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Trends in climate change observed under tropical wet and tropical montane climates ; A case study from Sri Lanka

NUWANTHI NISSANKA, ERANDATHIE LOKUPITIYA and SHIROMANI JAYAWARDENA*

Department of Zoology and Environment Sciences, University of Colombo, Colombo 00700, Sri Lanka

**Department of Meteorology, Colombo 00700, Sri Lanka*

N. A. Nuwanthi, Department of Zoology and Environment Sciences,

University of Colombo, Colombo 00700, Sri Lanka

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e mail : nuwanthi.nissanka1994@gmail.com

सार — जलवायु परिवर्तन से संबंधित तापमान और वर्षा की प्रवृत्तियों में परिवर्तनों की जांच स्थानीय, क्षेत्रीय और वैश्विक स्तर पर की जानी चाहिए। जलवायु परिवर्तन की अस्थायी गतिशीलता का मूल्यांकन करने के लिए, श्रीलंका में उष्णकटिबंधीय नम और उष्णकटिबंधीय पर्वतीय जलवायु (यानी क्रमशः कोलंबो और नुवारा एलिया) वाले दो चयनित क्षेत्रों में तापमान और वर्षा की प्रवृत्ति का अध्ययन 1989 से 2019 तक 30 साल की अवधि के लिए किया गया। वर्षा की प्रवृत्तियों का विश्लेषण वार्षिक, मासिक और ऋतुनिष्ठ पैमानों पर किया गया, जबकि औसत, न्यूनतम और अधिकतम तापमान के प्रवृत्तियों की वार्षिक और मासिक पैमानों पर जांच की गई। औसत तापमान और वर्षा की दशकीय भिन्नताओं का अध्ययन करने के लिए दशकीय समय श्रृंखला प्लॉटों का उपयोग किया गया। अत्यधिक तापमान और वर्षा की परिघटनाओं की प्रवृत्तियों का भी मूल्यांकन किया गया। इसके अलावा, दैनिक तापमान सीमा (DTR), ठंडी और गर्म रातों तथा ताप सूचकांक (HI) की प्रवृत्तियों का अध्ययन किया गया। मान-केंडल परीक्षण का उपयोग करके प्रवृत्तियों के महत्व का मूल्यांकन किया गया, जबकि ढलान के परिमाण का आकलन सेन के ढलान अनुमानक द्वारा किया गया। उष्णकटिबंधीय नम और उष्णकटिबंधीय पर्वतीय जलवायु के अंतर्गत औसत वार्षिक तापमान के लिए सांख्यिकीय रूप से महत्वपूर्ण बढ़ती प्रवृत्ति देखी गई, और दोनों जिलों में वार्षिक वर्षा में कोई स्पष्ट प्रवृत्ति नहीं देखी गई। उष्णकटिबंधीय पर्वतीय जलवायु के तहत नुवारा एलिया में उल्लेखनीय कमी के साथ दक्षिण-पश्चिमी मॉनसून वर्षा में कमी की प्रवृत्ति रही। कोलंबो में पिछले दशक (यानी, 2010-2019) में नवंबर में औसत मासिक वर्षा (अर्थात्, अंतर-मॉनसूनी वर्षा के दौरान) और अप्रैल में औसत मासिक तापमान (अर्थात्, सबसे गर्म महीना) में वृद्धि की प्रवृत्ति देखी गई। कोलंबो में पिछले तीन दशकों में DTR में काफी कमी आई है। कोलंबो में पिछले दशक के दौरान ताप सूचकांक (HI) के मान में महत्वपूर्ण रूप से ऊपर की ओर की प्रवृत्ति देखी गई। कोलंबो में पिछले दशक में ठंडी रातों की संख्या में सांख्यिकीय रूप से महत्वपूर्ण गिरावट और उष्णि रातों की संख्या में सांख्यिकीय रूप से महत्वपूर्ण गिरावट की प्रवृत्ति भी देखी गई।

ABSTRACT. Climate change-related changes in temperature and precipitation trends must be investigated at local, regional and global levels. Temperature and precipitation trends in two selected regions having tropical wet and tropical montane climates (*i.e.*, Colombo and Nuwara Eliya respectively) in Sri Lanka were studied for a 30-year period from 1989 to 2019, to evaluate the temporal dynamics of climate change. Precipitation trends were analyzed on annual, monthly, and seasonal scales, while the trends in mean, minimum, and maximum temperatures were examined on annual and monthly scales. Decadal time series plots were used to study decadal variations in average temperature and precipitation. The trends in extreme temperature and precipitation events were also evaluated. In addition, the trends in diurnal temperature range (DTR), cool and warm nights and heat index (HI) were studied. The significance of trends was evaluated using the Mann-Kendall test, while the magnitude of the slope was assessed by Sen's slope estimator. Clear statistically significant increasing trends were observed for the mean annual temperatures under the tropical wet and tropical montane climates and no clear trends were observed in annual precipitation in both districts. There were decreasing trends in south-west monsoon rainfall, with a significant decrease in Nuwara Eliya under the tropical montane climate. Increasing trends were observed for the average monthly precipitation in November (*i.e.*, during the inter-monsoonal rains) and average monthly temperature in April (*i.e.*, the hottest month) over the last decade (*i.e.*, 2010-2019) in Colombo. The DTR has significantly decreased over the last three decades in Colombo. A significant upward trend was observed for HI values during the last decade in Colombo. Colombo also showed a statistically significant decreasing trend in the number of cool nights and a statistically significant increasing trend in the number of warm nights over the last decade.

Key words – Temperature, Precipitation, Climate trends, Diurnal temperature range, Heat index, Extreme events.

1. Introduction

Climate change is one of the most pressing challenges of the 21st century, which is triggered by anthropogenic activities that release GHGs into the atmosphere. As a result, a number of negative consequences are already being felt in numerous parts of the world. According to the IPCC 5th Assessment Report (2014), assessing historical climate records is crucial for long-term climate projections. "Temperature and precipitation are two major climatic variables which display relatively high reliability and availability in climate records" (Stafford *et al*., 2000). These variables can be utilized to figure out the nature of the climate system in a specific area or region. The internationally approved reference period for defining the climate is 30 years (WMO, 2021).

