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Contribution of Tropical Cyclones to Extreme Rainfall Events in Sri Lanka

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ABSTRACT:
Sri Lankans often experience the adverse effects of heavy rainfall from tropical cyclones in the Bay of Bengal (BOB).Although a considerable amount of research has been conducted on TCs in the BOB, less attention has been given to the relationship between TCs and extreme rainfall events in Sri Lanka. The purpose of this study is to use statistical analysis and historical data to assess the role that tropical cyclones play in extreme rainfall events in Sri Lanka. The contribution of tropical cyclone precipitation relative to total extreme precipitation was examined for all weather systems combined.CHIRPS precipitation data for 15 observation network stations during the period 1981–2021 were used for the analysis. The orographic effect of Sri Lanka's topography significantly increases rainfall, especially on the western slopes. TCs generally produced heavy rainfall over the eastern, northern and north-central provinces of Sri Lanka and especially in the eastern coastal areas such as Trincomalee and Batticaloa. Also, for the dry zone, TCs were the main contributors to the top ten wettest days, in contrast to the monsoonal patterns in the wet zone. Temporal analysis revealed a slight, non-significant decrease in the annual number of TC-induced heavy precipitation days. Districts like Colombo, Galle, Katunayake and Ratnapura saw a significant increase in heavy rainfall events during the study period, with TCs contributing 18% to 22% of these events along the coast and inland.

Keywords—Tropical cyclone, Extreme Rainfall

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I. INTRODUCTION

Sri Lanka is an island located close to the equator in the North Indian Ocean (NIO) within the tropics between 5° 55' to 9° 51' North latitude and between 79° 42' to 81° 53' East longitude. Rainfall in Sri Lanka, which has a very rainy climate, is strongly influenced by topography and the surrounding ocean area [1]. SometimesTCs bring overcast skies and rains to the southwest, northeast, and eastern parts of the island. The average yearly temperature for the country, as a whole, ranges from 26° C to 28° C. Sri Lanka being a small island in the Indian Ocean in the path of two monsoons is mostly affected by weather related hazards. Floods mostly due to monsoonal rain or effects of low-pressure systems and droughts due to failure of monsoonal rain are the most common hazards experienced in Sri La Being a tropical island located in a disaster-prone region, Sri Lanka is vulnerable to severe weather extremes such as strong winds, droughts, and cyclones. The country has frequently been experiencing heavy rainy weather. Predictions by global studies on climate change suggest that both intensity and frequency of such extreme events are likely to increase in the future. Furthermore, several studies have dealt with the rainfall patterns in Sri Lanka and a majority of them are based on historical records [2]. Sri Lanka, located in a tropical region, is highly vulnerable to climate extremes such as tropical cyclones (TCs) and heavy rainfall events. Infrastructure, agriculture, water resources, and human settlements are all seriously at risk from these phenomena, underscoring the urgent need to comprehend their interactions and possible effects.

Changes in global climatic patterns brought about by climate change are resulting in modifications to the frequency, severity, and paths of tropical cyclones [3,4,5]. The rise in extreme weather occurrences in the region is linked to the rising temperature trend in the Indian Ocean (IO)[6].Tropical cyclone (TC) activity over the Bay of Bengal (BoB) appears to be decreasing trend, according to the seven-year running mean of TC numbers during the years 1891–2007[7]. [1]observed that the majority of Sri Lanka's extreme precipitation events showed increasing trends, and that the intensity of the rainfall also increased. Numerous extreme weather phenomena, such as hurricanes, severe cyclonic storms, floods, droughts, heat waves, and cold spells, have occurred over the world in recent decades [8]. For South Asia as well, this is true. For the northern Indian Ocean, there have been no significant recent changes in the overall annual tropical cyclone (TC) frequency, but the frequency of category 4 and 5 strong cyclones (SC) has increased significantly over the past few decades [9]. The deadliest cyclone to ever hit the North Indian subcontinent was the Bhola cyclone in 1970, which claimed over 300,000 lives in Bangladesh. Furthermore, according to data from the IMD's Regional Specialised Meteorological Centre (RSMC), nine out of ten tropical storms that have been documented worldwide and have resulted in significant human casualties originated in the North Indian cyclone basin. Therefore, Sri Lanka is vulnerable to severe weather conditions during the North Indian cyclone season [10]. It's critical to comprehend the features of extreme rainfall events since they inflict significant harm on the environment, human settlements, infrastructure, agriculture, and economy. Research on extreme rainfall events worldwide demonstrates that variations in these types of events can have considerable effects on how physical infrastructure is planned [11].

In the Bay of Bengal, landfall TCs accompanied by intense rainfall frequently resulted in floods in the coastal districts of Bangladesh, India, and Myanmar, putting local livestock homes, and human life in danger. For instance, Bangladesh suffered damage from coastal flooding caused by the very severe cyclonic storm Sidr (2007) to homes, crops, highways, and infrastructure. In Vanni, Cyclone Nisha (2008) caused up to 70,000 homeless people, while in the Jaffna district in Sri Lanka, excessive rainfall and coastal flooding caused 20,000 affected persons [12]. Furthermore, 2,753 houses in Sri Lanka were damaged, while 57 houses were completely destroyed. 10,336 persons were displaced, according to the European Civil Protection and Humanitarian Aid Operations. As of December 6, 2020, 11 individuals had died and 5 more were reported missing from Burevi. The Batticaloa cyclone of November 1978 was amongst the most destructive endured by Sri Lanka in the last 100 years with the huge loss and damages, and claimed more than 915 lives, injured more than 4,500 and severely damaged well over 100,000 buildings. An estimated more than one million people were affected, with over 250,000 buildings damaged, and one fifth of Batticaloa's fishing fleet destroyed. 9 of the 11 paddy stores were destroyed and 90 percent of the coconut plantation (28,000 odd acres of coconut plantation) in the Batticaloa district had been destroyed. The Sri Lankan government spent over 600 million Sri Lankan rupees in relief efforts in the aftermath of the disaster. Also, in May 2003, the very severe cyclone BOB01 did not pass over the island, and its track was about 700 km from the east coast, resulting in heavy rainfall over the island.It flooded the southwest of Sri Lanka, resulting in 260 deaths from landslides and floods [10].

