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Research Article

Five Decadal Trends in Averages and Extremes of Rainfall and Temperature in Sri Lanka

G. Naveendrakumar,[1,2] **Meththika Vithanage**,[3] **Hyun-Han Kwon**,[4] **M. C. M. Iqbal**,[5] **S. Pathmarajah**,[6] **and Jayantha Obeysekera**[7]

[1]*Postgraduate Institute of Science (PGIS), University of Peradeniya, Peradeniya, Sri Lanka*
[2]*Faculty of Applied Science, Vavuniya Campus of the University of Jaffna, Vavuniya, Sri Lanka*
[3]*Ecosphere Resilience Research Center, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka*
[4]*Department of Civil Engineering, Chonbuk National University, Jeonju, Republic of Korea*
[5]*Plant and Environmental Sciences, National Institute of Fundamental Studies (NIFS), Kandy, Sri Lanka*
[6]*Department of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka*
[7]*Sea Level Solutions Center, Florida International University, Miami, FL, USA*

Correspondence should be addressed to Meththika Vithanage; meththikavithanage@gmail.com

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In this study, we used a comprehensive set of statistical metrics to investigate the historical trends in averages and extremes of rainfall and temperature in Sri Lanka. The data consist of 55 years (1961–2015) of daily rainfall, maximum temperature (T_{max}), and minimum temperature (T_{min}) records from 20 stations scattered throughout Sri Lanka. The linear trends were analyzed using the nonparametric Mann–Kendall test and Sen–Theil regression. The prewhitening method was first used to remove autocorrelation from the time series, and the modified seasonal Mann–Kendall test was then applied for the seasonal data. The results show that, during May, 15% of the stations showed a significant decrease in wet days, which may be due to the delayed southwest monsoon (SWM) to Sri Lanka. A remarkable increase in the annual average temperature of T_{min} and T_{max} was observed as 70% and 55% of the stations, respectively. For the entire period, 80% of the stations demonstrated statistically significant increases of T_{min} during June and July. The daily temperature range (DTR) exhibited a widespread increase at the stations located within the southwestern coast region of Sri Lanka. Although changes in global climate, teleconnections, and local deforestation in recent decades at least partially influence the trends observed in Sri Lanka, a formal trend attribution study should be conducted.

1. Introduction

Understanding historical climate trend is the precursor of sound climate change investigations [1]. Assessing historical rainfall and temperature is essential for formulating plausible weather and climate predictions, especially for developing South Asian countries like Sri Lanka. Located at the southern tip of the Indian mainland, Sri Lanka geographically falls within the tropical latitude of 5°55′–9°51′N and longitude of 79°42′–81°53′E [2]. With a population of nearly 21 million and natural forest cover over 29% of the total land area, Sri Lanka has undergone rapid transformations in land use during the past decades due to deforestation for crop and plantation agriculture, increased need for infrastructure, and significant conversions of wetlands and agriculture land to human settlements. These land use changes are likely to have a feedback effect on the local climate and cannot be ruled out as a factor in historical trends. Increases in extreme weather, both in terms of frequency and magnitude, are a serious challenge for coping with changing climate. The IPCC (Intergovernmental Panel on Climate Change) has determined with high confidence that the intensity of rainfall events will increase with warming temperatures in some parts of the globe [3]. Often, climate change first appears as an increase of intensity and frequency of extreme weather events [4], and therefore, it is essential for historical trend assessments to include extreme events. Sri Lanka is affected by both floods and severe droughts, and the impacts of both have intensified in recent years [5–8].

Assessments of changes in historical trends regarding averages and extremes are essential to introduce adaptation policies to prepare for future extreme events in Sri Lanka. The analyses of extreme rainfall and temperature investigations are also crucial for developing policies associated with long-term planning in agriculture sectors, national heritage sites, tourism sectors, disaster resilience, and many commercial entities which have a direct connection to weather events. Because Sri Lanka is an agricultural country, trend and extreme climate studies will help the agriculture and plantation sectors to introduce appropriate cropping patterns and develop new varieties that can tolerate extreme temperatures.

There have been some prior investigations of rainfall and temperature in Sri Lanka, and such studies have demonstrated significant trends [9–11]. For instance, the dynamic trends in rainfall extremes in Sri Lanka have shown that Colombo experienced the highest value in 2010 among all severe extremes in the historical records [12].

Rather than a parametric analysis, like those used in previous studies to examine rainfall and temperature trends [13–15], the nonparametric investigation used in this study is more appropriate for detecting historical rainfall and temperature trends due to a variety of factors. It is even true in situations with missing/censored data as in Sri Lanka. In particular, such methods are more appropriate for situations in which climatic records include missing/censored data as in Sri Lanka. Prior studies lacked appropriate statistical methods for investigations of extremes. Although nonparametric statistical techniques were previously used by Karunathilaka et al. [11], Herath and Rathnayake [9], and Jayawardene et al. [10], seasonality components were not addressed appropriately for the detection of long-term trends. Recognizing the incomplete nature of prior studies, the objective of this investigation was set to reveal consistent historical linear trends in averages and extremes of rainfall and temperature records of Sri Lanka using both parametric and more robust nonparametric statistical techniques with appropriately handled seasonal components and potential autocorrelation.

In the next section, we review previous studies of factors that influence the climate of Sri Lanka. The sources are described in terms of their necessity and importance. We follow by describing the methods used for the analysis of climatic trends. We finalize by summarizing consistent trends and results and presenting conclusions.

2. An Overview of Climate in Sri Lanka

2.1. Current Climate. Two monsoonal winds primarily influence the climate of Sri Lanka. The first southwest monsoon (SWM) and second northeast monsoon (NEM) reach Sri Lanka during the months of May to September (MJJAS) and December to February (DJF), respectively [16]. During the SWM and NEM seasons, winds come from the northeast and southwest [17], respectively (Figure 1). The periods between these primary monsoons are referred to as intermonsoonal seasons, which usually last for two months. They are called the first intermonsoon (FIM) and second intermonsoon (SIM) and occur during the periods of March-April (MA) and October-November (ON), respectively [16, 18]. Regional climatic patterns in Sri Lanka are primarily influenced by the El Niño-Southern Oscillation (ENSO) [19]. Due to its island geography, seasonal monsoons moderate the climate of Sri Lanka [20, 21]. There is significant spatial variation in temperature due to variations in elevation across the island. Accordingly, two very distinct temperature regimes occur, low-country (or lowlands) and up-country (highlands >300 m MSL), characterized by annual average temperatures of 26.5–28.5°C and 15.9°C, respectively [22]. Due to its tropical climate, evapotranspiration losses are high in the higher temperature regimes of Sri Lanka [23]. In addition to monsoonal seasons, teleconnections influence the climate of Sri Lanka, as rainfall and temperature are strongly influenced by those phenomena. Climate change may cause increases in temperature in Sri Lanka that are more rapid than the rate of global warming [24]. As a result of climate change, drought is inevitable in almost all regions of Sri Lanka [25].