1.1. *Previous climate records in Sri Lanka*

According to previous studies, there is sufficient evidence to prove that Sri Lanka's climate has already changed (Baba, 2010). During the 100-year period (1896-1996), Sri Lanka's temperature changed by 0.003 °C per year (IPCC, 2001), while it was 0.025°C per year for the ten years from 1987-1996, indicating a faster warming trend in recent years (Eriyagama *et al*., 2010). The century-scale analysis in Sri Lanka by Jayawardene *et al*. (2005) evaluated decreasing trends in rainfall among 13 stations out of 15, mostly from 1949 onwards. A recent study by Karunathilaka *et al*. (2017) revealed both increasing and decreasing trends in annual total rainfall in Sri Lanka. Furthermore, the five decadal trend analysis by Naveendrakumar *et al*. (2018) has analyzed the overall increasing and decreasing trends in temperature and precipitation data in Sri Lanka both annually and seasonally.

1.2. *Climate of Sri Lanka*

Sri Lanka is a tropical island located in the Indian Ocean between the Bay of Bengal and the Gulf of Mannar (Zubair *et al*., 2010). It extends over an area of 65,610 km^2 while stretching over 433 km from North to South (latitude 5°55' North to 9°51' North) and 244 km from East to West (longitude 79°41' East to 81°53' East) (Seo *et al*., 2005). The country is characterized by three agro-ecological zones, based on annual rainfall: wet zone, intermediate zone, and dry zone (Seo *et al*., 2005).

Colombo and Nuwara Eliya are two major districts located in Sri Lanka with tropical wet and tropical montane climates, respectively (Eggleston *et al*., 2006). Considering coastal precipitation in Sri Lanka, the NEM season brings rain to the northern and eastern coastal lines, while the SWM season brings rain to the southern and western coastal lines. Colombo district lies in the western coastal region of Sri Lanka and is affected by SWM rainfall.

The characteristic low temperatures in Nuwara Eliya district are remarkable, with the lowest average minimum temperature of 17 °C in month of December. In contrast, significant high temperatures can be seen in Colombo, with the highest average temperature of 31 °C during the months of March and April (Weather Atlas, 2017). The considerable difference in altitude and topography has resulted in unique climatic conditions and characteristic weather hazards between the two districts.

1.3. *Temperature*

Global warming is defined as an increase in the combined surface air and sea surface temperatures within a specific time period, apparently a 30-year period (IPCC, 2018). The global mean temperature has reached approximately 1 °C above the pre-industrial level, ranging from 0.8 °C to 1.2 °C in 2017. It is more likely to increase from 1 °C to 3 °C at the end of the 21st century, if emissions reductions fail. A warming higher than the global average temperature has already been experienced in several areas of the world (IPCC, 2018).

The diurnal temperature range (DTR) is the difference between the daily maximum temperature and the daily minimum temperature (Global warming science, 2010). During 1950-2000, the observed surface warming over land has been associated with higher increases in daily minimum temperatures (Tmin) than in maximum temperatures (Tmax) on earth (Easterling *et al*., 1997; New *et al*., 2000). This warming asymmetry has resulted in a decrease in the area's average DTR and a drastic increase in night time temperatures in most regions of the world (Easterling *et al*., 1997). However, according to previous observations or general circulation models, this variation is not spatially uniform (Braganza *et al*., 2004).

Heat waves are periods of exceptionally high temperatures that occur in many parts of the world.

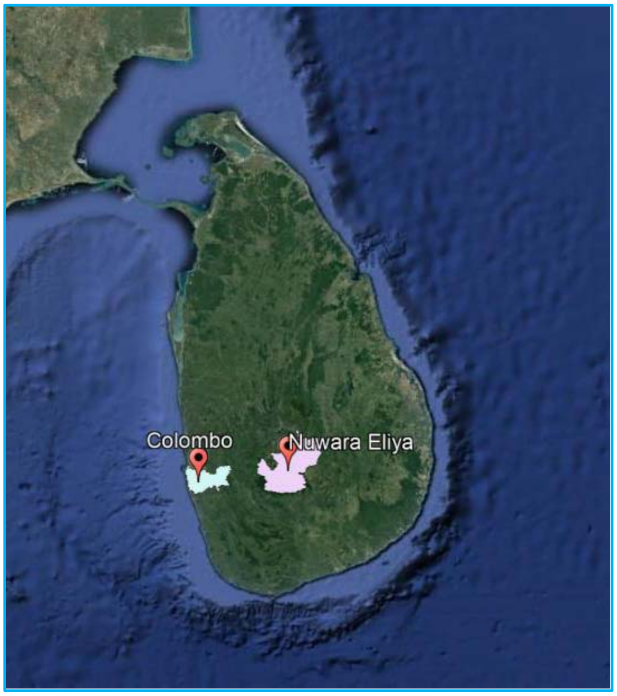


Fig. 1. Map of Sri Lanka- Arial view of Colombo and Nuwara Eliya districts (*Source* : Google Earth, 2021)

According to International Water Management Institute (2017), over 23% of the Sri Lankan population was exposed to hazardous heat waves between 2001 and 2013. Furthermore, the average annual number of days with a heat index of more than 35 °C is expected to rise dramatically by the end of this century (Climate risk country profile, 2020). The heat index describes how the human body perceives the temperature of the outside air in relation to humidity (National Weather Service, 2011).

1.4. *Precipitation*

In Sri Lanka, precipitation is mainly determined by four monsoon seasons: southwest monsoon (SWM), northeast monsoon (NEM), first inter-monsoon (FIM) and second inter-monsoon (SIM). The average annual rainfall ranges from 900 mm in the dry zone to more than 5000 mm on the central highlands' western slope (Department of Meteorology, 2019).

1.5. *Climate extremes*

Climate extremes are expressions of climate variables which fall above or below a precise threshold value near the upper or lower ends of an observed range. The cause of climate extremes can be natural climate variations, such as the El Niño-Southern Oscillation, and decadal or multi-decadal climate variations, as well as anthropogenic climate change. A changing climate can affect different aspects of climate extremes, including intensity, frequency, spatial extent, timing, and duration, resulting in unprecedented extremes (Seneviratne *et al.*, 2012).