In year 2020, Sri Lanka was affected by three major cyclones (named as Amphan, Nivar and Burevi) which were formed in the Bay of Bengal [13].Among these, Super cyclonic storm “Amphan” which developed during the 3rd week of May brought very heavy rainfall exceeding 200mm over southwestern parts of the island due to outer feeder bands of the system and very severe cyclonic storm “Nivar” skirt northern coast of Sri Lanka while propagating towards Tamilnadu coast, bringing strong winds and heavy falls exceeding 100mm over northern coastal area from 23 to 26th November. Cyclonic storm “Burevi” cause extensive damages to Northern part of the country as it crossed Sri Lanka coast on 2nd December 2020, bringing strong winds, heavy rainfall, storm surge and flash floods in low lying areas in Northern and Eastern provinces. According to the Disaster Management Centre, at least two people died, six people were injured. 99 houses were fully destroyed while 3,486 houses were partially damaged with a total of 95,734 persons affected by Cyclone Burevi. This included 79,564 in the Jaffna district alone [14]. Especially in Sri Lanka's southwest, hydrometeorological hazards like landslides, flash floods, and floods are frequent. Every year, floods frequently affect citizens in the districts of Galle, Kalutara, Ratnapura, and Colombo [15].

Although losses associated with TC precipitation are significant, it is not known how much of the island's total precipitation comes from TCs. Significant advantages are also afforded in some places that less receive rain. Therefore, in this paper were used CHIRPS satellite data over Sri Lanka during 1981–2021 to analyse the TC rainfall contribution in this region. The remainder of the paper is structured as follows. The data and methodology are described in Section II. Results and discussion are explained in Section III. Summary and conclusions are presented in Section IV.

II.DATA ANDMETHODOLOGY

A. Study Domain

The BOB is the world's largest bay with a length of 2090 km and a width of 1610 km.It is bordered by Sri Lanka and India to the west, Bangladesh to the north and Myanmar to the east [16].Tropical cyclones generated in BOB have been used forthis study.For this study, point rainfall data were selected for 41 years, from 1981 to 2021, for network of 15 out of 23 main surfacemeteorological stationsacross the Sri Lanka [17] (Figure 01 and Table 01).

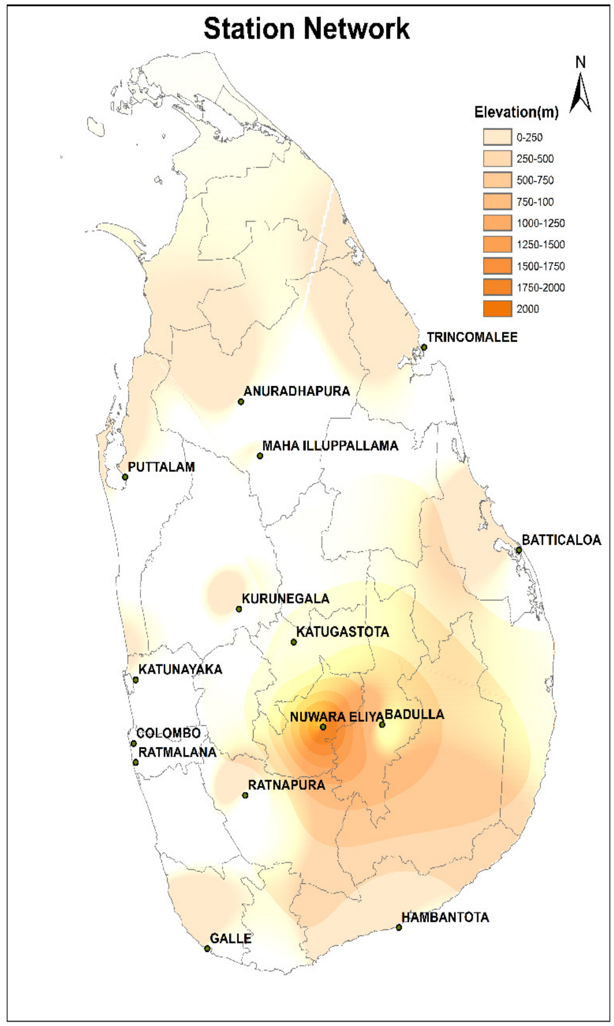

Figure 01: Network of 15 surface meteorological observation stations

B. Rainfall Data

Due to the lack of quality of available data and gaps in data availability at both temporal and spatial scales, there are several disadvantages to using observational data in an analysis.Therefore, CHIRPS (0.05x0.05) was selected for further analysis in this study after multi-source data verification. The Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset uses novel interpolation techniques with highresolution

Table1: Station Network with Abbreviations, Longitude, Latitude and Elevation

Station Id	City	Province	longitude	latitude	Elevation(m)
43421	ANURADHAPURA	North-central	80.38	8.35	93.9
43479	BADULLA	Uva	81.05	6.98	864.9
43436	BATTICALOA	Eastern	81.7	7.72	7.2
43466	COLOMBO	Western	79.87	6.9	10.2
43495	GALLE	Southern	80.22	6.03	17.3
43497	HAMBANTOTA	Southern	81.13	6.12	16
43444	KATUGASTOTA	Central	80.63	7.33	561
43450	KATUNAYAKA	Western	79.88	7.17	14
43441	KURUNEGALA	North-western	80.37	7.47	144.2
43422	MAHA ILLUPPALLAMA	North-central	80.47	8.12	117
43473	NUWARA ELIYA	Central	80.77	6.97	1973.1
43424	PUTTALAM	North-western	79.83	8.03	13.9
43467	RATMALANA	Central	79.88	6.82	5
43486	RATNAPURA	Sabaragamuwa	80.4	6.68	96
43418	TRINCOMALEE	Eastern	81.25	8.58	18.4

precipitation estimates which runs for a long period which are based on infrared Cold Cloud Duration (CCD) observations. The algorithm is developed around a 0.05° climatology that includes satellite data to represent areas which does not have a lot of gauge data. Monthly CCD-based precipitation estimates of resolution 0.05° from 1981-present merges station data to generate an initial product and uses a modern interpolating process which incorporates the spatial correlation structure of CCD-estimates to assign interpolation weights [18]. In this study, daily rainfall data spanning from 1981 to 2021 of resolution Methodology.