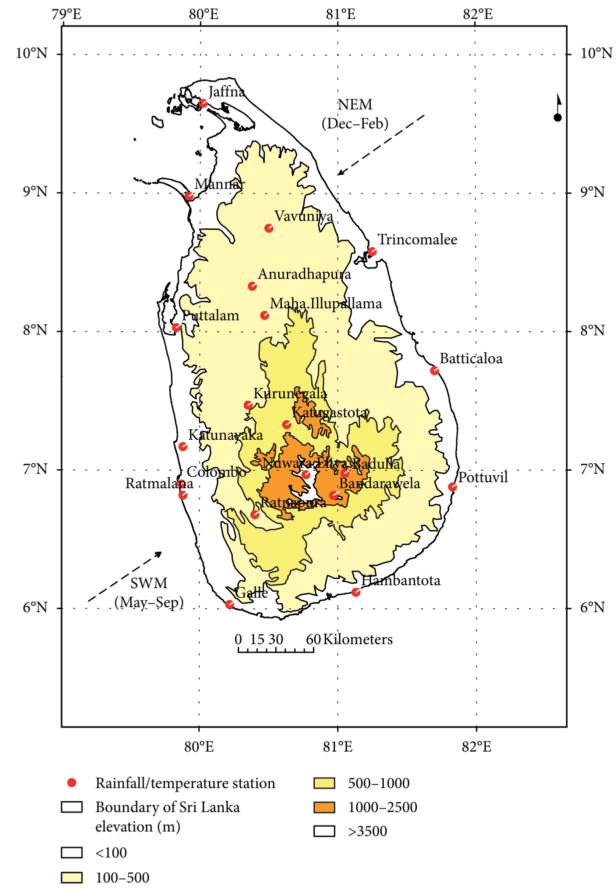

Figure 1: Long-term temperature stations used for historical analysis. NEM (northeast monsoon) and SWM (southwest monsoon) indicate the directions of monsoonal winds in Sri Lanka. Topographical variation is shown in colored gradient.

2.2. Rainfall. Previous studies on rainfall in Sri Lanka emphasize that extraordinary rainfall extremes are concentrated in the southwestern part of the country, especially the Colombo and Ratmalana regions [12]. According to Karunathilaka et al. [11], annual rainfall data demonstrate that nearly two-thirds of monitored stations indicate increasing trends, while the remaining one-third showed decreasing trends. High-intensity rainfall events cause flash floods in urban areas, and such flooding has been frequent during recent years. An exception is the Nuwara Eliya station, which showed decreasing trends for all extreme indices, including frequency and intensity of rainfall [12]. Wet-zone cities such as Ratnapura, Ratmalana, and Colombo are profoundly affected by rainfall extremes. The annual maximum consecutive five-day rainfall also shows significant increasing trends in Batticaloa, Colombo, Hambantota, Ratmalana, and Trincomalee [12]. Teleconnections play a significant role in driving rainfall over Sri Lanka [26]. The El Niño-Southern Oscillation (ENSO) phenomenon is the primary climate driver in Sri Lanka and on the Indian mainland. Variation in both means that rainfall intensity and total rainfall across monsoon seasons showed high correlations with ENSO events [16, 27, 28].

2.3. Temperature. Most of the temperature-related investigations in Sri Lanka have demonstrated warming trends [15, 27, 29, 30]. Using monthly mean temperature as baseline data, De Costa [13] detected long-term (1869–2007) annual temperature increases. De Costa [13] also showed that the mean monthly maximum and minimum temperature trends were 2.6°C per 100 years and 1.7°C per 100 years, respectively. According to Zubair et al. [15], the recent period (1961–2000) shows accelerated daytime warming trends. Other studies of Sri Lankan annual mean temperature data for the period 1871–1990 confirmed significant warming trends in most districts [14, 27]. The factors contributing to increasing temperatures in Sri Lanka are anthropogenic activity connected with forest cover depletion, urbanization, natural teleconnections, and global climate change. Although the urban "heat island" effect probably influences temperature increases in Sri Lankan cities, studies are unable to confirm this relationship. It is evident from the above-described trends that temperatures in Sri Lanka are changing, but it is difficult to extract patterns of extreme temperature events from some previous studies because monthly mean and average daily temperatures are used as baseline data [31].

3. Materials and Methods

3.1. Data. We investigated station records of daily total rainfall (mm) and raw (or unadjusted) temperature (°C) for the 55-year period between 1961 and 2015. Daily total rainfall and daily maximum ($T_{\max}$) and minimum ($T_{\min}$) ambient air temperature records at 20 synoptic meteorological stations scattered throughout the island were selected for analysis (Figure 1). These records were obtained from the Meteorological Department of Sri Lanka. The rainfall and temperature data investigated are subject to consistency checks related to station relocations, instrumentation upgrades, and changes in the surrounding ecosystem that are likely to introduce heterogeneity in data, leading to partly misrepresenting the actual trend. Furthermore, adjustments to such heterogeneities may introduce spurious trends in the data [32]. Therefore, initially, raw (unadjusted) data were chosen to quantify the trends. The statistical trends in rainfall, $T_{\max}$, and $T_{\min}$ were investigated using a suite of climate metrics (Table 1). The DTR in Table 1 was computed as the difference between $T_{\max}$ and $T_{\min}$ [1, 33]. The measures of rainfall and temperature trends were investigated for annual and the four monsoonal seasons in Sri Lanka. Table 1 groups months to represent the distinct monsoonal seasons in Sri Lanka. Such partitioning into seasons has been used widely in previous investigations relevant to the climate of Sri Lanka [16, 18, 19, 34].