2. Methodology

2.1. *Study area*

Colombo district or Colombo Metropolitan Area is Sri Lanka's largest city and the country's commercial capital (Fonseka *et al*., 2019). It is located in the Western Province of Sri Lanka, at a latitude of 6° 56' 2.39" N and a longitude of 79° 50' 20.39" E. (Climatemps, 2016). It has a tropical wet climate, with an average annual temperature of 26.5 °C (79.7 °F) and annual rainfall of 2348 mm (Eggleston *et al*., 2006).

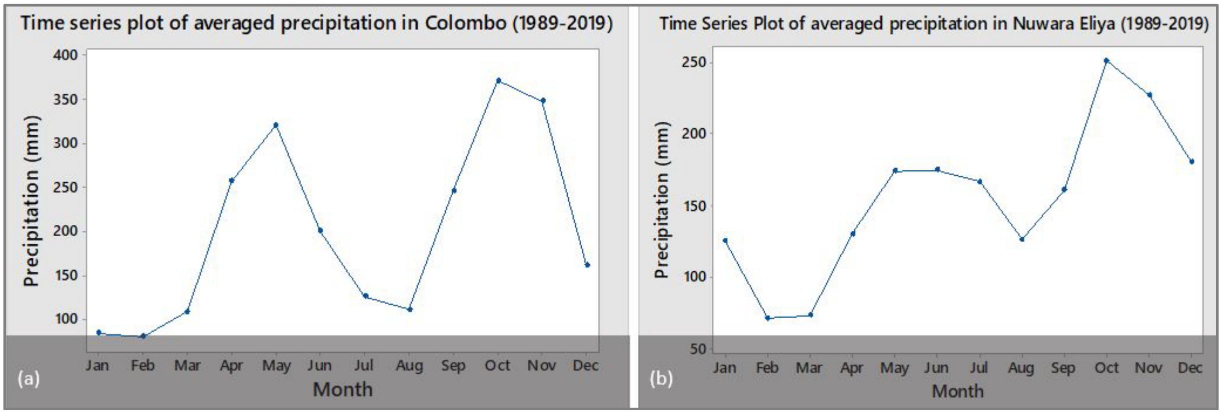
Nuwara Eliya district is located at an elevation of 1850 m in the southern central highlands of Sri Lanka in the Central province (Elevation Map, 2018), with a tropical montane climate (Eggleston *et al*., 2006). It is located at 6° 58' 14.81' N latitude and 80° 46' E longitude (Climatemps, 2013). The district's average annual rainfall is 2161 mm, while average temperatures are below 22 °C (71.6 °F) throughout the year (Climate-Data.org, 2020).

2.2. *Data and analysis*

Temperature and precipitation data were collected for the two districts, Colombo and Nuwara Eliya, from the Department of Meteorology, Sri Lanka. Data on daily minimum and maximum temperatures and daily precipitation was collected for the period 1989-2019. The missing data was filled in by means of the corresponding values for the previous year and the immediately following year in any given year. For the decadal analysis of temperature and precipitation, the time period was taken as three consecutive decades: Decade 1 (1990-1999), Decade 2 (2000-2009), and Decade 3 (2010-2019). Considering the non-normal distribution of the data Mann-Kendall Trend test was used to determine the significance of the trend analysis, and Sen's slope estimator was used to estimate the magnitude of the slope at a significance level of 0.05 (*i.e*., $\alpha = 0.05$). The advantage of the non-parametric Mann-Kendall test is that, unlike the parametric tests, the distribution of Kendall's can be simply computed from a single time series without the need for additional simulation or observations. Therefore, compared to the parametric tests, the non-parametric modified Mann-Kendall test is computationally significantly faster.

2.3. *Precipitation analysis*

Data on rainfall was determined at three-time scales: annual, monthly and seasonal. The significance of



Figs. 2(a&b). Time series plot of average monthly precipitation during 1989-2019 (a) Colombo and (b) Nuwara Eliya

TABLE 1

Results for monthly rainfall trends in the Colombo and Nuwara Eliya districts during 1989-2019 (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

Month	Colombo			Month	Nuwara Eliya		
	$z_{(M-K)}$	p-value	Trend		$z_{(M-K)}$	p-value	Trend
May	-1.67	0.05	↓↓	Mar	1.80	0.04	↑↑
Jul	-1.94	0.03	↓↓	Jun	-2.86	0.00	↓↓
				Jul	-2.01	0.02	↓↓

precipitation distribution at each time scale was assessed using Mann-Kendall trend analysis. Decadal time series plots of average precipitation were analyzed to study decadal rainfall variations. Trends for extreme precipitation events were analyzed using high and low precipitation events determined at the 90th and 10th percentiles of the daily total precipitation distribution, respectively.

2.4. *Temperature analysis*

The distribution of mean, minimum, and maximum temperatures during the period 1989-2019 and for individual decades were analyzed at annual and monthly time scales. Decadal time series plots of average temperatures were also analyzed (*i.e.*, Decade 1 (1990-1999), Decade 2 (2000-2009) and Decade 3 (2010-2019). Furthermore, trends in the diurnal temperature range (DTR) and the heat index (HI) were analyzed for the 1989-2019 period and in each decade. HI values were calculated using monthly maximum temperatures and the Heat Index calculator by the National Weather Service (National Weather Service, 2020).

Trends for extreme temperature events were evaluated for warm and cool days and warm and cool nights. Warm and cool days were determined as the days above and below the 90th and 10th percentiles of the daily mean temperature distribution, respectively, while warm and cool nights were determined as the nights above and below the 90th and 10th percentiles of the daily minimum temperature distribution respectively.