C. Tropical cyclone dates

The extreme rainfall that Sri Lanka experienced on the days when cyclones formed in the Bay of Bengal (BOB) region was taken into consideration when conducting this study. Days when tropical storms were active in the BOB were selected as TC days, using IMD best track data and International Best track Archive for Climate Stewardship (IBTrACS) best track version_3[19].Because the Indian Meteorological Department (IMD) is in responsible for collecting, processing, and archiving TC best track data over the BOB,as well as monitoring and predicting TC activity, I used theirbest track data for the purpose of this study[20].The best track data with 3 hourly temporal resolution can be downloaded from the IMD official website (http://www.rsmcnewdelhi.imd.gov.in). IMD categorised TCs into seven groups based on their maximum sustained surface winds speeds: Depression (De), 17–27 knots; Deep Depression (DD), 28–33 knots; Cyclonic Storm (CS), 34–47 knots; Severe Cyclonic Storm (SCS), 48–63 knots; Very Severe Cyclonic Storm (VSCS), 64–119 knots; and Extreme Severe Cyclonic Storm (ESCS), larger than 120 knots. I only consider CS, SCS, VSCS, and ESCS as tropical cyclone events for my research. De and DD were excluded from this study because depressions in the BOB could include monsoon depressions without a warm core[12]. A criterion of radial distance between the cyclone track and the meteorological station receiving theprecipitation was used to detect extreme precipitation events caused by TCs crossing the island. Based on the previous researches [21], in this study, a precipitation event is considered induced by a TC if the cyclone track passes within an 800km radius of the station.

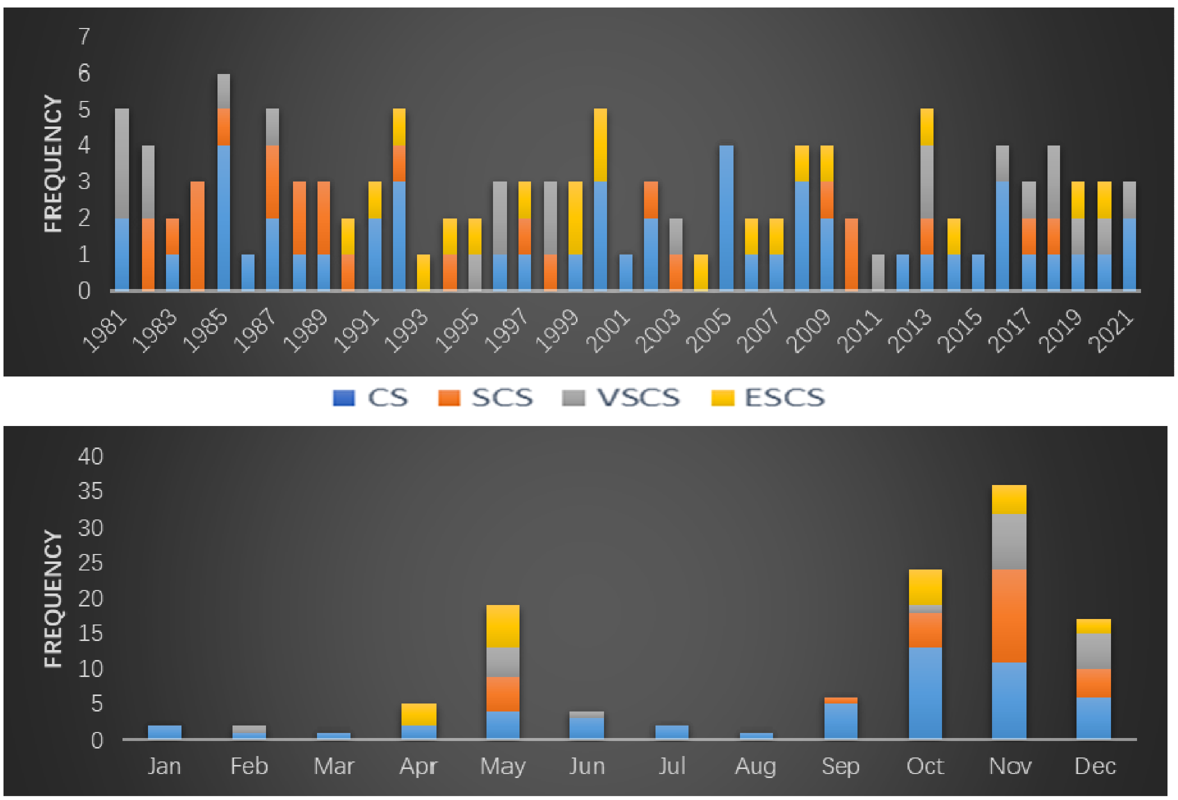

Figure 02: a). Yearly, b). Monthly distribution of Tropical Cyclones (TCs) in the Bay of Bengal during 1981-2021

D. TC activity in the Bay of Bengal

This analysis was conducted based on the data of tropical cyclones formed in the Bay of Bengal. A total of 119 TCs crossed the BOB from 1981 to 2021 (Figure 02-a), including 51 CSs,28 SCSs,20 VCSs and 20 ESCSs. Two VCSs and one CS have passedover Sri Lanka during this time period, whilenumerous additional cyclones that have moved close to land have affected rainfall in Sri Lankaboth

directly and indirectly. Except for 1983, 1986, 1990, 1993, 2001, 2004, 2011, 2012 and 2015, all other years had formed 3 or more TCs. The years 1985 had the strongest TC activity with 6 TCs, including 4 CSs.1VSCS and 1 ESCS.On a monthly basis, TC activity was strong in November (36 TCs), October (24 TCs), May (19 TCs), and December (17 TCs) (Figure 02-b).This suggests that TC activity increases during post-monsoon in the BOB.