3.2. Mann–Kendall Test for Trend Detection. Although it is possible that nonlinear trends describe rainfall and temperature data, in this work, we first aim to reveal the presence or absence of linear trends using the year as the explanatory variable. We used standard methods to assess the statistical significance of the slope parameter in the linear trend. For the majority of the measures in this study, the nonparametric Mann–Kendall trend test and Sen–Theil regression were also utilized. Unlike prior investigations that have focused on monthly and annual sums and averages of rainfall and temperature in Sri Lanka, in this study, we also attempted to investigate trends in extreme events using parametric methods. For this purpose, we used the generalized extreme value (GEV) distribution with and without nonstationary parameters [35]. We performed the analysis in the R-programming environment (hereafter R). R is an integrated, interactive environment for data manipulation and serves as a platform for high-level statistical data analysis [36]. We used multiple statistical libraries available in R for trend detection. A significance level of 0.05 was maintained as default for all statistical tests.

The Mann–Kendall test, which is a nonparametric alternative for ordinary least squares (OLS) regression, was used to detect trends. This test [37–39] is resistant to outlier effects and is considered an improvement to OLS [40]. It is capable of detecting nonlinear trends and is ideal for situations in which data are missing, censored, or nonnormally distributed [1, 40]. This situation is typical in Sri Lanka for the rainfall and temperature data.

The Mann–Kendall test is determined by summing the signs of the differences between pairs of sequential data values in a time series as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right), \tag{1}$$

where x_j and x_k are the sequential data values for times t_j and t_k (here, $j > k$), n is the length of the data set, and sgn is the sign function:

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1 & \text{if}\left(x_j - x_k\right) > 0, \\ 0 & \text{if}\left(x_j - x_k\right) = 0, \\ -1 & \text{if}\left(x_j - x_k\right) < 0, \end{cases} \tag{2}$$

Table 1: Rainfall, temperature measures, and seasons investigated to determine average and extreme trends in Sri Lanka.

Variable	Measure
Rainfall	Seasonal total rainfall Seasonal wet days[a] Number of extreme rainfall values (>1-in-2) in seasons[b] Seasonal maximum rainfall Monthly total rainfall Mean and maximum rainfall events of duration 2, 3, 5, and 7 days Number of heavy rainfall events (>1-in-2) of duration 2, 3, 5, and 7 days[c] Mean and maximum number of consecutive dry days
Daily temperature (maximum, minimum, and daily temperature range)	Seasonal average temperature Number of extreme temperature values (>1-in-2) in seasons[b] Maximum and minimum seasonal temperatures Monthly average temperature Maximum temperature values for events of duration 2, 3, 5, and 7 days Number of extreme temperature (>1-in-2) events of duration 2, 3, 5, and 7 days[c]
Duration of seasons	Annual (Jan–Dec) Southwest monsoon (May–Sep) First intermonsoon (Mar–Apr) Northeast monsoon (Dec–Feb) Second intermonsoon (Oct–Nov)

[a]Rainfall > trace amount (0.254 mm). [b]Those exceeding the value corresponding to the 1-in-2 recurrence interval for the particular seasonal maximum (Table 1). [c]Numbers of events of heavy rainfall and extreme temperature are those exceeding the value corresponding to a 1-in-2 recurrence interval for the maximum magnitude event of the specific duration 2, 3, 5, and 7 days.

The null (H_0) and alternate (H_a) hypotheses were set as follows:

$$\begin{aligned} H_0 &: S = 0, \\ H_a &: S \neq 0. \end{aligned} \quad (3)$$

The null hypothesis, H_0, is that the observations, x, represent a sample from n iid (independent and identically distributed random variables) and that there is no trend. The alternate hypothesis, H_a, states that there is a trend in the data (i.e., the distributions of x_k and x_j are not identical for all x, $j \leq n$ and $k \neq j$). Here, H_0 is rejected when the magnitude of S is statistically significant. We used Kendall package in R to perform the Mann–Kendall test.

When $n \geq 10$, S in the Mann–Kendall test approximately follows the normal distribution and is therefore converted to a standard normal variate, Z_S (i.e., $N \sim (0, 1)$) [38]. Here, Z_S is determined using

$$Z_S = \begin{cases} \dfrac{S-1}{\sigma_S} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \dfrac{S+1}{\sigma_S} & \text{if } S < 0, \end{cases} \quad (4)$$

The standard deviation, σ_s, of S is given by Kendall [38] as follows:

$$\sigma_s = \sqrt{\frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right]}, \quad (5)$$

where t_p is the size of the p^{th} tied group and q is the number of tied pairs. H_0 is rejected if $|Z_S|$ is greater than the critical value, $Z_{\alpha/2}$, where α is the level of significance.

The Sen–Theil estimator was used to compute the magnitude of the slope of the trend when it is significant [41, 42]. The fitted regression, or Sen–Theil trend line, is a nonparametric alternative to linear regression that is used in conjunction with the Mann–Kendall test. Unlike linear regression, Sen–Theil regression does not require the data to be normally distributed. However, the method still assumes that the residuals are statistically independent, and that there is a linear relationship between variables. It has the additional advantage of handling censored and missing data, and therefore, it is considered to be robust.

The Sen–Theil slope estimation method consists of computing a simple pairwise estimate as shown in the following equation, for all distinct pairs of observations (x_j, x_k), where $(t_j > t_k)$:

$$S_{kj} = \frac{\left(x_j - x_k\right)}{\left(t_j - t_k\right)}. \quad (6)$$

There will be $N = (n(n-1))/2$ slope pairs in the sample size of n. The slope (b) can be determined as the median of all pairwise slopes [$b = \text{median}\,(S_{kj})$], whereas the intercept (c) is given by $c = \text{median}\,(x - bt)$. Because it takes median pairwise slopes instead of the average, the extreme pairwise slopes caused by outliers have little impact on the magnitude of the slope.

The Mann–Kendall and Sen–Theil methods rely on the underlying assumption that observations are independent and identically distributed (iid). Therefore, if there is a significant positive autocorrelation, the test tends to overestimate significance, which leads to the rejection of H_0 according to the selected level of significance. The opposite is also true when the test tends to underestimate significance, possibly when negative autocorrelation exists [43].

Since rainfall and temperature data for Sri Lanka show significant autocorrelation, prewhitening is applied to remove positive autocorrelation. In this investigation, we performed an iterative prewhitening method as executed in the *zyp* package in R [44]. We performed the Mann–Kendall test and Sen–Theil slope estimation after prewhitening the data.

A modified version of the Mann–Kendall trend test was also used to analyze the data set when mild serial autocorrelation is present [45]. When serial dependence is absent, the modified Mann–Kendall trend test is less efficient than the original test. Therefore, in this investigation, we applied the modified Mann–Kendall trend test only when lag-1 autocorrelation coefficient was significant, and if it was not significant, then the original seasonal Mann–Kendall test was performed.

