

Recent Trends in Climate Extreme Indices over Sri Lanka

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How to cite this paper: Jayawardena, I.M.S.P., Darshika, D.W.T.T. and Herath, H.M.R.C. (2018) Recent Trends in Climate Extreme Indices over Sri Lanka. *American Journal of Climate Change*, 7, 586-599. <https://doi.org/10.4236/ajcc.2018.74036>

Received: June 11, 2018

Accepted: November 16, 2018

Published: November 19, 2018

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Abstract

Trends in 20 extreme indices of temperature and precipitation are examined for Sri Lanka using high-quality datasets for 19 meteorological stations, for a period between 1980 and 2015. It is evident that annually averaged mean minimum temperatures are increasing across most of Sri Lanka. The difference between maximum and minimum temperatures, diurnal temperature range is decreasing, indicating that the minimum temperature is increasing faster than the maximum temperature. Significant decrease in the annual occurrence of cold nights and increase in the annual occurrence of warm nights are also obvious. When compared with temperature changes, less spatially coherent pattern of change and a lower level of statistical significance were observed in precipitation indices. The annual total precipitation (PRCPTOT) has indicated a significant increasing over 1980-2015. More than 80% of stations showed an increasing trend in precipitation indices. The trends in extreme precipitation events such as maximum one-day precipitation, maximum five-day precipitation, and total precipitation on extreme rainfall days (R95p and R99p) are increasing at most locations, indicating that the intensity of the rainfall is increasing. Increase of precipitation extreme trends indicates that occurrence of extreme rainfall events notably influences total annual precipitation in Sri Lanka. Therefore, the observed increases in total rainfall observed in many locations may be due in part to an increase in of extreme rainfall events. Patterns of change in precipitation extremes are more heavily influencing the climate variability by aggravating the variability, significantly influencing climate sensitive sectors such as agriculture and water resource management.

Keywords

Extreme Indices, Climate Change, Trends, Precipitation

1. Introduction

Over the last few decades, it has become increasingly evident that the frequency

and intensity of extreme climate events have been changing especially under the anthropogenically induced climate warming (IPCC, [1]). Climate change can be defined as a trend in one or more climatic variables characterized by a fairly smooth continuous increase or decrease of the average value during the long period of record. Changes in the frequency, intensity, spatial extent, duration, and timing of weather and climate extremes due to climate change can result in increasing vulnerability of people and major economic threat from climate related disasters (IPCC, [1]). Past climate trends based on historical data provide evidence of changing climate conditions. Knowing how the climate has already changed and how those changes have affected the vulnerable sectors such as water resources, Agriculture and food security, Human health and eco system provides insight into what may happen in the future.

A number of studies have been done to investigate the trends in temperature and precipitation records in the world. Using global station data for the period from 1951 and 2003, Alexander *et al.* [2] found that widespread significant changes in temperature extremes associated with warming with a positive shift in the distribution of daily minimum temperature throughout the globe. Daily maximum temperature indices showed similar changes but with smaller magnitudes. Precipitation changes showed a widespread and significant increase, but the changes are much less spatially coherent compared with temperature change. Vinnikov *et al.* [3], Groisman and Easterling [4], Karl and Knight [5], Zhang *et al.* [6], Groisman *et al.* [7] and Griffiths and Bradley [8] found increases in both precipitation amount and its intensity across the United States and Canada. Trends in Australian temperature and precipitation extremes have been examined broadly. These studies reported widespread increases in warm temperature extremes and decreases in cold temperature extremes, while trends in rainfall extremes show more regionally dependent variations (Hennessy *et al.* [9]; Plummer *et al.* [10]; Collins *et al.* [11]; and Griffiths *et al.* [12]).

Using temperature data from 210 stations for the period 1971-2000 and precipitation data from 265 stations from 1961 to 2000, Sheikh *et al.* [13] studied trends in climate extremes indices for the South Asian region. Changes in the frequency of temperature extremes over South Asia are consistent with globally averaged results; warm extremes have become more common and cold extremes less common. Changes in the indices of extreme precipitation are less coherent than those of temperature. However, on average most extreme precipitation indices show increases in the South Asia (Sheikh *et al.*, [13]). Using a high resolution daily gridded rainfall data set, Goswami *et al.* [14] showed that there are significant rising trends in the frequency and the magnitude of extreme rain events over central India during the monsoon season. This study also showed that significant decreasing trend in the frequency of moderate events (5 to 100 mm/day rainfall) during the same period, thus leading to no significant trend in the mean rainfall. Using 104 years (1901-2004) of high resolution daily gridded rainfall data over central India, Rajeevan *et al.* [15] found that the frequency of extreme rainfall events shows significant inter-annual and inter-decadal variations

in addition to a statistically significant increasing long term trend of 6% per decade.