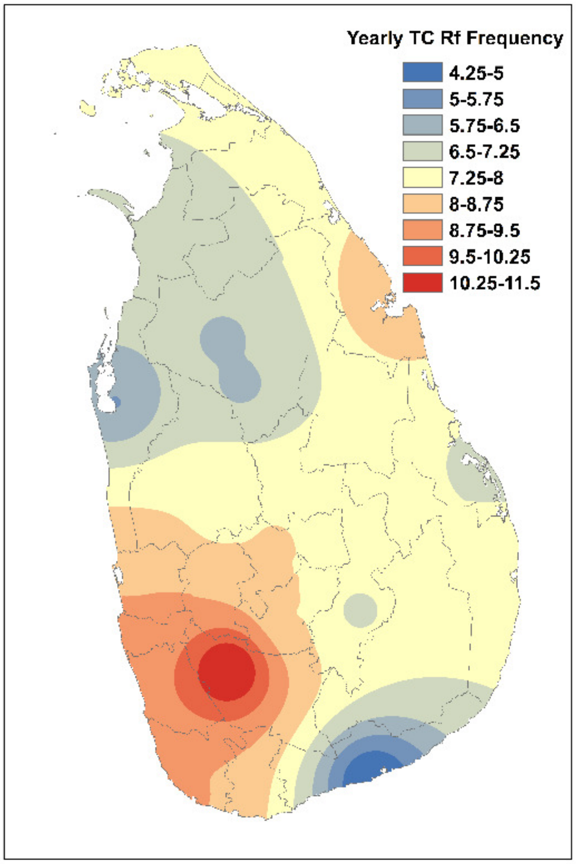

Figure 03: Yearly Climatology of the number of tropical cyclone (TCs) producing precipitation across the Land.

Figure 03 displays a yearly climatology of the average numbers of TCs producing precipitation across our study region. This climatology includes storms whose rain shield produced significant precipitation at a station within a TCs. TCs occurrence is most frequent along the eastern side of the coastal regions of the island, and more stormsinfluence stations in the western slope of the central hills than the eastern coastal portion of the island. Previous analyses clearly showed that the orographic effect of the Central Highlands of Sri Lanka has similar patterns to the global figures of the orographic rainfall in thetropical mountains and highlands [22]. It is evident that the orographic influence of the island's geographical structure has resulted in increased precipitation in the western slope of the central highlands due to the atmospheric wind conditions caused by TCs.

There are a number of methods to determine how tropical cyclones contribute to extreme precipitation.

E. Frequency of Extreme Precipitation Days

A different approach focused on the frequency of extreme rainfall events[23,24]. Events that surpass the extreme precipitation threshold and profoundly affect human society are classified as extreme precipitation events. Establishing the disaster-triggering daily precipitation threshold (DDPT) is the basis and crucial element to assessing the intensify and frequency of extreme [25]. The Department of Meteorology has classified 150mm more as very heavy rainfall, 100-150mm heavy rainfall, and 50-100mm rains as fairly heavy rainfall, but currently no specific value has been given as the extreme rainfall value for Sri Lanka [17]. Past studies have used a number of statistical methodologies to assess changes in extreme precipitation events. The most commonly used nonparametric method is the percentile method. These indices are used to address moderate to heavy precipitation events, i.e. precipitation events that are larger than average events (that may be assessed by their mean daily intensity), but smaller than rare extremes (that require more sophisticated statistical approaches)[26].

For present study, the definition of extreme precipitation (EP) [27] was applied and the value of 95th percentile was selected as the threshold. This method, [28] also used to determine the extreme precipitation value. Counted both the number of TC days and all days that exceeded 2.12 cm of precipitation for Sri Lanka. Considered an event to be an extreme precipitation event if the daily rainfall across Sri Lanka on all days in January–December 1981–2021 exceeds the 95th percentile of daily rainfall. Therefore, 21.2 mm of precipitation day−1 is the precipitation threshold for an extreme precipitation event, and throughout the analysis period, 757 out of 14,976 days had extreme precipitation occurrences.

In this study, on TC days, if the cyclone track passes within a radius of 800 km from the station and, the daily rainfall value is within the extreme rainfall threshold it is considered as TC rainfall data and has analysed.

F. Top 10 Wettest Days

Examined the number of TC days that occurred in the top 10 wettest days of each year at each station, following the methodology of [29]. The temporal changes in the percentage of the wettest days of the year that have been reported on by TCs were further examined on a network-wide basis. The goal of this method is to determine whether there has been a recent change in the influence of TCs on the wettest days of the year. This strategy avoids using set bins based on precipitation percentiles, which has been noted as a potentially problematic method when analysing climate change.

G. Top Percentile of Precipitation Days

Many studies have used a combination of percentile indices.For example, [30] discovered that increases in heavy and intense daily precipitation events are the main cause of the observed precipitation increase of about 10 percent over the contiguous United States. They did this by using both frequency- and intensity-based indices [26].Examined trends inthe upper 10th percentile of precipitation averaged on days with TC compared to the upper 10th percentile of precipitation averaged on all days with precipitation for each station.Furthermore, observedfluctuations in the top 10th percentile value when TC days were removed from the data set. Past studies have used this method [23].To determine how the top 10th percentile valuewhich represents the contribution of TCs to extreme rainfallmight vary over time,conducted this for each year at each station.

H. Trends in Percentage Contribution of Tropical Cyclones

In addition, determined the percentage that TCs contributed to all observed precipitation in the upper 5th, 10th, and 20th percentiles of precipitation amounts for each year. For each percentile at each location, temporal changes in this contribution were evaluated. This method yields a physically comprehensible value that quantifies the contribution of TC precipitation to the overall extreme precipitation. Used linear regression to glance at the rainfall's temporal behaviour in each of the approaches.

III.RESULTSAND DISCUSSION

A. Frequency of Extreme Precipitation Days

This section focuses on extreme rainfall, based on the frequency of events involving rainfall exceeding the threshold of 21.2 mm/d.Figures 4a and 4b show the number of days exceeding this threshold for TC days and all days over the period of record for the CHIRPS data set, respectively. There are two distinct spatial patterns that stand out. In the areas near the coast from the north of the island through the east coast to the southeast, extreme events are characterised by a relatively moderate frequency.As mentioned in the previous article, due to the orographic effect, it is not surprising that the highest number of extreme events have occurred in the western slopes of the Central Highlands.

Not surprisingly, the highest number of extreme events occur in the western slope of the central hills,due of the orographic effect similarly to previous paper [22]. The orographic effect is responsible for the heavy rainfall experienced during cyclones in Sri Lanka on the western slope of the central hills.