The seasonal Sen–Theil slope estimator is computed by calculating pairwise slopes within each season and obtaining slopes from all seasons to compute a median slope for the entire period of record. In this approach, if there are opposing trends, then the power of the test is reduced because such trends may cancel each other out. Therefore, homogeneity between seasons was initially verified using the van Belle and Hughes trend test [46] prior to the application of seasonal Mann–Kendall and Sen–Theil tests. If the data were heterogeneous between seasons, then the original trend test was performed with prewhitening.

In cases of extremes, the data were fitted using the generalized extreme value (GEV) distribution given in [35] as follows:

$$G(z) = \exp\left\{-\left[1 + \zeta\left(\frac{z-\mu}{\sigma}\right)\right]^{-1/\zeta}\right\}, \quad (7)$$

where μ, σ, and ζ indicate the location, scale, and shape parameters of the GEV, respectively. The GEV is fitted to data by maximum likelihood. The GEV is appropriate for analyzing block-maxima of extreme values [35]. To model block-minima, z is replaced with $(-z)$ in equation (7).

Using a nonstationary GEV model, H_0 was tested for the absence of a trend in location parameter. Under H_a, there exists a trend in the location parameter in the GEV, indicating potential increases in extreme rainfall or temperature. The significance of the trend in the location parameter was evaluated using the likelihood ratio test, which uses the deviance statistic [35] defined as follows:

$$D = 2\{l_1(M_1) - l_0(M_0)\}, \quad (8)$$

where $l_1(M_1)$ and $l_0(M_0)$ are the log-likelihoods of the models M_1 (with trend) and M_0 (without trend). Here, the distribution of D is approximated by χ^2 with degrees of freedom (df) equal to one. The null hypothesis H_0 is rejected when the calculated D critical value for the $\chi^2_{\text{critical, df=1}}$ with the selected significance level (α) is typically assumed to be 5%.

4. Results and Discussions

The trend results for rainfall, $T_{\max}$, $T_{\min}$, and daily temperature range (DTR) in Sri Lanka over the study period 1961–2015 are presented separately. The number of stations (out of a total of 20) with significant values for average and extreme measures listed in Table 1 are summarized in Tables 2–6 for rainfall, $T_{\max}$, $T_{\min}$, and DTR, respectively. The statistical significance of all trends was tested against a consistent α level of 0.05.

4.1. Rainfall Trends. Plots of rainfall data show dynamic trends with increases and decreases during the study period (Table 2). Only two stations show significant trends in annual total rainfall, Katunayaka (decreasing) and Bandarawela (increasing) (Figure 2(a)). A recent study by Karunathilaka et al. [11] also reported both increasing and decreasing trends in annual rainfall in Sri Lanka. However, a previous study using a century-long dataset by Jayawardene et al. [10] reported that the annual rainfall calculated using monthly averages did not show consistent increases or decreases in Sri Lanka. Although annual rainfall showed dynamic trends, one station demonstrated an increase for the NEM season (Figure 2(a)). Katugastota was the only station that detected significant rainfall increase for the NEM season. Although the increases were not statistically significant, 80% of the stations showed increasing rainfall during the NEM season. This overall increase in rainfall during the NEM season agrees with the results reported by Karunathilaka et al. [11]. Trends of rainfall patterns are spatially less coherent [16], but most of the stations in the interior of the island documented increases in rainfall, although only one station showed that it was statistically significant. A decrease in monthly total rainfall was observed throughout the island during the month of May, with two stations (Colombo and Ratmalana) showing that the trend was statistically significant (Figure 1). Such decreases in rainfall are likely due to the delay in the SWM seasonal wind in the region [47–49], which may have affected Sri Lanka. In contrast to this decreasing rainfall, during October and November, rainfall appears to have increased at two stations in the peripheral region of Sri Lanka (Jaffna and Pottuvil), showing a statistically significant trend. This finding of surplus rainfall during the SIM season agrees with the results obtained by Hapuarachchi and Jayawardena [50]. Heavy rainfall during the SIM season is mainly due to massive cyclonic thunderstorms that occur over the northern and eastern parts of Sri Lanka [51] during that period. The rainfall received during this season is critical for the off-season irrigation of agricultural fields.

There have been increasing trends in 2-day, 3-day, and 7-day mean rainfall events, with at least two stations showing statistically significant trends. Only one station has experienced significantly decreasing trends in rainfall for 3-day, 5-day, and 7-day durations (Table 2). This pattern indicates increasing tendencies for short duration heavy rainfall to occur during the study period. Extensive studies of rainfall extremes in Sri Lanka are lacking, but some studies have reported increasing trends in the intensity of rainfall [7, 9, 12, 52].

Another measure for detecting increasing rainfall is calculating the number of wet days in a given season. Only one station showed a statistically significant increase in the

Table 2: Number of stations exhibiting statistically significant trends in measures listed in Table 1 for daily total rainfall from 1961 to 2015.

	Total		Wet days		Extreme days		Maximum values			Total	
	−	+	−	+	−	+	−	+		−	+
Annual	1	1	0	1	0	0	0	2	Monthlies	1	1
SWM	0	0	3	1	0	0	0	3	Jan	0	0
FIM	0	0	0	1	0	0	0	1	Feb	0	0
NEM	0	1	0	0	0	0	0	1	Mar	0	0
SIM	0	0	0	1	0	0	0	3	Apr	0	0
			Mean events for the duration						May	2	0
	2 d		3 d		5 d		7 d		Jun	0	0
	−	+	−	+	−	+	−	+	Jul	1	0
	0	3	1	2	1	0	1	2	Aug	1	0
			Max events for the duration						Sep	0	0
	2 d		3 d		5 d		7 d		Oct	0	1
	−	+	−	+	−	+	−	+	Nov	0	1
	0	0	0	0	0	1	1	1	Dec	0	0
			Number of heavy events for the duration								
	2 d		3 d		5 d		7 d				
	−	+	−	+	−	+	−	+			
	0	0	0	0	0	0	0	0			
			Dry events								
			Mean duration		*Max duration*						
			−	+	−	+					
			0	7	0	4					

Table 3: Decadal changes in rainfall of Sri Lanka during 1961–2010.

Decade	Trend slopes (mm/decade)
1961–1970	−2.9
1971–1980	−2.7
1981–1990	−0.2
1991–2000	−0.9
2001–2010	+0.6

number of wet days during the annual, SWM, FIM, and SIM periods. For the NEM season, none of the stations showed significant trends. Significant decreasing trends were observed at three stations (15% of the total stations) during the SWM season: Anuradhapura, Batticaloa, and Kurunegala (Table 2 and Figure 3). Further investigations may be necessary to detect whether such reductions in wet days during SWM compared to NEM will persist in the future. Jacobi [48] also reported a similar shift in the rainfall pattern of Sri Lanka. Further analyses may also be required to test these shifting trends.