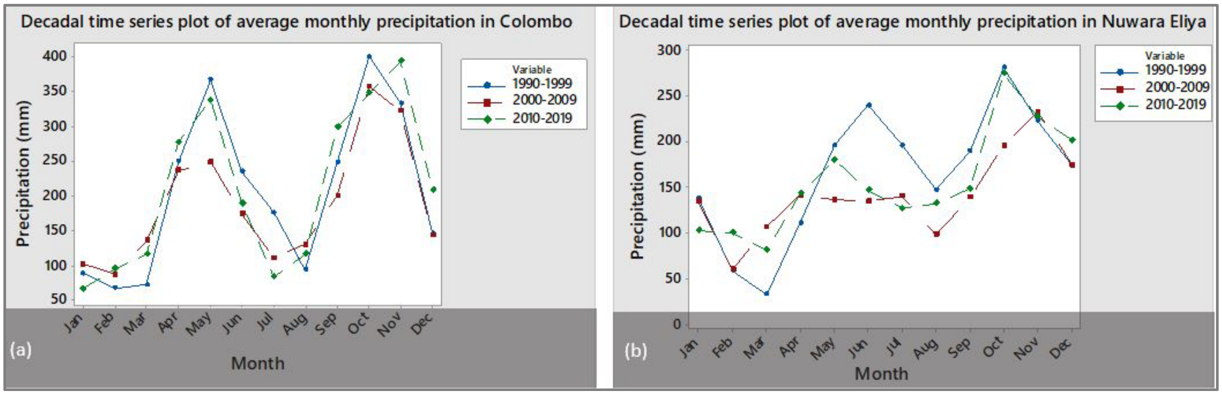
3. Results

3.1. *Precipitation analysis*

(*i*) *Annual Precipitation*

The average annual precipitation for the past 31 years in Colombo, which represents a tropical wet climate, was recorded as 2410.89 mm, while it was 1862.13 mm in Nuwara Eliya, which has a tropical montane climate. The following year (2011) recorded the lowest annual precipitation (1774.2 mm) during the period. However, in Nuwara Eliya, the highest precipitation over the past 31 years was recorded in 2006 (*i.e.*, 2555.30 mm), while it was 1138.20 mm in 2016, the lowest of all.

In both districts, there were non-significant trends in annual precipitation during 1989-2019; an increasing trend in Colombo and a decreasing trend in Nuwara Eliya.



Figs. 3(a&b). Decadal time series plots of average monthly precipitation during the decades : 1990-1999, 2000-2009 and 2010-2019) (a) Colombo and (b) Nuwara Eliya

The increase in precipitation per year in Colombo was 5.838 mm, while it decreased by 6.86 mm per year in Nuwara Eliya.

(*ii*) *Monthly Precipitation*

Average monthly precipitations from 1989 to 2019 indicated October, November, and May as the highest precipitation months in Colombo, while in Nuwara Eliya they were October and November (Fig. 2). In both districts, January, February and March had the least amount of average monthly precipitation.

In monthly precipitation trends during 1989-2019, significant decreasing trends were observed in Colombo in May and July, and in Nuwara Eliya in June and July (Table 1). In Nuwara Eliya, there was a significant increasing trend in precipitation in March. In Colombo, the wettest month on record over the entire study period was in November 2010 with 971.5 mm of monthly precipitation, while in Nuwara Eliya it was in June 1989 with 530.6 mm of monthly precipitation.

In decadal time series plots of average monthly precipitation in Colombo, during the last two decades (*i.e.*, 2000-2009 & 2010-2019), there was a decrease in average rainfall in May, June and July and an increase in September, November, and December compared to the decade 1990-1999 [Fig. 3(a)]. In Colombo in the first half of the year (January to June), the highest average precipitation was recorded in May in all three decades. However, in the second half of the year (July to December), it has shifted from October to November over the last decade.

In Nuwara Eliya district, a decline in average precipitation was observed in the last two decades (*i.e.*, 2000-2009 and 2010-2019), compared to the previous decade (*i.e.*, 1990-1999), particularly from May to November [Fig. 3(b)]. There was an increase in average precipitation in February, March and April during the last two decades in Nuwara Eliya. June had the highest precipitation in the first half of the year during 1990-1999. However, it has shifted to May during the last two decades. In all three decades, the maximum precipitation in the second half of the year occurred in October and November.

TABLE 2

Average seasonal precipitation in Colombo and Nuwara Eliya districts for the period 1989-2019

Season	Average Seasonal Precipitation (mm)	
	Colombo	Nuwara Eliya
SWM (May-Sep)	1002.24	783.60
SIM (Oct-Nov)	717.99	477.59
NEM (Dec-Feb)	325.43	383.12
FIM (Mar-Apr)	365.22	199.02

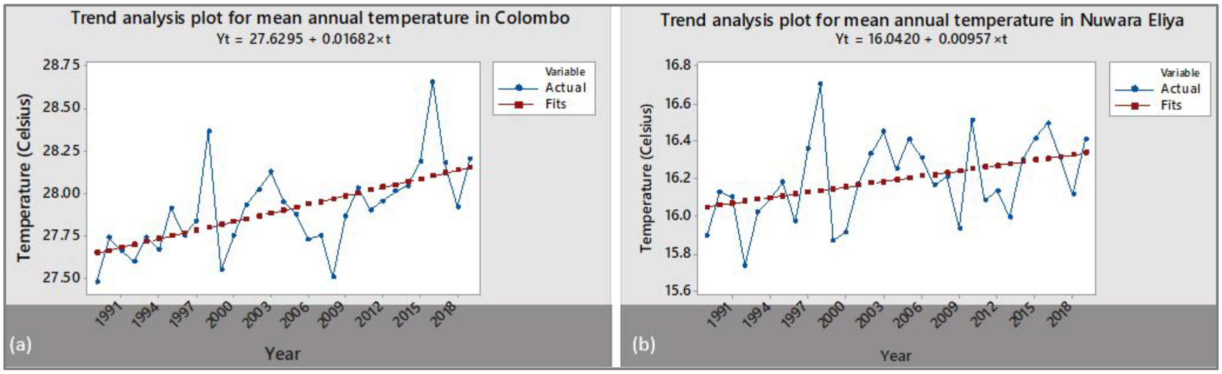
TABLE 3

Results of trends for total seasonal precipitation during 1989-2019 (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

District	Season	$z_{(M-K)}$	p-value	Trend	Sen's Slope (mm/yr)
Nuwara Eliya	SWM	-2.28	0.01	↓↓	-13.27
	FIM	2.14	0.02	↑↑	4.62

(*iii*) *Seasonal Precipitation*

Table 2 shows the average seasonal precipitation values during the last 31 years. During the southwest monsoon (SWM), both districts showed declining precipitation trends, with Nuwara Eliya displaying a statistically significant decreasing trend (Table 3). The following three seasons displayed non-significant