Contrastingly, the overall extreme precipitation frequency pattern (Figure 4b) does not have the same gradient it is very similar to annual rainfall pattern in
the country. It has expanded to the island's wet zone as a more extreme rainfall frequency, the intermediate zone as a medium frequency, and the dryzone as a low frequency in Sri Lanka.This time series was used for a regression analysis.Over the time, there has been an increase in all extreme events with an annual trend of 2.205, while the frequency of extreme TC events has risen with an annual trend of 0.2662 (not shown).

Furthermore,examined the tendencies that each station experienced within this time frame (not shown). With the exception of Hambantota, the number of extreme precipitation days across all days has been trending positively. There is a non-significant drop in Hambantota. Prior research indicates that dynamic rainfall trends with both increasing and decreasing patterns in Sri Lanka[31].In addition, another researcher points out that during the period of his analysis, the annual rainfall trend was high in the majority of measuring points in the country [32]. It has been shown that there is an increasing trend in the eastern part of the country and a decreasing trend in the western region.

The frequency of extreme TC events has increased rapidly in Colombo,Galle,Katunayake andRathnapura districts (not shown).This finding is consistent with prior research indicating that TC is likely to produce greater impacts South and west of the country, including themajor cities of Galle, Matara, Kalutara, Rathnapuraand Colombo [33]. A non-significant decline trend exhibits on other stations.

Finally, by analysing theratio between Figures 4a and 4b,examined the role that TC eventscontributed in the overall extreme (more than 21.2mm) precipitation occurrences.As shown in Figure 05, thespecific spatial pattern in the study area,the

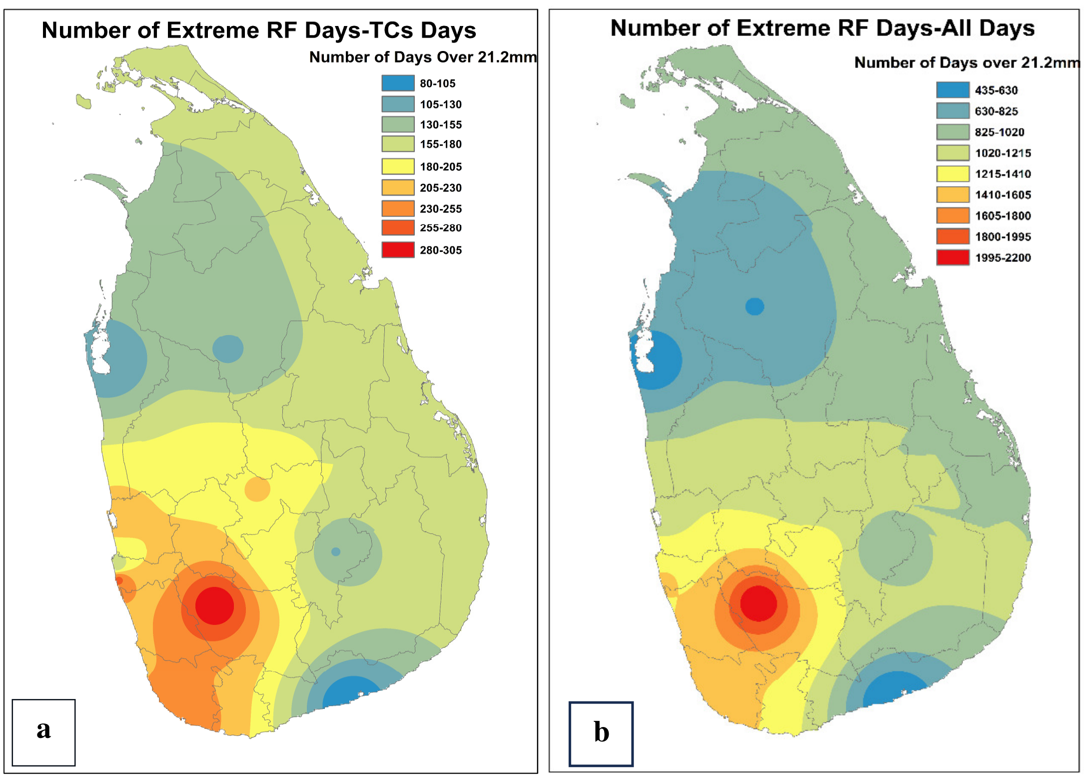

Figure 04: Number of days exceeding 21.2mm rainfall per day for (a) TC days and (b) all days

North, North-central, Eastern, North-Western and Southern provinces of the island have a high value and the rest of the regions show a lower value.

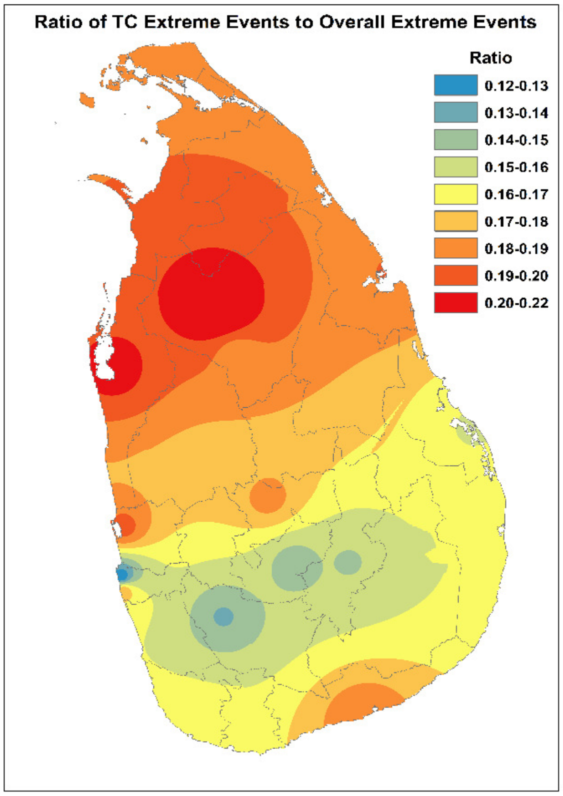

Figure 05: Ratio of number of TCs extreme rainfall events to overall extreme rainfall events (greater than 21.2mm rainfall per day)

Previous studies have discovered that whilst ESCS produce 3% of low rain rates and 24% of extreme rain rates, CS TCs produce 55% of low rain rates but only 10% of extreme rain rates in the BOB [12].In additionally, theyindicated that these findings are similar to those of previous research conducted in the Southeast of the United States [34]. They found that while the rainfall ratio of tropical storms/depressions (TD/TS) continued to decrease, the rainfall ratio of major hurricanes (CAT12 and CAT35) continued to increase from low to high rain rates. However, a higher proportion of heavier rainfall was typically produced by stronger TCs, and strong TCs were a key contributor to extreme rainfall.Contribution of TC precipitation to extreme precipitation in Sri Lanka, TCs are has influenced by track area, frequency, and magnitude, as well as by other events.