Seasonal rainfall maxima were investigated using the GEV distribution, and the significance of trends in location parameters was tested using the likelihood ratio test. Such tests demonstrate possible nonstationarity in rainfall extremes [35]. In terms of seasonal maximum rainfall, at least one station showed a statistically significant trend and none showed decreasing trends. During the SWM and SIM seasons, three stations showed significant increases in seasonal maxima rainfall. During SWM, coastal stations (Colombo, Katunayaka, and Ratmalana) and during SIM, stations in the interior parts of Sri Lanka (Badulla, Bandarawela, and Ratnapura) demonstrated significant increases in seasonal maxima rainfall (Figure 4 and Table 2).

The decadal changes in rainfall obtained using the island average values of daily rainfall among meteorological stations in Sri Lanka suggest an overall increasing rainfall trend in recent decades. The decadal changes in trend slopes of the Sen–Theil regression are summarized in Table 3. Switching in the signs of rainfall trend slopes occur in very recent decades. The trend slopes during the 1961–1970 and 2001–2010 periods were found to be −2.9 and +0.6 mm/decade, respectively. This indicates that island-wide rainfall shows an increasing trend, especially during the most recent decade.

Even though the number of extreme rainfall or precipitation events has increased across the continents, global historical trends in different countries have mixed anomalies in terms of those events [4]. Extreme rainfall events have been observed in a few countries, whereas in many countries, those extremes have been recorded at 70% below average [49]. Trends in Asian rainfall events indicate that South Asian monsoon rainfall extremes are becoming relatively frequent [53]. An increased frequency of intense rainfall has already been reported with an increased likelihood of extreme rainfall in parts of South Asia [54]. Nepal has shown an increasing trend of annual mean rainfall, especially during the months of June and July [55] agrees with rainfall pattern in Sri Lanka. Though generalized trends in averages have been much studied in the countries of South Asia, extreme rainfall trends are scarcely reported in existing literature.

4.2. Temperature Trends. Results of trend analysis showed a general temperature increase across Sri Lanka, which suggests warming of $T_{\max}$ and $T_{\min}$ for most stations,

Table 4: Number of stations with statistically significant trends in measures listed in Table 1 for daily maximum temperature (T_{max}) from 1961 to 2015.

	Average		Extreme days		Maximum values		Minimum values			Average	
	−	+	−	+	−	+	−	+		−	+
Annual	0	11	0	3	0	9	0	8	Monthlies	0	16
SWM	0	12	1	6	0	12	0	12	Jan	0	11
FIM	1	8	0	3	0	9	0	2	Feb	0	11
NEM	0	9	0	0	0	11	0	5	Mar	0	10
SIM	0	13	0	5	0	9	0	6	Apr	1	7
	Maximum events for the duration								May	0	13
	2 d		3 d		5 d		7 d		Jun	0	14
	−	+	−	+	−	+	−	+	Jul	0	12
	1	4	1	4	1	4	0	2	Aug	0	14
	Number of extreme events for the duration								Sep	0	12
	2 d		3 d		5 d		7 d		Oct	0	15
	−	+	−	+	−	+	−	+	Nov	0	10
	0	0	0	0	0	0	0	0	Dec	1	10

Table 5: Number of stations with statistically significant trends in measures listed in Table 1 for daily minimum temperature (T_{min}) from 1961 to 2015.

	Average		Extreme days		Maximum values		Minimum values			Average	
	−	+	−	+	−	+	−	+		−	+
Annual	0	14	0	2	0	10	0	7	Monthlies	0	15
SWM	0	15	0	6	0	11	0	12	Jan	1	10
FIM	0	10	0	0	0	9	0	10	Feb	2	7
NEM	0	13	0	6	0	13	0	7	Mar	1	10
SIM	0	13	0	8	0	13	0	10	Apr	0	9
	Maximum events for the duration								May	0	14
	2 d		3 d		5 d		7 d		Jun	0	16
	−	+	−	+	−	+	−	+	Jul	0	16
	0	2	0	2	0	4	0	3	Aug	0	13
	Number of extreme events for the duration								Sep	0	14
	2 d		3 d		5 d		7 d		Oct	0	14
	−	+	−	+	−	+	−	+	Nov	1	13
	0	0	0	0	0	0	0	0	Dec	0	12

Table 6: Number of stations with statistically significant trends in measures listed in Table 1 for daily temperature range (DTR) from 1961 to 2015.

	Average		Extreme days		Maximum values		Minimum values			Average	
	−	+	−	+	−	+	−	+		−	+
Annual	3	3	0	3	0	7	0	4	Monthlies	5	6
SWM	1	3	1	2	0	10	0	3	Jan	2	3
FIM	3	4	1	1	0	6	0	4	Feb	2	3
NEM	2	3	1	1	0	6	0	2	Mar	3	3
SIM	2	3	0	1	0	6	0	2	Apr	3	3
	Maximum events for the duration								May	1	3
	2 d		3 d		5 d		7 d		Jun	2	3
	−	+	−	+	−	+	−	+	Jul	5	4
	2	0	2	2	1	2	1	3	Aug	2	5
	Number of extreme events for the duration								Sep	2	3
	2 d		3 d		5 d		7 d		Oct	1	3
	−	+	−	+	−	+	−	+	Nov	3	3
	0	0	0	0	0	0	0	0	Dec	2	2