Figs. 4(a&b). Trend analysis plot for mean annual temperature during 1989-2019 (a) Colombo (z(M-K) =3.98, p-value = 0.00, Sen's Slope = 0.02 °C/yr) (b) Nuwara Eliya (z(M-K) =2.11, p-value = 0.02, Sen's Slope = 0.01 °C/yr)

TABLE 4

Results for the trend analysis of annual low precipitation days in Colombo district during the period 1989-2019 (↓↓-Significant decreasing trend)

District		$z_{(M-K)}$	p-value	Trend	Sen's Slope (No. of days/decade)
Colombo	Annual Low precipitation days	-1.91	0.03	↓↓	-4.74

TABLE 5

Results of trend analysis for monthly high precipitation days in Colombo and Nuwara Eliya (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

Month	Colombo			Month	Nuwara Eliya		
	$z_{(M-K)}$	p-value	Trend		$z_{(M-K)}$	p-value	Trend
Feb	3.72	0.00	↑↑	Feb	1.72	0.04	↑↑
Dec	2.08	0.02	↑↑	Jun	-2.82	0.00	↓↓
				Jul	-2.37	0.01	↓↓

increasing or decreasing trends, whereas FIM precipitation showed a significant increasing trend in Nuwara Eliya.

(*iv*) *Extreme Precipitation Events*

During 1989-2019, increasing and decreasing trends in annual high precipitation days were observed in Colombo and Nuwara Eliya districts respectively, although the trends were not statistically significant at 95 % level. In Colombo, there was a significant downward trend for annual low precipitation days below the 10th percentile (Table 4).

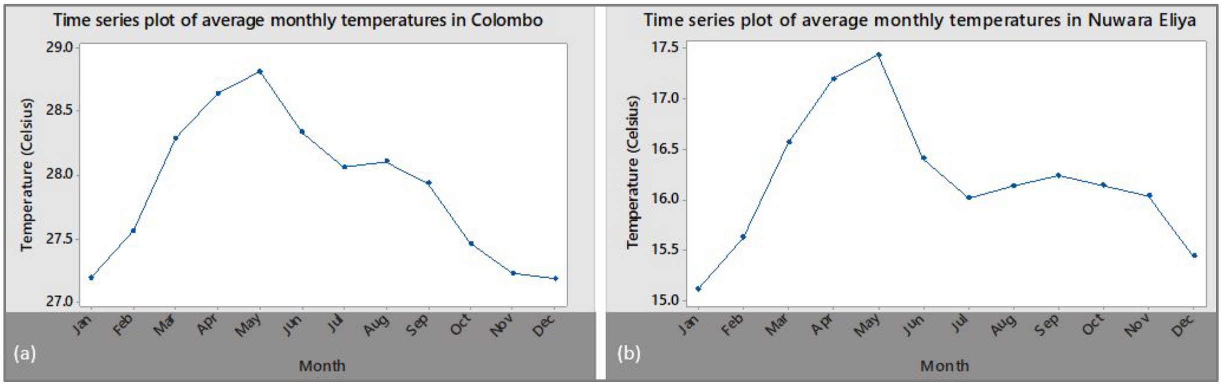
In the trend analysis for monthly high precipitation days during 1989-2019, in Colombo, there was a significant increasing trend in December (Table 5). In February, both Colombo and Nuwara Eliya districts indicated statistically significant upward trends. In Nuwara Eliya, there were significant decreasing trends in high precipitation days for both June and July.

TABLE 6

Results of Trend analysis for seasonal high precipitation days in Nuwara Eliya (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

Season	Nuwara Eliya		
	$z_{(M-K)}$	p-value	Trend
SWM	-1.68	0.05	↓↓
FIM	2.21	0.01	↑↑

The number of high precipitation days per season indicated trends which correspond to their total seasonal precipitation trends. In Nuwara Eliya, statistically significant decreasing and increasing trends in seasonal precipitation were observed during SWM and FIM, respectively (Table 6).



Figs. 5(a&b). Time series plot of monthly average temperatures during 1989-2019 (a) Colombo and (b) Nuwara Eliya

TABLE 7

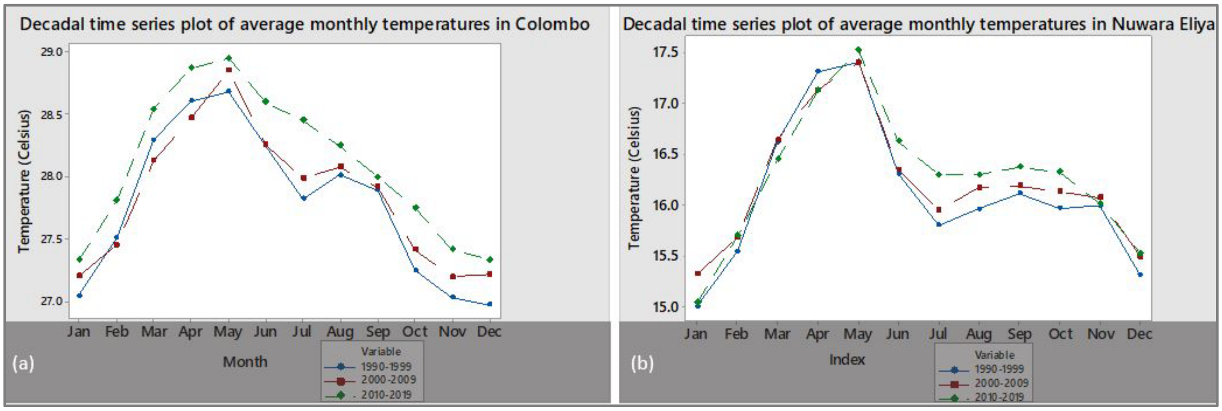
Results for the maximum and minimum annual temperature trends in Colombo and Nuwara Eliya districts (↑↑-Significant increasing trend)

	District	Time range	$z_{(M-K)}$	p-value	Trend
Maximum Annual Temperature	Nuwara Eliya	(1989-2019)	2.09	0.02	↑↑
	Colombo	Decade 3 (2010-2019)	1.97	0.02	↑↑
Minimum Annual Temperature	Colombo	(1989-2019)	4.45	0	↑↑
		Decade 1 (1990-1999)	1.79	0.04	↑↑

TABLE 8

Trend analysis for monthly mean, high and low temperatures in Colombo and Nuwara Eliya districts during 1989-2019 (↑↑-Significant increasing trend)

	Colombo				Nuwara Eliya			
	Month	$z_{(M-K)}$	p-value	Trend	Month	$z_{(M-K)}$	p-value	Trend
Mean monthly temperatures	Feb	1.68	0.05	↑↑	Jun	2.18	0.01	↑↑
	Mar	1.68	0.05	↑↑	Jul	2.28	0.01	↑↑
	May	2.28	0.01	↑↑	Aug	3.18	0.00	↑↑
	Jun	2.69	0.00	↑↑	Sep	1.82	0.03	↑↑
	Jul	3.20	0.00	↑↑	Oct	2.11	0.02	↑↑
	Oct	2.18	0.01	↑↑				
	Nov	2.67	0.00	↑↑				
Mean low temperatures	Dec	2.23	0.01	↑↑				
	Jan	2.75	0.00	↑↑	Aug	2.24	0.01	↑↑
	Feb	2.55	0.01	↑↑				
	Mar	3.71	0.00	↑↑				
	May	2.21	0.01	↑↑				
	Jun	2.97	0.00	↑↑				
	Jul	3.98	0.00	↑↑				
	Oct	1.97	0.02	↑↑				
	Nov	4.20	0.00	↑↑				
	Dec	4.49	0.00	↑↑				
Mean high temperatures	Jul	1.82	0.03	↑↑	Jun	2.26	0.01	↑↑
					Jul	2.43	0.01	↑↑
					Aug	2.80	0.00	↑↑
					Sep	2.1249	0.0168	↑↑



Figs. 6(a&b). Decadal time series plots of average monthly temperatures during the decades: 1990-1999, 2000-2009 and 2010-2019 (a) Colombo and (b) Nuwara Eliya

TABLE 9

Results for trend analysis of monthly mean, low and high temperatures in Colombo and Nuwara Eliya during the last decade (2010-2019) (↑↑-Significant increasing trend)

	Colombo				Nuwara Eliya			
	Month	$z_{(M-K)}$	p-value	Trend	Month	$z_{(M-K)}$	p-value	Trend
Mean monthly temperatures	Dec	2.15	0.02	↑↑				
Mean low temperatures					Jun	3.04	0.00	↑↑
Mean high temperatures	Apr	1.79	0.04	↑↑				
	Dec	2.15	0.36	↑↑				

3.2. *Temperature analysis*

(*i*) *Annual Temperature*

In both tropical wet and tropical montane climate districts, the mean annual temperature showed statistically significant increasing trends during the period 1989-2019 (Fig. 4). In Colombo, the minimum annual temperature increase (0.31 °C/decade) was higher than the maximum annual temperature increase (0.02 °C/decade), whereas in Nuwara Eliya, the maximum annual temperature increase (0.14 °C/decade) was higher than the minimum annual temperature increase (0.07 °C/decade) (Table 7). In both districts, the decadal trends for mean, minimum, and maximum annual temperatures showed independent increasing and decreasing trends.

(*ii*) *Monthly Temperature*

The average mean monthly temperatures from 1989-2019 indicated May and April as the hottest months of the year, while December and January were the coldest in both tropical wet and tropical montane areas (Fig. 5).

In Colombo, the trend analysis for the mean monthly temperatures showed statistically significant increasing trends in May, June, July, October, November and December during 1989-2019 (Table 8). More than half of the months indicated statistically significant upward trends for monthly low temperatures in Colombo. In Nuwara Eliya district, mean monthly temperature trends in June, July, August, September and October displayed statistically significant increasing trends (Table 8).

In the analysis of monthly temperature trends over the last decade (2010-2019), in Colombo, the mean high temperature in April and December indicated substantial increasing trends (Table 9). Also, there was a significant increasing trend for mean monthly temperatures in December in Colombo. Throughout the last decade, Nuwara Eliya district has experienced both increasing and decreasing trends, with the monthly low-temperature trend for June displaying a significant upward trend (Table 9).

In the decadal time series plots of monthly average temperatures in Colombo, average temperatures in all months have increased over the last decade, whereas in Nuwara Eliya an increase of average temperatures was observed from May to October (Fig. 6).

(*iii*) *Extreme Temperature Events*

The trends for annual high temperature days during 1989-2019 indicated increasing trends in both districts,

TABLE 10

Results of trends for annual extreme temperature days in Colombo and Nuwara Eliya during 1989-2019 (↑↑-Significant increasing trend, ↓↓- Significant decreasing trend).

District		z(M-K)	p-value	Trend	Sen's Slope (No. of days/decade)
Colombo	Annual high temperature days	3.08	0.00	↑↑	11.05
	Annual low temperature days	-3.69	0.00	↓↓	-11.6
Nuwara Eliya	Annual low temperature days	-2.37	0.01	↓↓	-5.63

TABLE 11

Results of trend analysis for monthly high and low temperature days in the Colombo and Nuwara Eliya during 1989-2019 (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

District	Month	High			Month	Low		
		z(M-K)	p-value	Trend		z(M-K)	p-value	Trend
Colombo	May	2.33	0.01	↑↑	Mar	-2.43	0.01	↓↓
	Jun	2.99	0.00	↑↑	Jul	-2.62	0.00	↓↓
	Jul	2.62	0.00	↑↑	Nov	-2.24	0.01	↓↓
	Aug	1.69	0.05	↑↑	Dec	-1.96	0.02	↓↓
Nuwara Eliya	Aug	1.98	0.02	↑↑	Jun	-2.43	0.01	↓↓
	Sep	2.24	0.01	↑↑	Aug	-2.73	0.00	↓↓
	Oct	2.30	0.01	↑↑	Oct	-2.82	0.00	↓↓

TABLE 12

Results of trend analysis for annual warm and cool nights in Colombo during 1989-2019 (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

District		z(M-K)	p-value	Trend	Sen's Slope (No. of nights/decade)
Colombo	Annual warm nights	4.05	0.00	↑↑	16.0
	Annual cool nights	-4.61	0.00	↓↓	-15.9