B. Top 10 Wettest Days

Then presented a yearly climatology of the number of TC days that are within the top 10 wettest days of the year (Figure 06). Not surprisingly, values are highest in North-western, North central, North and Eastern provinces of island because that areas are belongs to dry and intermediate zone which are received low precipitation. From that it is clearly concluded that tropical cyclones have mainly contributed to those areas receiving the highest rainfall.In addition, high values are also shown in some areas of Western and Southern provinces.

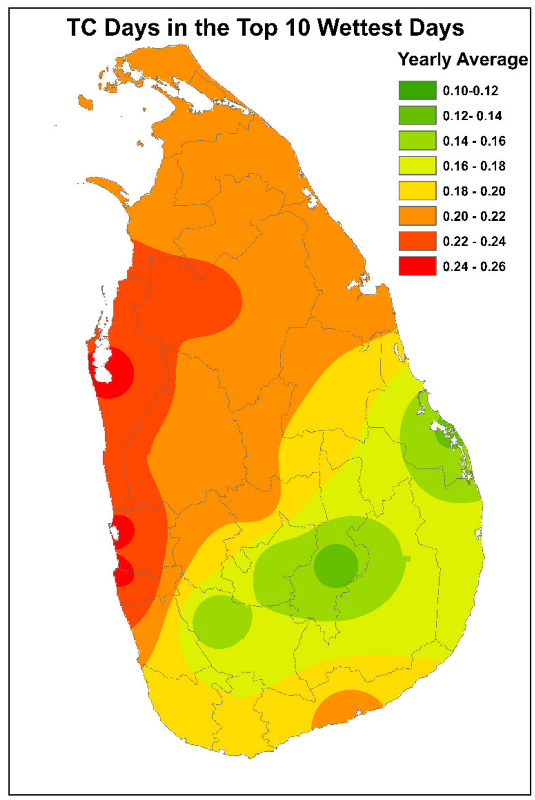

Figure 06:TC days in the Top 10 wettest days

Furthermore, four cyclones have passed through the island during this period and the SCS in November 1992 entered in the Pothuvil area of the island and left the island between Colombo and Puttalam via

Bibila. The ExtraSevere Cyclone Storm (ESCS) that occurred in December 2000 was the first to make

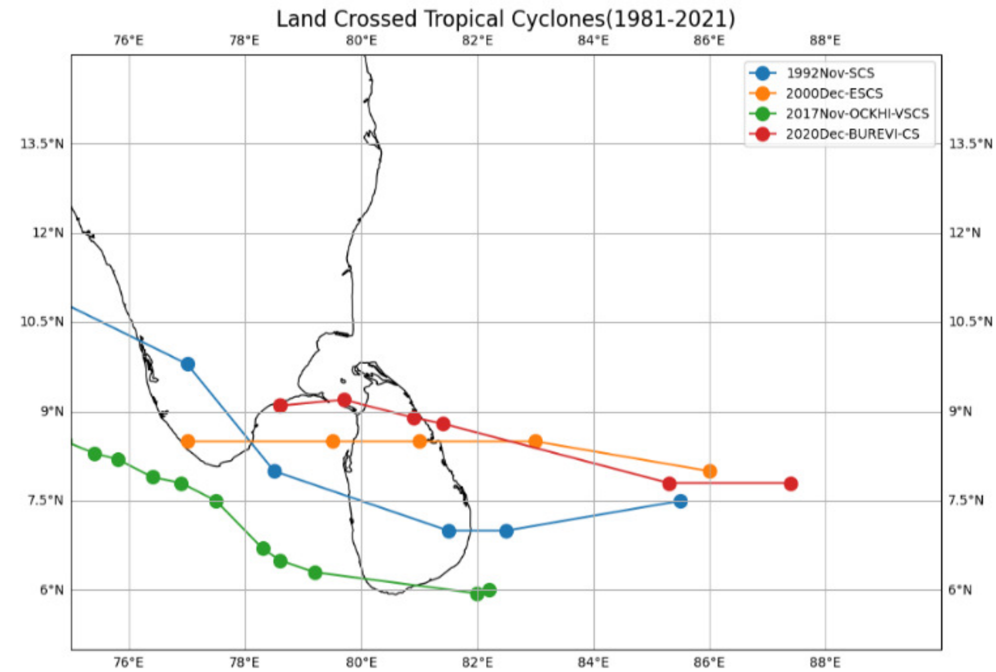

Figure 07: Track of TCs which Land crossed tropical cyclones during 1981-2021

landfall in Trincomalee. A gradually weakened but very severe cyclone (VSCS) storm passed through the Wilpattu area of the island and left the island south of Mannar. In 2017, the OCKHI VSCS has generated off the Pothuvil coast and departed south of Colombo via Ratnapura. The Burevi cyclonic storm (CS) occurred in 2020 crossed the coast of Sri Lanka close to north of Trincomalee and left the island from Thalaimannaram area [20].

Figure 08: Time series, linear regression and two period moving average of the number of top 10 wettest days that were TC days

Most of these areas are spread over the North, North Western, North central, Eastern, Western and Southern provinces of the island (Figure 07). Furthermore, most of the TCs formed in the Bay of Bengal have moved close to the northern and eastern parts of the island. The southern portion of the island is also having significant value, and because there were a smaller amount tropical cyclones that passed closetothose areas during this period, their influence on the Top 10 rainfall in other areas has declined.