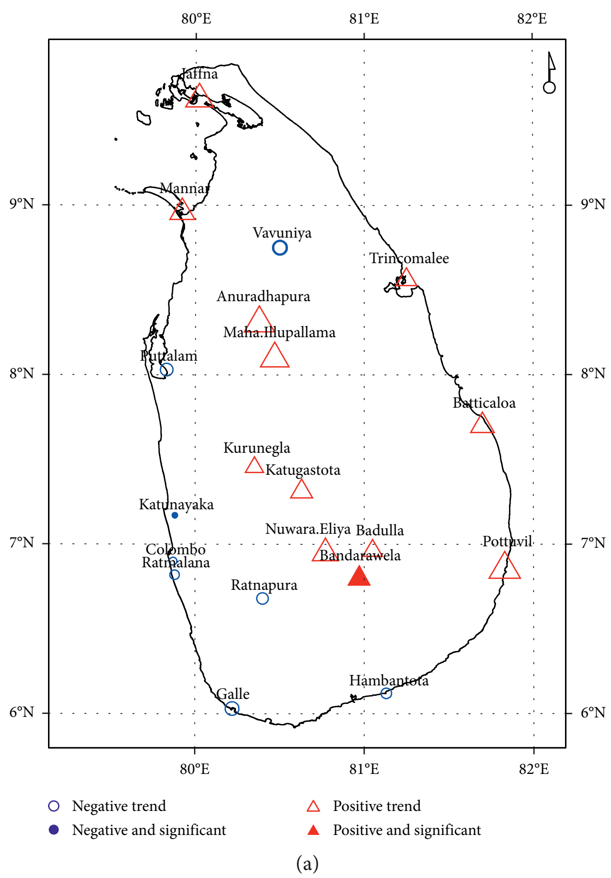

FIGURE 2: Trends in total rainfall: (a) annual and (b) NEM seasons during the study period. Triangles indicate an increasing trend, and circles indicate a decreasing trend. Filled markers indicate significant trends at the α level of 0.05.

except for a few stations in the Southwestern region. Overall, our results show that 55% and 70% of the stations show significant increases in T_{max} and T_{min}, respectively. The overall trends we observed agree well with the results of previous studies [14, 27, 56] indicating overall warming in Sri Lanka.

Increases of daily T_{max} during the study period were observed during October, with the highest number of stations (75%) confirming statistically significant increases (Figure 2(a) and Table 4). During the SWM season, we observed that at least 60% of stations showed significant increases in monthly average T_{max}, and this result agrees with seasonal averages of T_{max}. In all months except for April, at least 50% of stations experienced significant increasing trends. In April, only 35% of stations showed statistically significant increases in T_{max}. Moreover, during May, T_{max} decreased at a small number of stations (10%). This finding may be due to wind effects during the SWM season in Sri Lanka, which might have reduced the ambient temperature. Moreover, during October when SIM is prevalent none of the stations showed significant decreases in monthly averages of either T_{max} or T_{min} (Figure 2).

In contrast to increasing T_{max} trends, Nuwara Eliya and Ratnapura observed decreases during the months of April and December, when the number of stations reporting statistically significant increases in monthly averages of T_{max} were low compared with other months (Table 4).

Regarding seasonal maximum temperature, at least 45% of stations showed statistically significant increases, with 60% of the stations doing so during SWM followed by 55% during the NEM season. Fewer stations showed annual and seasonal minimum values with statistically significant trends compared with seasonal maximum and seasonal averages of T_{max}, except during SWM. No station showed a significant decreasing trend in either seasonal maxima or minima.

The main finding drawn from our observations of daily T_{min} is that more stations reported increases than decreases (Table 5) for almost all the analyzed statistical metrics. At least 50% of stations showed significant increases in averages for all seasons, with 75% of stations doing so during the months of MJJAS coinciding with the SWM season. At least 50% of stations showed significant increases in seasonal maxima, and only 35% of stations did so for seasonal minima. During the NEM and SIM seasons, 65% of stations reported significant increases in seasonal maxima and 60% demonstrated significant increases for the seasonal minima of T_{min} during the SWM season. Moreover, half of the stations demonstrated increases in annual maxima and one-third of the stations demonstrated increases in annual minima. The monthly averages for T_{min} show that 80% of

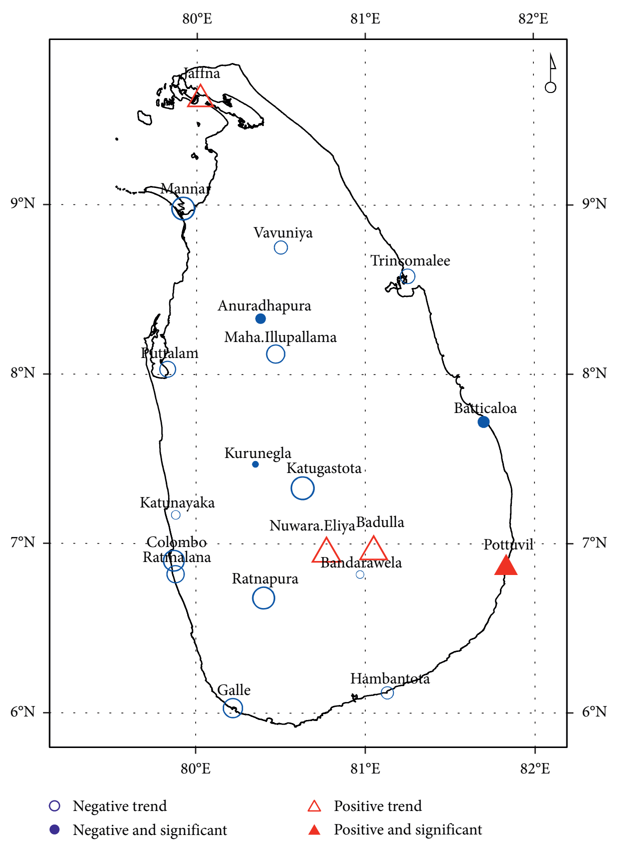

FIGURE 3: Trends in the number of wet days for the SWM season during the study period. Triangles indicate an increasing trend, and circles indicate a decreasing trend. Filled markers indicate significant trends at the α level of 0.05.

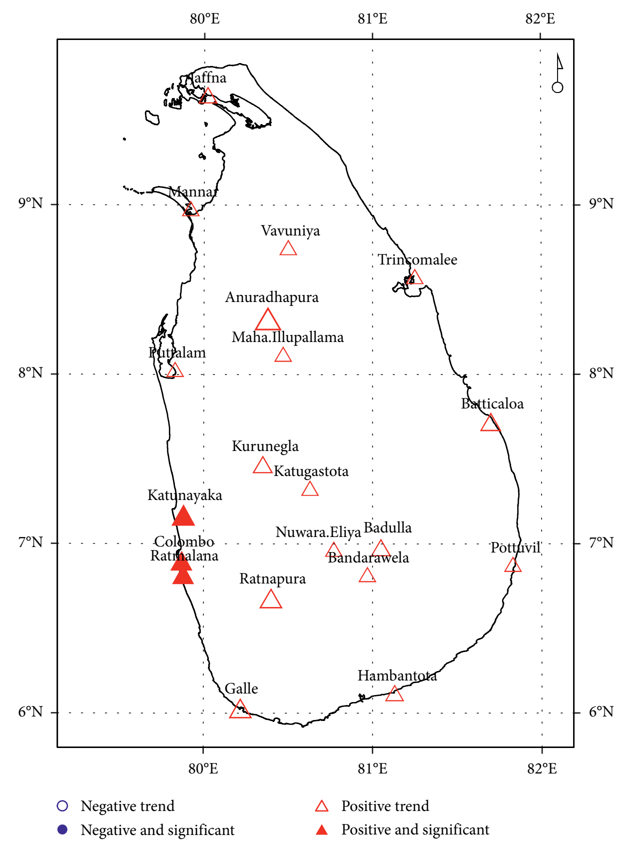

FIGURE 4: Trends in seasonal rainfall maxima of SWM during 1961–2015. Triangles indicate an increasing trend, and circles indicate a decreasing trend. Filled markers indicate significant trends at the α level of 0.05.