Several studies have been conducted relevant to the climate change and climate variability on the basis of trend analysis of climatic variables such as precipitation, temperature in Sri Lanka. Increasing trend in temperature is evident in most parts of the country (Chandrapala [16]; Basnayake [17]; Eriyagama *et al.* [18]). It has been reported that both mean maximum and mean minimum air temperatures have increased and increase in minimum air temperature contributes more to average increase in annual temperature than day time maximum air temperature (Basnayake [17]).

Previous studies indicated that no clear pattern or trend has been observed in precipitation in Sri Lanka. Some studies identified that average rainfall is showing a decreasing trend (Basnayake [17]) while Premalal [19] observed that heavy rainfall events have become more frequent in central highlands during the recent period. Analyzing fluctuations in rainfall associated with the four climatic seasons using rainfall data for nearly 130 years (1870-2000) from 15 rainfall stations Malmgren *et al.* [20] identified that decrease of rainfall in higher elevation areas and increase of rainfall in lowlands in the southwestern sector of Sri Lanka during southwest monsoon season. None of the stations show any significant change in Northeast Monsoon precipitation. While analyzing rainfall data for more than 100 years (1895-1996) Jayawardena *et al.* [21] found that no coherent increase or decrease of rainfall was observed in stations in the wet or dry zones. According to Sheikh *et al.* [13], declining rainfall has observed (1961-2000) in southern part of Sri Lanka with increasing trends in extreme temperatures. Sheikh *et al.* [13] identified an increase in the warmest day temperature of the year (TXx), and the coldest night temperature of the year (TNn) over Sri Lanka.

Over the past few years, Sri Lanka has witnessed numerous sequential extreme weather events, such as floods, and droughts causing catastrophic losses to life and property. Most of the previous studies of observed changes in temperature and precipitation extremes in Sri Lanka were used historical data only up to year 2000 (Malmgren *et al.* [20]; Jayawardena *et al.* [21] and Sheikh *et al.* [13]). The purpose of this study is to identify the recent trends in rainfall and temperature indices using recent historical data from 1980 to 2015.

The paper is organized as follows. We briefly describe the definitions of indices discussed in this paper in Section 2. Our results are presented in Section 3 for several different categories of temperature- and precipitation-based indices. A summary of the main findings and concluding remarks are given in Section 4.

2. Data and Methodology

Precipitation and temperature indices developed by the World Meteorological Organization–Commission for Climatology (WMO–CCI)/World Climate Research Program (WCRP)/Climate Variability and Predictability (CLIVAR) project’s Expert Team on Climate Change Detection and Indices (ETCCDI) (Easterling *et al.* [22], Alexander *et al.* [2]) were calculated using daily precipitation,

daily maximum temperature and daily Minimum temperature data, from 19 surface weather stations (**Figure 1** and **Table 1**) of the Department of Meteorology, Sri Lanka covering the period 1980-2015. The long-term trends for these indices in Sri Lanka during the period 1980-2015 were then examined, using quality-controlled daily station data.

Precipitation Indices and Temperature Indices

10 extreme precipitation indices, including precipitation totals (PRCPTOT), and 9 extreme temperature indices including diurnal temperature range (DTR), were computed for each of the stations. Data were analyzed by using the RCLimDex software, which is developed by ETCCDMI. The package were used and developed in previous studies (Easterling *et al.* [22], Alexander *et al.* [2]). The RCLimDex was used for quality control of the data by checking for inaccurate data such as negative precipitation, maximum temperature less or equal to minimum temperature, outliers data. After quality control, RCLimDex was used to compute climate indices from the daily data. RCLimDex calculates 11 precipitation and 9 temperature indices (**Table 2** and **Table 3**), at yearly and (where appropriate) monthly time steps. The details of the indices presented by **Table 2** and **Table 3**.

A 5% level (large triangles) and 10% level (small triangles) of statistical significance was also taken into consideration.

3. Results and Discussion

Figure 2 presents the time series of mean Maximum and mean Minimum temperature at few stations over wet zone (A and B) and dry and intermediate zone

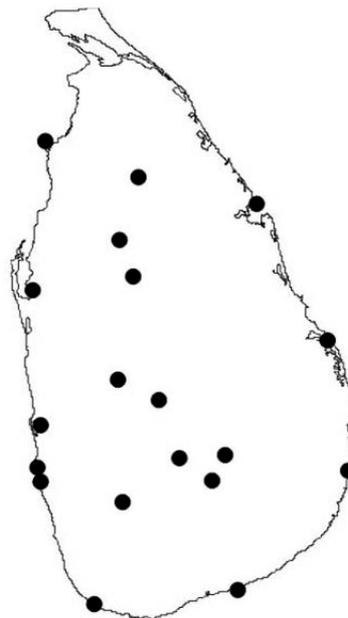


Figure 1. Locations of 19 rainfall stations in Sri Lanka as used in this study.

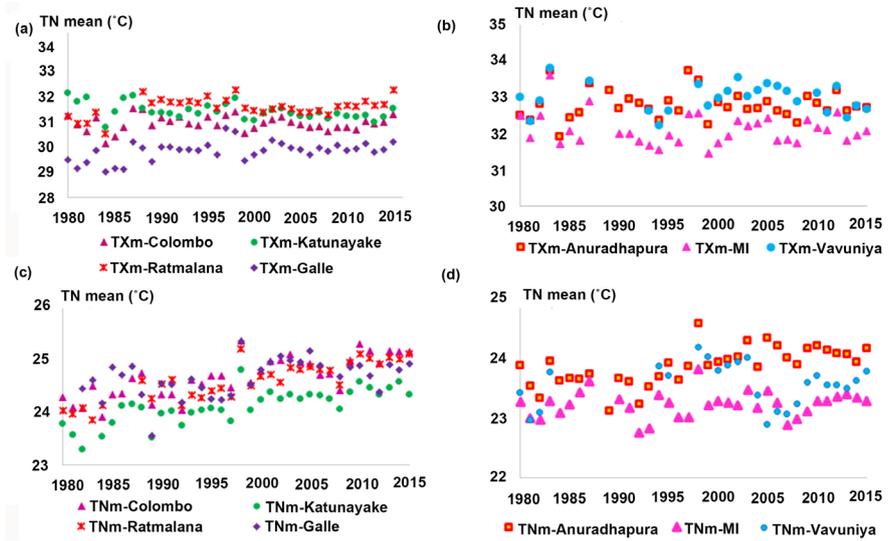


Figure 2. Time series for Maximum mean (a) and Minimum mean temperature (c) at few stations located in wet zone (Colombo, Katunayake, Galle and Ratmalana), Maximum Mean (b) and minimum Mean temperature (d) at few stations located in dry zone (Anuradhapura, MahaIlluppallama and Vavuniya).

Table 1. Station location details.

	Name of the Station	Longitude	Latitude
1	Ratnapura	80.4	6.68
2	Nuwaraeliya	80.76	6.96
3	Katugastota	80.63	7.33
4	Badulla	81.05	6.98
5	Kurunegala	80.37	7.46
6	Puttalam	79.83	8.03
7	Galle	80.22	6.03
8	Ratmalana	79.88	6.81
9	Colombo	79.86	6.9
10	Hambantota	81.13	6.12
11	Katunayake	79.88	7.17
12	Anuradhapura	80.38	8.35
13	Batticaloa	81.7	7.71
14	Trincomalee	81.25	8.58
15	Pottuwil	81.83	6.88
16	Vavunia	80.5	8.75
17	Mannar	79.91	8.98
18	Bandarawela	80.967	6.817
19	MahaIlluppallama	80.467	8.117

Table 2. Precipitation indices.

Index	Descriptive Name	Definition	Units
PRCPTOT	Wet day precipitation	Annual total precipitation from wet days	Mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/d
CDD	Consecutive dry days	Maximum number of consecutive dry days	Days
CWD	Consecutive wet days	Maximum number of consecutive wet days	Days
R10mm	Precipitation days	Annual count of days when RR \geq 10	Days
R20mm	Precipitation days	Annual count of days when RR \geq 20	days
R30mm	Precipitation days	Annual count of days when RR \geq 30	days
R95p	Very wet day precipitation	Annual total precipitation when RR > 95 th percentile daily rainfall	mm
R99p	Extremely wet day	Precipitation Annual total precipitation when RR > 99th percentile of daily rainfall	mm
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm

Table 3. Temperature indices.

Index	Descriptive Name	Definition	Units
DTR	Diurnal temperature range	DTR Diurnal temperature range Monthly mean difference between TX and TN	$^{\circ}$ C
TXx	Hottest day	Monthly highest TX	$^{\circ}$ C
TNx	Hottest night	Monthly highest TN	$^{\circ}$ C
TXn	Coolest day	Monthly lowest TX	$^{\circ}$ C
TNn	Coolest night	Monthly lowest TN	$^{\circ}$ C
TN10p	Cool night frequency	Percentage of days when TN < 10th percentile	%
TX10p	Cool day frequency	Percentage of days when TX < 10th percentile	%
TN90p	Hot night frequency	Percentage of days when TN > 90th percentile	%
TX90p	Hot day frequency	Percentage of days when TX > 90th percentile	%

TX is the daily maximum temperature; TN is daily minimum temperature.

(C and D) respectively. Even though the rise in mean maximum temperature can be seen in most of the stations, the trend is not significant. Significant increasing trend in minimum temperature is apparent in western coastal area and southern part of Sri Lanka (**Figure 2(c)**).

Contrary to the mean maximum temperatures, significant increasing trends can be observed in the mean minimum temperatures. Diurnal Temperature Range (DTR), is defined as the difference of daytime maximum temperature and night time minimum temperature. The change in DTR is regional rather than to be global. Many studies have revealed that there is a decrease in DTR since the mid 20th century (Easterling *et al.* [23]). It is shown clearly that DTR is decreasing

over most stations except Hambantota and Trincomalee (**Figure 3(a)**). This decreasing trend is due to the rapidly rising trend of minimum temperatures shown in **Figure 1**. Two main agricultural seasons in Sri Lanka is Yala season from March to September, and Maha season from October to February (Premalal *et al.* [24]). Decreasing trend at Anuradhapura located in dry zone is more significant in Maha season (**Figure 3(b₁)**) than in Yala season (**Figure 3(b₂)**).

Over 60% of the stations show significant increasing trends in the percentage of warm nights (**Figure 4(a)**) and 70% of the stations show significant decreasing trends in the percentage of cold nights (**Figure 4(b)**). This means that many stations have seen fewer cold nights and more warm nights during the past 3 - 4 decades. This result is consistent with previous studies conducted by Alexander *et al.* [2] who found that over 70% of the land area showed a significant increase in the annual occurrence of warm nights while the occurrence of cold nights showed a similar proportion of significant decrease. Over nearly all parts of the globe both tails of the minimum temperature distribution have warmed at a similar rate (Alexander *et al.* [2]).

An increasing trend was observed for the annual total rainfall in Sri Lanka as shown in **Figure 5**, for the period used in this report *i.e.* 1980-2015. 65% of stations show significant increasing trend for annual precipitation at 5% or 10% level (**Figure 5(a)**). Simple Daily Intensity of Rainfall (SDII) increasing trend in Anuradhapura, Batticaloa, and Katugastota (**Figure 5(b)**) at 5% level and Trincomalee (**Figure 5(b)**) in 10% level. It is obvious that Simple Daily Intensity of Rainfall shows a decreasing trend in Puttlum in 10% level (**Figure 5(b)**).

Figure 6 and **Figure 7** represents the time series of annual total precipitation at few stations over wet zone and simple daily intensity of rainfall at few stations

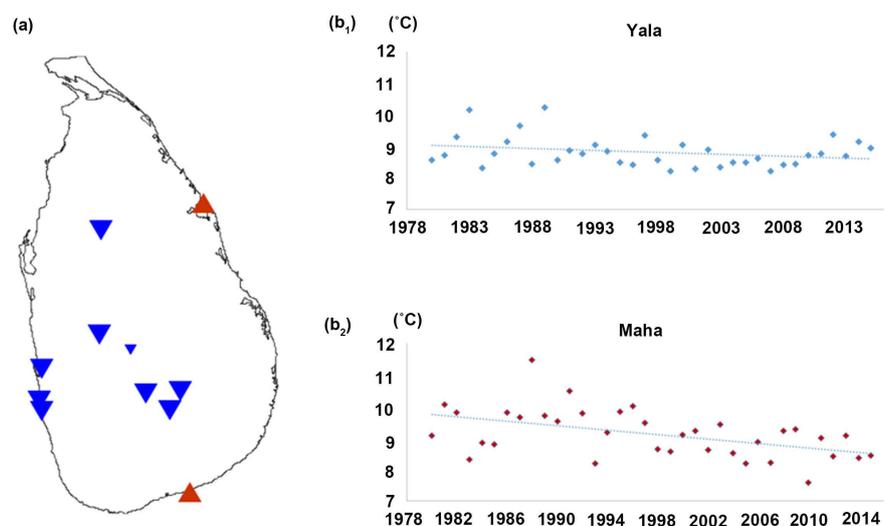


Figure 3. Spatial distribution maps of trends in Diurnal Temperature range (a) and Time series for Diurnal temperature range for Yala (b₁) and Maha (b₂) seasons at Anuradhapura. The upward-pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

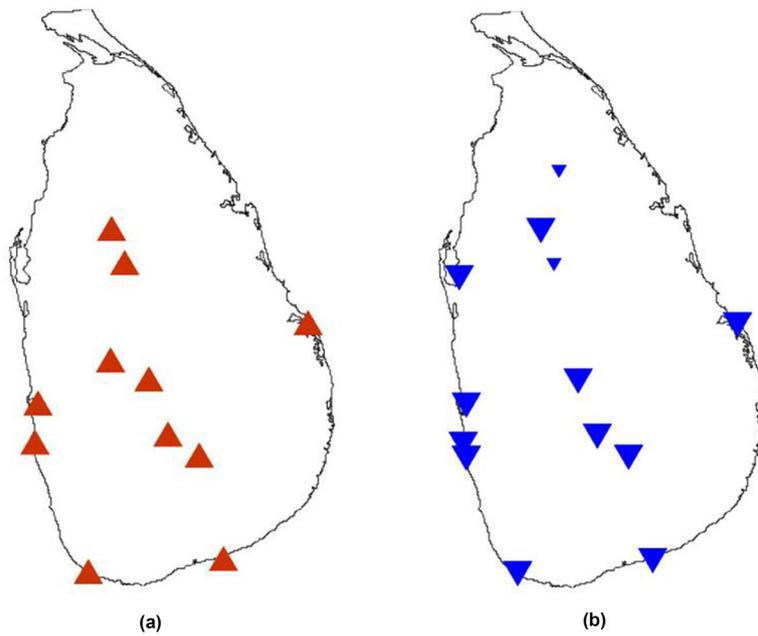


Figure 4. Spatial distribution maps of trends in Occurrence of warm nights (a) and Occurrence of cold nights (b). The upward-pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

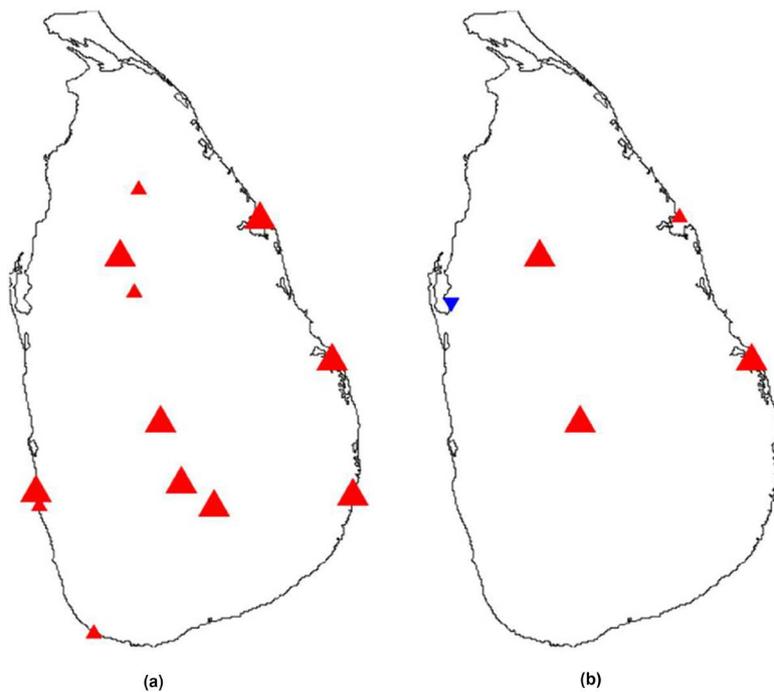


Figure 5. Spatial distribution maps of trends for annual Total Precipitation (a) and simple daily intensity of rainfall (b). The upward-pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

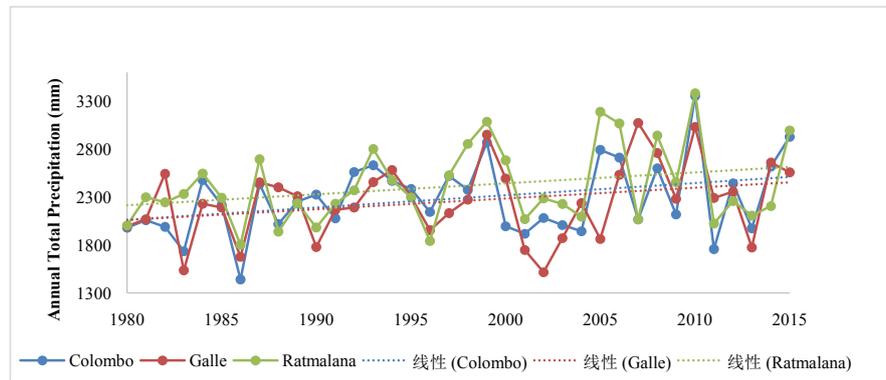


Figure 6. Time series for Annual Total Precipitation at few stations located in wet zone (Colombo, Galle and Ratmalana).

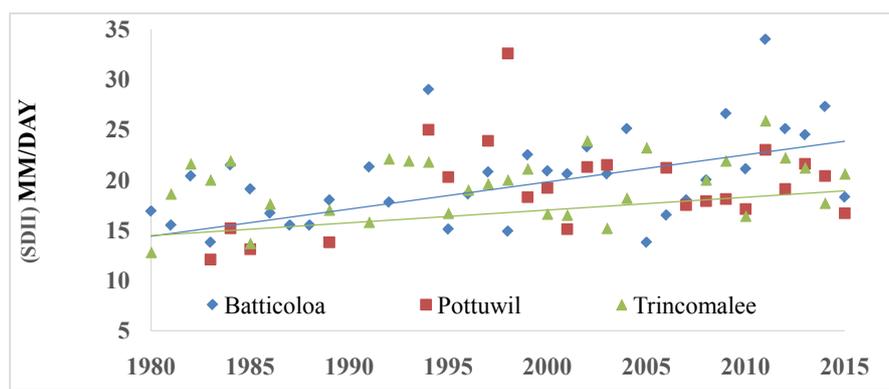


Figure 7. Time series for Simple Daily Intensity of Rainfall (SDII) at few stations located along Eastern Coast (Trincomalee, Batticaloa and Pottuivil).

located in Eastern coast respectively. Within the inter-annual variability, an increasing trend in annual total precipitation is evident in wet zone (Figure 6).

Figure 8 represents the Spatial distribution maps of trends in maximum one-day precipitation (RX1day, Figure 8(a)) and maximum 5-day precipitation (RX5day Figure 8(b)). RX1day trends in increasing except in Puttalam, although relatively few of them are statistically significant. The RX1day showed only positive trends (10% of stations) with statistical significance, but positive trends were predominant (80% of stations). The RX5day showed also positive trends (85% of stations) with 35% of statically significance. Comparing with decadal changes , it is found that significant increase in maximal one-day precipitation and maximal five-day precipitation during the period from 2010 to 2015 (Table 4) in station located in all 3 climatic zones. It is evident that 60% and 50% increase in maximal one-day and 5 day precipitation amount respectively at Anuradhapura during the from 2010 to 2015. Similarly 110% and 60% increase in maximal one-day and 5 day precipitation amount can be seen in Batticaloa for same period compare to 30 year average (Table 4).

90% stations show non-significant increasing trend in total precipitation on extreme rainfall days (R95p and R99p) but only 20% - 25% of the station trends

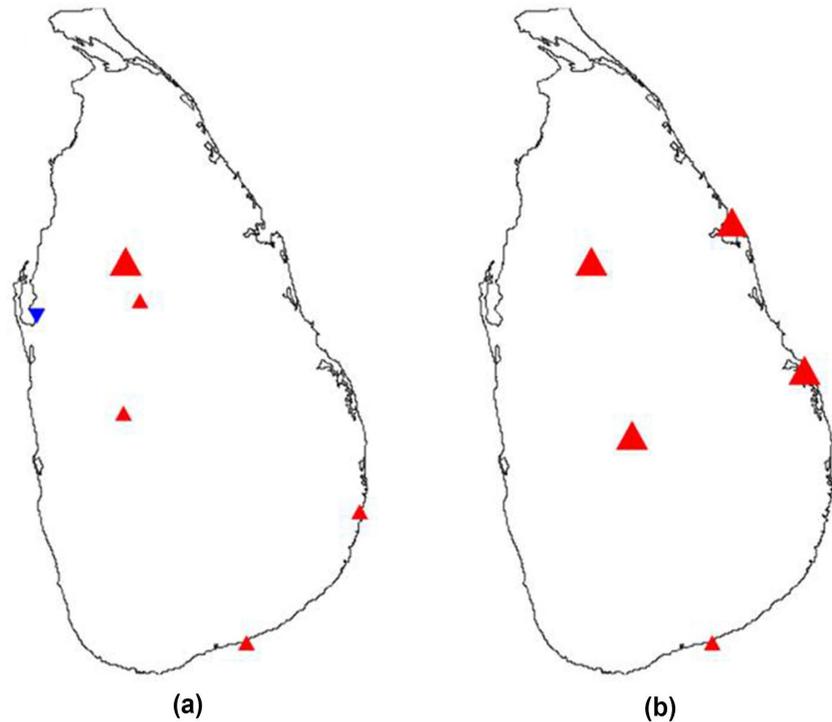


Figure 8. Spatial distribution maps of trends for maximum one-day precipitation (RX1day) (a) and maximum 5-day precipitation (RX5day) (b). The upward-pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

Table 4. Decadal changes in Extreme Rainfall events defines as Maximum 5 day rainfall amount (mm) and Maximum 1 day rainfall amount (mm).

Extreme Rainfall Event defined as Maximum Five Day Rainfall (5Day_Max) and Maximum One Day Rainfall (1Day_Max)									
	Dry Zone			Intermediate zone			Wet zone		
5Day_Max	Anuradhapura	Puttatum	Batticoloa	Kurunegala	Badulla	Bandarawela	Katunayake	Katugastota	NuwraEliya
average 30	175	193	251	221	192	159	142	93	85
decade 80	166	213	238	229	237	177	123	95	91
decade 90	176	189	225	214	168	144	162	94	94
decade 2000	184	180	286	219	171	160	133	90	70
2010-2015	281	159	528	301	257	192	146	127	95
1Day_Max	Anuradhapura	Puttatum	Batticoloa	Kurunegala	Badulla	Bandarawela	Katunayake	Katugastota	NuwraEliya
average 30	89	113	126	123	95	76	257	177	188
decade 80	73	133	130	123	110	78	243	178	217
decade 90	99	114	113	115	94	75	265	179	197
decade 2000	94	95	135	131	81	75	252	173	150
2010-2015	135	79	200	172	124	91	263	249	198

are significant at the 5% - 10% level (**Figure 9**). Anururadhapura, Katugastota, Batticaloa and Pottuwil stations show significant increasing trend in very wet days and extreme rainfall days (R95p and R99p) (**Figure 9**) evidencing the increase of precipitation in extreme events at these locations.

Figure 10 represents map of the trends for number of days with precipitation equal to or greater than 10 mm (a), 20 mm (b) and 30 mm (c) rainfall in Sri Lanka. It is shown that 75% of stations show a significantly increasing trend in number of days with precipitation equal to or greater than 10 mm and nearly 50% of stations shows a significantly increasing trend in number of days with precipitation equal to or greater than 20 mm and 30 mm rainfall.

Consecutive Wet Days (CWD) and Consecutive Dry Days (CDD) show mixed trends. There is increasing trend in CWD in Katugastota, and decreasing trend in CWD in Nuwaraeliya and Ratnapura. Less consecutive dry days (CDD) is observed in stations located in western coastal areas such as Colombo, Katunayake, Ratmalana and Puttalam.

4. Summary

This study presents analyses of the trends in 20 annual extreme indices of temperature and precipitation for Sri Lanka. The analyses were conducted using long term and high-quality datasets for 19 meteorological stations, for a period between 1980 and 2015. The difference between maximum and minimum temperatures is decreasing, indicating that the minimum temperature is increasing

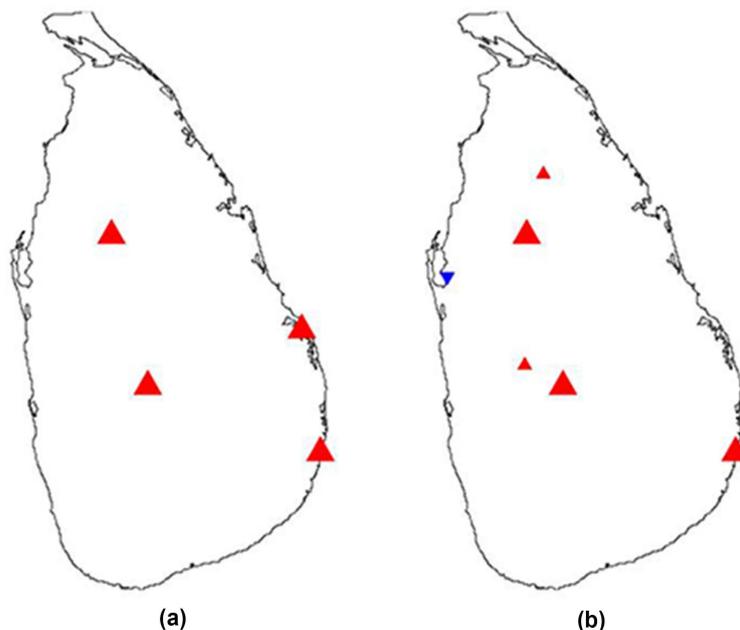


Figure 9. Spatial distribution maps of trends for very wet days (a) and Extremely wet days (b), The upward-pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

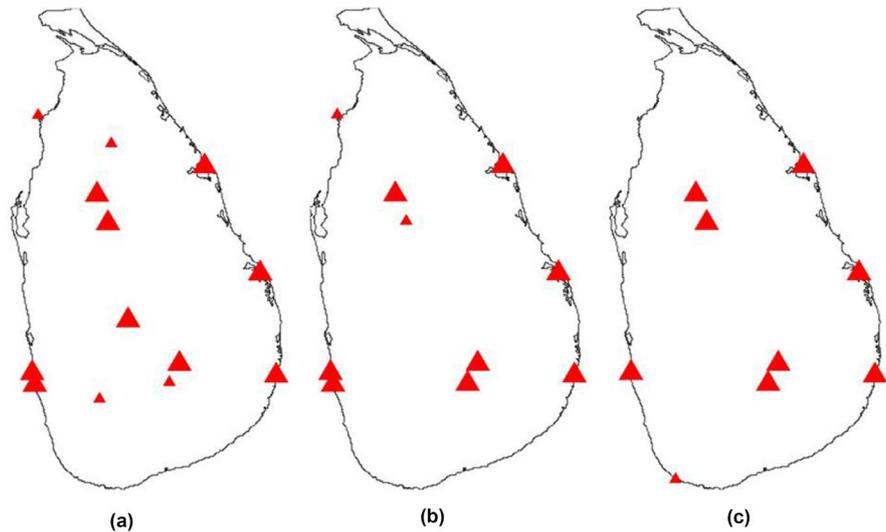


Figure 10. Spatial distribution maps of trends for number of days, above 10 mm rainfall (a), above 20 mm rainfall (b) and above 30 mm rainfall (c). The upward pointing red triangles show increasing trends, while the downward-pointing blue triangles indicate decreasing trends. Significant changes at the 5% level are indicated by large triangles and 10% level are indicated by small triangles.

faster than the maximum temperature. It is evident that annually averaged mean minimum temperatures are increasing across most of Sri Lanka. Significant decrease in the annual occurrence of cold nights and increase in the annual occurrence of warm nights are also obvious.

When compared with temperature changes, less spatially coherent pattern of change and a lower level of statistical significance were observed in precipitation indices. Some of the indices in this study can be good indicators for climate extremes in Sri Lanka. The annual total precipitation (PRCPTOT) has indicated a significant increasing over 1980-2015. More than 80% of stations showed an increasing trend in precipitation indices. Nearly 75% and 65% of the station showed significant increasing trend in annual total precipitation and number of days above 10 mm rainfall at the 5% - 10% level. The trends in extreme precipitation events such as maximal one-day precipitation, maximal five-day precipitation, and total precipitation on extreme rainfall days (R95p and R99p) are increasing at most locations, indicating that the intensity of the rainfall is increasing. Increase of precipitation extreme trends indicate that occurrence of extreme rainfall events notably influence total annual precipitation in Sri Lanka. Therefore, the observed increases in total rainfall observed in many locations may be due in part to an increase in of extreme rainfall events. Patterns of change in precipitation extremes are more heavily influencing the climate variability by aggravating the variability, significantly influencing climate sensitive sectors such as agriculture and water resource management.

Conflicts of Interest

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

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