Additionally examined at the fluctuations in the number of TC days in the top 10 wettest days over the entire network (Figure 08). The highest value that may be achieved for a given year is 150 days, which would happen if the top 10 wettest days of a given year were all TC days at all 15 stations. A statistically similar and non-significant pattern of decline was found with a slope of 0.15 days per year.However, it is evident that the years 1992, 2000, 2017, and 2020, when the TC moved across the land, contributed considerably more. In addition, there was a significantly higher contribution in years when TCs moved very close to land.Nonetheless, there are comparatively equal amounts of TC days throughout the wettest days of the year during this time.The main reason of this is that in 2001, 2004, 2011, 2012, 2015, and 2016, there was a minimum BOB TCs frequency (Figure 02-a) which had a less impact on the top 10 wettest days during those years.This has also been confirmed in a previous paper that BOB TCs frequency values are similar [12].

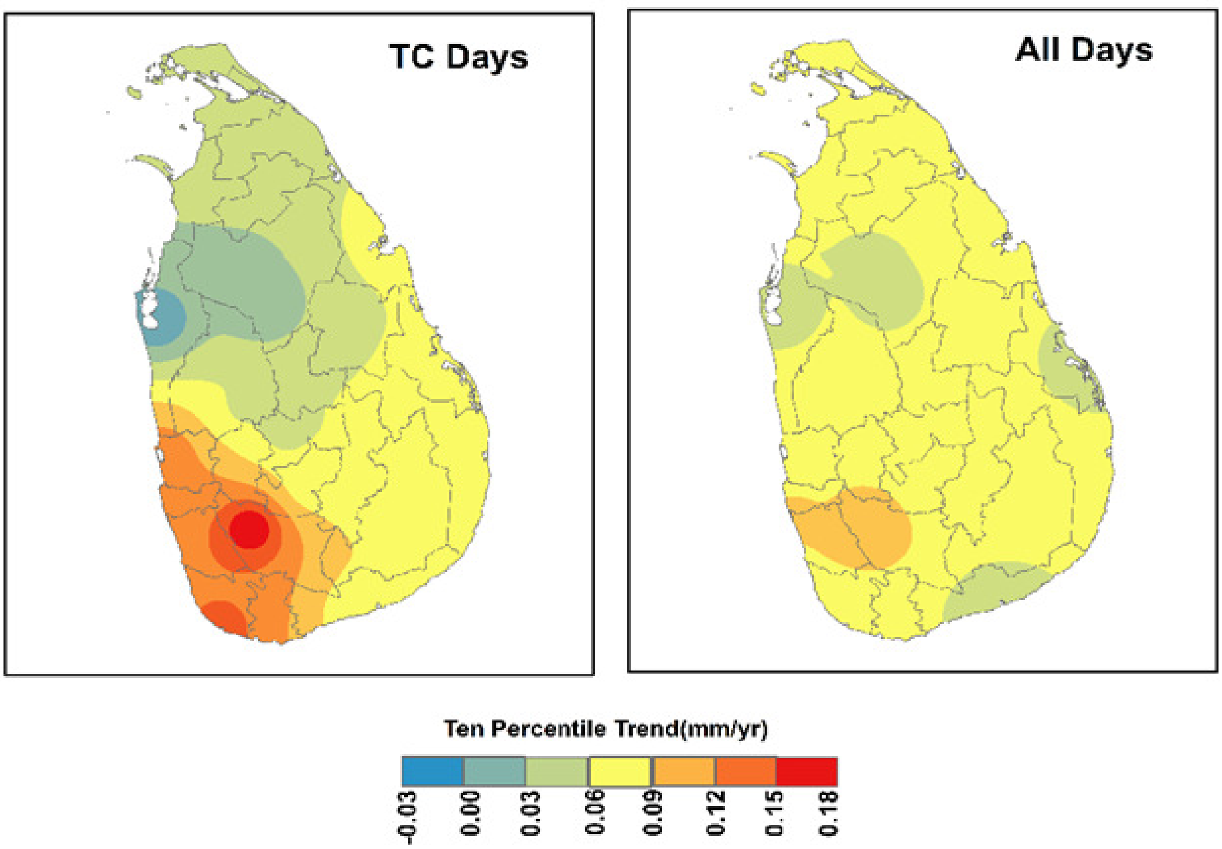

Figure 09: Trend (in millimetres per year) in the average precipitation of the top 10th percentile for (a) TCs and (b) all precipitation

C. Top Percentile of Precipitation Days

The top 10th percentile of TC precipitation and all precipitation were the focus of as our next metric, which allowed us to compare the temporal changes in both.The trend in the average precipitation of the top 10th percentile for TCs and all precipitation is illustrated in Figures 09a and 09b. Since the same scale was used when making both maps, the gradations are directly comparable.

With the exception of the Puttalam district in northwest region on the TC days map, both maps generally depict a positive trend over this time period. Significant contrasts between the two maps are clearly evident on the western slope of the central hills of the study region.Overall, extreme rainfall is increasing slightly in all parts of the country.

However, the total rainfall trends during the recorded period of this study were positive but lower in the North-Western and North-Central provinces (Figure 10). Despite the high contribution of the top 10 wettest days to the north-western part of the island,
the TC days extreme rainfall trend has decreased as TCs do not impact this region on a yearly basis. A recent study demonstrated a declining trend in annual counts of days with heavy rainfall in g trend in annual counts of days with heavy rainfall in Southern India and Sri Lanka based on a different extreme event [35].

In addition, past researchers have showed the spatial patterns of the number of days with heavy rainfall for summer and winter halves of the year for the present analysis. According to that research, the spatial distribution patterns show a declining trend in the northwestern region of Sri Lanka, and it is also mentioned that the remaining regions of Sri Lanka show an increasing trend during the summer half year [36]. Furthermore, the study examined that, similar to extreme rainfall, heavy rainfall events are high in the western region up to the highlands and show an increase when moving towards the northern and eastern regions. In addition, he mentioned that for the winter half of the year, heavy rainfall events are also high in the western part of Sri Lanka but show a declining trend. In general, the NEM is weaker compared to the SWM in terms of winds, and hence, gives widespread light rainfall to the entire country, but more for the Dry Zone. Depressions and occasional tropical cyclones have been shown to contribute toheavy rainfall in this region.