stations exhibited significant trends during June and July (Figure 5). This general increase in $T_{\min}$ is thought to be caused by warming nighttime temperatures in many cities [57, 58], and is consistent with global trends [33].

Figure 6 presents the annual daily mean temperature over 20 stations, along with a moving average. It is evident that there has been an overall increase in the temperature over time for the island as a whole. Also, there is a considerable degree of interannual variability in the average temperature data. It may be possible due to several factors including the changes in rainfall and large scale climate circulation.

Although averages of DTR show both increasing and decreasing trends, significant increases in seasonal maxima and minima are evident in Table 6. At least 30% and 10% of stations recording maxima and minima, respectively, demonstrate significant increases in DTR. This finding is consistent with trends observed for 2-day maximum events. We observed a general trend demonstrating increasing monthly DTR, although more stations demonstrated decreases during July (Figure 7), including stations at Colombo, Katunayaka, Katugastota, Puttalam, and Ratnapura. The Jaffna, Hambantota, and Trincomalee stations often showed increasing trends in seasonal and monthly averages and in seasonal maxima of DTR. A decreasing trend for DTR was mostly observed at the Colombo, Katunayaka, and Nuwara Eliya stations. Several factors may have caused decreases in DTR, such as natural variability in the immediate atmosphere. Especially land use and land cover changes in the stations with extended and rapid regional urbanization in Colombo, Katunayaka, Katugastota, Puttalam, and Trincomalee have led to a reduction in forest cover [31] which may have altered the temperature regime.

Research on daily temperature extremes in South Asian countries has revealed the warming of both extreme-cold and extreme-warm distributions [59]. As in Sri Lanka, increases in nighttime temperatures and warmest daytime temperatures have been observed at most weather stations across Nepal, India, and Pakistan [60]. In Pakistan, a greater number of warmer winter months were observed than summer months from 1975 to 2005 [61]. The Punjab province of Pakistan has been shown to have increased numbers of hot days and nights with prolonged summer days [62]. Several countries in South Asia have reported above-normal temperatures in the recent past. In India, temperatures higher than the normal 30-year average have been reported in recent years with a warming of 0.51°C [63, 64]. Also, reports and research studies have indicated rising temperature trends all over the states of India [30, 65]. Available studies suggest that sea surface temperatures and nighttime marine air temperatures over

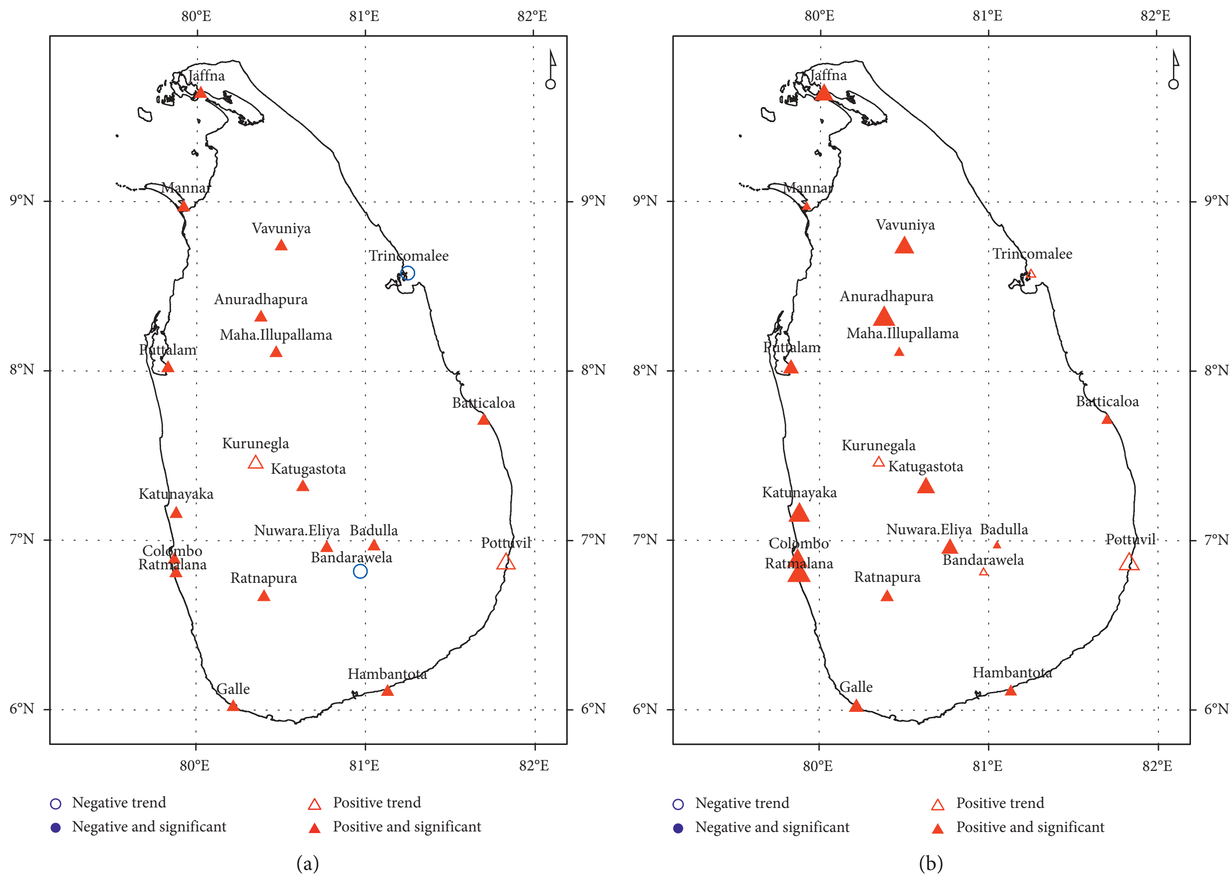

Figure 5: Trends in monthly averages in T_{min} for (a) June and (b) July during 1961–2015. Triangles indicate an increasing trend, and circles indicate a decreasing trend. Filled markers indicate significant trends at the α level of 0.05.

oceans worldwide have shown an increase in temperature. Global air temperatures over land surfaces have increased at about double the rate of the oceans [66]. Moreover, in regions of Europe, the high-temperature increase has become more frequent, while low-temperature extremes have become less frequent. The average length of summer days across Western Europe have doubled and the frequency of warm days has almost tripled in recent weather history [67]. Indeed, being an island and not connected to the Indian mainland, Sri Lanka experiences the regional and global increasing temperature trend.

5. Conclusions

Our trend investigations reveal dynamic rainfall trends with both increasing and decreasing patterns in Sri Lanka. Despite these varying trends, in general, we observed significant increases in seasonal rainfall at stations near the coastal regions of Sri Lanka. Decreases in rainfall are most evident for the month of May, likely due to the delay in the SWM winds in Sri Lanka. Furthermore, we observed a decrease in the number of wet days during the SWM season. The reduced number of wet days during the primary monsoonal season will influence agriculture in Sri Lanka. We detected no significant rainfall trends during the NEM season, one of the most important seasons in Sri Lanka. Notable increases in T_{min} and T_{max} were observed at 70 and 55% of the stations in Sri Lanka, respectively. The increase in T_{min} indicates likely warming of nighttime temperatures in Sri Lanka. Regarding monthly averages in T_{min}, 80% of stations showed significant increases during June and July. The DTR in the southwestern coastal region of Sri Lanka demonstrated a decreasing trend during July. Increases in T_{max} were often detected at stations all across the island.

This investigation, which addresses seasonality and extremes, provides a good understanding of historical temperature and rainfall trends in Sri Lanka. Our methods are ideal for situations in which historical observations consist of missing or censored data, which are common in developing countries such as Sri Lanka. Although the data are subject to general quality control procedures, station displacements, instrumentation upgrades, and changes in station surrounding environment may introduce inhomogeneities. Except for a few, most of the gauging stations in Sri Lanka still operate in the same locations that they historically monitored. Therefore, heterogeneity due to changes in location is not a significant confounder. However, changes in the environments of the station surroundings are challenging to quantify. Therefore, trends in raw (or unadjusted) data were used to quantify temperature trends. In the future, raw and adjusted data at a station may be compared to better understand the homogeneity

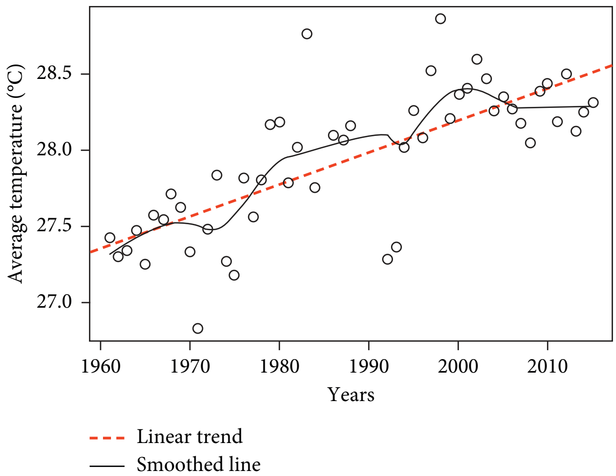

FIGURE 6: Annual daily mean temperature over the 20 stations, along with a moving average, during the period of 1961–2015. The dashed line represents the linear trend from the ordinary least square regression, whereas the solid line is the curve smoothed at the span of 0.25.

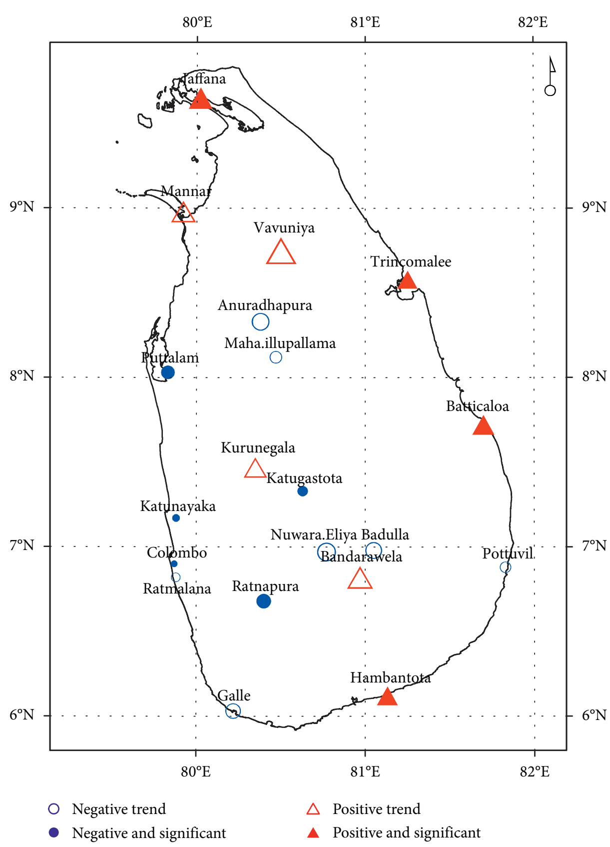

FIGURE 7: Trends in monthly averages of DTR during July from 1961 to 2015. Triangles indicate an increasing trend, and circles indicate a decreasing trend. Filled markers indicate significant trends at the α level of 0.05.

corrections performed and their impact on trends. The trends we report, along with the attribution study, may provide the key to future investigations of heterogeneities in the rainfall and temperature of Sri Lanka.

Data Availability

The rainfall and temperature data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Supplementary Materials

Supplementary Figure 1. Annual maximum rainfall trend in Sri. Triangles indicate increasing trend, and circles indicate decreasing trend. Filled markers indicate significant trends at the 0.05 level of α. Supplementary Figure 2. Annual maxima of temperature in Sri Lanka (a) T_{max}, (b) T_{min}, and (c) DTR. Triangles indicate increasing trend, and circles indicate decreasing trend. Filled markers indicate significant trends at the 0.05 level of α. Supplementary Table 1. Threshold values of the variables for the statistical measures Supplementary Table 2. Summary of averages in Tave and RH estimated for climatic zones of Sri Lanka for the period of 1996-2015. (*Supplementary Materials*)

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