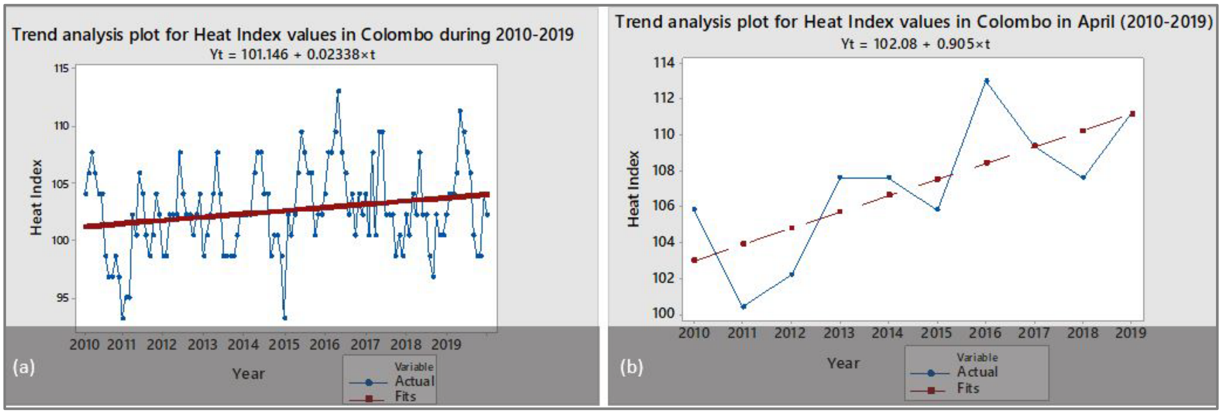
with a significant increasing trend in Colombo (Table 10). Both districts showed statistically significant decreasing trends in annual low temperature days at 95 % level.

In both districts during 1989-2019, the highest number of high-temperature days were observed in May. Low-temperature days were most abundant in January and December.

Trends for monthly high temperature days in Colombo resulted in statistically significant increasing trends in May, June and July (Table 11). In Nuwara Eliya district, significant increasing trends for monthly high temperature days were observed in August, September and October. In the trend analysis of low-temperature days per month in Colombo, the trends for March, July, November and December indicated significant decreasing trends, while in Nuwara Eliya significant decreasing trends were observed in June, August and October.

(*iv*) *Warm nights and cool nights and Diurnal Temperature Range (DTR)*

In Colombo district, there was a significant increasing trend for annual warm nights above the 90th percentile, while annual cool nights below the 10th percentile indicated a significant downward trend during 1989-2019 (Table 12).



Figs. 7(a&b). (a) Trend analysis plot for the heat index in Colombo during 2010-2019 [z(M-K) = 2.00, p value = 0.02] and (b) Trend analysis plot for heat index of April in Colombo during 2010-2019 [z(M-K) = 2.19, p- value = 0.01]

TABLE 13

Results of trends for diurnal temperature range (DTR) in Colombo and Nuwara Eliya (↑↑-Significant increasing trend, ↓↓-Significant decreasing trend)

Time period	Colombo			Nuwara Eliya		
	z(M-K)	p value	Trend	z(M-K)	p value	Trend
1989-2019	-3.88	0.00	↓↓			
1990-1999 (Decade 1)	-8.52	0.00	↓↓	-3.21	0.00	↓↓
2010-2019 (Decade 3)	3.60	0.00	↑↑			

In Colombo the trend analysis of the DTR during 1989-2019 showed a statistically significant decreasing trend (Table 13). However, decadal trends for DTR indicated both increasing and decreasing trends in Colombo and Nuwara Eliya districts.

(*v*) *Heat Index (HI) Analysis*

Only Colombo district indicated HI values which represented HI impact levels. In Colombo, during the period 1989-2019, HI values indicated a statistically non-significant rising pattern. However, during the last decade (*i.e.*, 2010-2019), there was a significant upward trend in HI values [Fig. 7(a)]. In addition, the month of April has shown a statistically significant upward trend for HI values during the last decade [Fig. 7(b)].

4. Discussion and conclusion

4.1. *Precipitation*

(*i*) *Annual Precipitation*

The current 31-year analysis of annual precipitation resulted in no remarkable change in the total annual precipitation in both tropical wet and tropical montane climatic regions, indicating non-significant increasing and decreasing trends in Colombo and Nuwara Eliya districts respectively. The non-significant increasing trend of annual precipitation in Colombo is similar to the analysis by Karunathilaka *et al.* (2017) and Naveendrakumar *et al.* (2018). The century scale analysis by Jayawardene *et al.* (2005) indicated a significant increasing trend in Colombo for annual precipitation and recorded an increase of 3.15 mm/yr during the last century (*i.e.*, 1869-1998). According to a previous long-term study (1869-2006) by De Silva and Sonnadara (2016), the trend analysis for annual precipitation in Nuwara Eliya recorded a significant decreasing trend at a 0.05 significant level with a reduction of 5.2 mm/year.

(*ii*) *Monthly and seasonal precipitation*

In decadal time series plot analysis, overall, Nuwara Eliya district indicates more variations in precipitation compared to Colombo district. Compared to the 1989-1999 period, monthly mean precipitations in the next two decades (*i.e.*, 2000-2009 and 2010-2019) represent many fluctuations in Nuwara Eliya district.

In Colombo, the reduction in average precipitation in May, June, and July and the increase in September in the last decade (2010-2019) revealed both the reduction and delay of the SWM rainfall in the tropical wet zone [Fig. 5(a)]. Also, in Nuwara Eliya, which represents a tropical montane climate, there was an obvious reduction in average rainfall from May to September during the last two decades (2000-2009 and 2010-2019). Furthermore, as Colombo represents a district that lies on the western coastal line and Nuwara Eliya represents an inland mountain region, this indicates an increase in coastal precipitation along the western coastal line and a decrease in inland precipitation.

In both regions, the SWM is the predominant source of precipitation. The reduction and delay of SWM rainfall may have an unfavorable impact on agricultural production in both areas. Since precipitation is regarded as a primary resource in agriculture, a decrease in average rainfall below the ideal amount can result in a significant decrease in crop yield. This information would be useful to stakeholders such as farmers and tea producers, who could alter their crop calendars according to changes in precipitation patterns. The previous study, by De Silva and Sonnadara (2016), identified a substantial drop in SWM precipitation from 1986 to 2006 in Nuwara Eliya.

In Colombo, a delay in SIM for the tropical wet region may be explained by the decrease in October precipitation, which used to be the maximum, and shifting it towards November during the last decade. The dramatic rise in FIM may be the reason for the increase in March and April average precipitation during the last two decades in Nuwara Eliya.

4.2. *Temperature*

(*i*) *Annual and monthly temperatures*

In both tropical wet and tropical montane regions, there were significant increasing trends in mean annual temperatures for the period 1989-2019, corresponding to the global annual temperature variation, which is 0.07 °C (0.13 °F) per decade since 1880 (NOAA, 2019). The increase in mean temperature per decade in the Colombo district (*i.e.*, 0.17 °C) was higher than that of the Nuwara Eliya district (*i.e.*, 0.10 °C).

In Colombo, representing a tropical wet climate, during 2010-2019, there was a statistically significant increasing trend in April maximum temperatures, which highlights one of the decade's most remarkable temperature increases. As a consequence, the warmest month of the year, which used to be May, has been replaced by April during recent years. The statistically significant increasing trends observed in December maximum and mean temperatures during 2010-2019 were also remarkable.

(*ii*) *Warm and cool nights*

Several studies have investigated a substantial decline in cool nights and a rise in warm nights in most of the world's regions (Zhou and Ren, 2011; Choi *et al*., 2009). In Colombo district, the observed significant increasing and decreasing trends in annual warm and cool nights, respectively, may have been influenced by the significant increasing trend in the mean minimum temperature in the tropical wet region. A substantial increase in mean minimum temperatures in Colombo was observed by Jayawardena *et al*. (2018) too. Since the district's mean minimum temperature did not change significantly, neither the warm nor the cool nights in Nuwara Eliya changed significantly at 95% level.

(*iii*) *Diurnal temperature range*

The daily maximum and minimum temperatures have discrete variations that affect the mean surface temperature differently. The statistically significant decreasing trend in mean DTR in Colombo during the period 1989-2019 reflected the global explanation for DTR reduction, as the minimum temperature increase in the tropical wet region was greater than the maximum temperature increase. It could be influenced by anthropogenic activities such as recent landscape changes and rapid infrastructural urban development. Urbanization may have more impact on the nighttime temperature than the daytime temperature. Especially the development projects occurred in the western coastal areas such as Colombo port city, an extension to the districts major business center and adjoining projects in the eastern Colombo after 2009 may result this rapid decrease in DTR. Furthermore, establishing high-density built-up areas and transportation development projects that result in the removal of agricultural land and vegetated areas would be the reason for this discretion (Ranagalage *et al*., 2018).

Observed and modeled intrinsic DTR fluctuations on decadal timescales are independent of changes in global mean temperature (Braganza *et al*., 2004). While the DTR during the whole study period (*i.e*., 1989-2019) displayed a decreasing trend, during 2010-2019 it indicated a significant increasing trend in Colombo district. A significant decreasing trend in DTR was observed in Nuwara Eliya during the decade 1990-1999. This significant reduction in DTR in Nuwara Eliya would have adverse impacts on potato cultivation in the region (Marambe *et al*., 2015).

(*iv*) *Heat index*

Heat extremes have become one of the leading causes of mortality and morbidity in both developed and developing countries (De Perez *et al*., 2018). The heat index assesses the potential dangers of excessive heat to the human body. In Colombo district, the significant increasing trend in the heat index during 2010-2019 and especially the significant increasing trend in April during 2010-2019, reveals the high risk encountered in the region. If the substantial increase in maximum temperatures in the tropical wet regions over the last decade continues, very high heat index values may result in serious health effects in the future (National Weather Service, 2011).

4.3. *Extreme events*

In Colombo district, the statistically significant increasing trend in annual high temperature events may cause an increase in future hot spells/heatwaves in the region. Apart from recent climate change, the high degree of urbanization and the urban heat island effect in Colombo district could have an effect on the high intensity and frequency of high temperatures (Fonseka *et al*., 2019). As a result of the temperature increase, the trends for annual low-temperature days below the 10th percentile decreased dramatically in both districts.

In both tropical wet and tropical montane climatic regions, trends for monthly high temperature days indicated increasing trends in both moderate and high temperature months. In Colombo, a substantial number of high-temperature days have been noted in recent years in April and May. In 2016, April had the highest number of monthly high-temperature days above the 90th percentile (*i.e*., 28 in total) during 1989-2019. The El Niño conditions that prevailed during the period may have had an influence on this substantial temperature increment (Northon, 2017). While the effects of extreme temperature may be exacerbated in cities like Colombo, due to the urban heat island effect, the livelihoods and social wellbeing can also be severely disrupted during and after periods of unusually hot weather. Urban surfaces such as roads and roofs absorb, hold, and re-radiate heat; raising the temperature in urban areas.

In Colombo the trend for the total number of high precipitation days per year has increased non-significantly, which may have resulted in the recurrent flood events that have occurred over the last decade (Amarnath *et al*., 2017). Strong flood events that were recorded during May 2010, November 2010 and May 2016, with catastrophic impacts on livelihoods and properties, brought out the most exceptional cases recorded in the period. The lack of a proper drainage system and excessive land use may also have a significant impact on the flooding in Colombo (Japan International Cooperation Agency, 2017).

In conclusion, analyzing climate variability in different climatic regions would aid in comprehending climate-related hazards and developing adaptive responses. Knowledge of changes in climate patterns and extreme events can be used to alter behavior, systems, economies, and environments in a favorable manner for human beings. Adapting to expected future climate responses such as extreme weather events and food insecurity would reduce the risks of harmful effects. It is essential to conduct more regional analysis of climate variables for all the districts in Sri Lanka, representing all climatic zones, to identify and differentiate the climate impacts at regional levels. Identifying patterns in climate variables and their extremes would be favorable for decision making by the authorities and for establishing climate policies in the future.

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