However, the western slopes of the island's central highlands have a stronger tendency in the top 10th percentile of average rainfall for TCs days, and the eastern and southeastern coastal regions also exhibit a notable increase.Furthermore, prior research has amply demonstrated it.TC is likely to produce greater impacts when it is formed close to Sri Lanka or having a projected path along or when it is formed close to the Eastern coast of Sri Lanka and the areas that usually receive the heaviest rainfall are the south and west of the country, including the major cities of Galle, Matara, Kalutara, Rathnapura and Colombo have been mentioned in those studies [33].

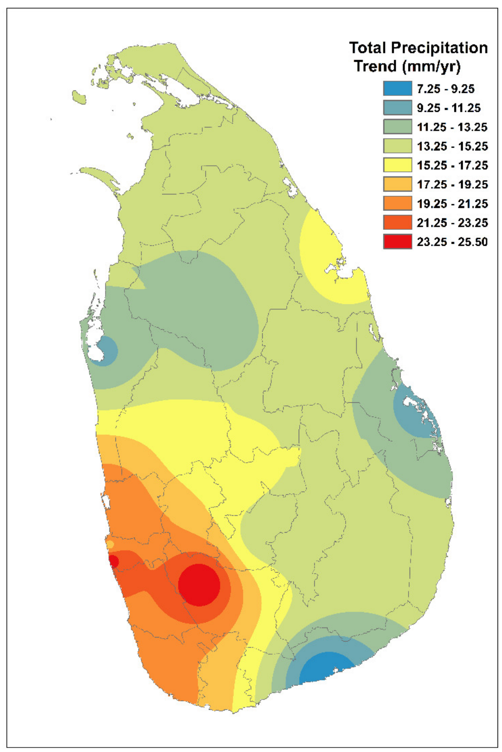

Figure 10: Trend in total precipitation,1981 – 2021

Next evaluated at how removing TC days from the record might affect the top 10th percentile figure of precipitation. Figure 11a shows this analysis for the entire period of record. The largest reductions are along the Eastern to North -western coastlines and interior regions of the that regions.The upper 10th percentile value would decrease by approximately 5% – 9% in these areas if TC precipitation days were removed.

This map is quite similar to the maps shown in Figure 5 because this analysis essentially removes TC precipitation days that were in the top 10 wettest days of the year.A regression analysis was performed at each station using this time series, and the variable of interest is the percent reduction of the top 10thpercentile value following the elimination of TC precipitation days (Figure 11b). The percent reduction of the upper 10th percentile value has increased over time over the island. On the western slopes of the central hills, there is a noticeable increase.In other words, precipitation generated by TCs is contributing an increasing percentage of the overall extreme precipitation over time. When TC precipitation days are removed from the entire period, the Eastern, Northern, Northern-central and Northwestern provinces exhibit the largest decrease in the percentage of the top 10th percentile value of precipitation; however, when examining the trend of increase over time, the increase in those regions is less than that of the other regions. This is due to the fact that these areas are not annually affected by cyclones that originate in the Bay of Bengal. Prior research supports this, as was previously indicated that TC is likely to produce greater impacts when it is formed close to Sri Lanka or having a projected path along or when it is formed close to the Eastern coast of Sri Lanka and the areas that usually receive the heaviest rainfall are the South and west of the country [33].

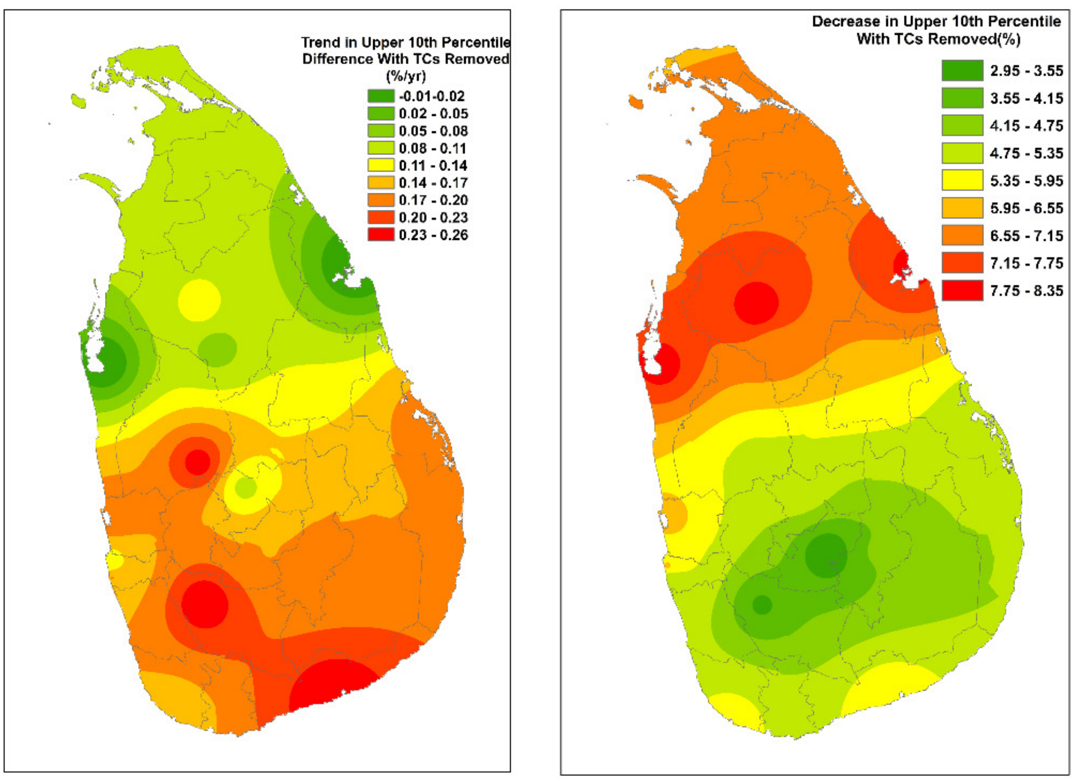

Figure 11: (a) Percentage reduction of the upper 10th percentile value of precipitation if TC precipitation days are removed from the overall period. (b) