the three regions. The increase in maximum temperature during the south-west monsoon season which is the main cropping season may have implications on the crop characteristics and yield. The minimum temperature during the winter and summer season is increasing whereas it has no statistical significance in north Kerala.

The extreme climate indices R95 and R95p show a strong decreasing trend over northern Kerala and southern Kerala. It may be observed that the R5 index (extreme dry days) has increased overall the three parts of Kerala but significant in central Kerala and southern Kerala only. The warm days (TX90, TX95, and TX99) have increased all over the state which is a matter of concern due to the impact on the agricultural sector. Also, in southern Kerala TX95 showed the highest increasing trend (4.4 days/decade) compared to other parts of the state. TX5 (cold days) exhibits a significant decreasing trend in all over Kerala. This reduction in the number of cold days in northern Kerala is very alarming with a reduction of 4.2 days/decade. The results indicated that there is a significant increase in TN95 in northern Kerala and central Kerala. It is found that TN90 is significantly increasing over the entire state whereas increasing TN99 has significance in northern Kerala. The index TN5 exhibited a significant decreasing trend in central Kerala and southern Kerala. This increase in long-term temperature would have an impact on heatwaves, reduction in annual water availability, sea-level rise, and loss of agricultural yield.

The frequency analysis of SPI values shows that the percentage of occurrence of moderate, severe, and extreme drought in terms of SPI values is high and increases from SPI1 to SPI12. The moderate, severe, and extreme drought occurred more in southern and central Kerala than in northern Kerala. The trend analysis of SPI3 revealed that most of the stations in Kerala show a significant falling trend in the SPI values indicating that, the severity of the drought is increasing in the study area. From the trend analysis, it was found that all the stations in Kerala experienced a drought of varying severities during the study period with extreme drought (SPI3<-2) in August 2005. Therefore, this paper concludes with an attempt to investigate and link several pressing environmental issues in Kerala to climate change signals and to cater to a wide range of readership. The outcomes of this investigation may be useful for sustainable regional planning.

Data availability

Some or all data, models, or code used during the study were provided by a third party. Direct requests for these data may be made to the India Meteorological Department (IMD), Pune.

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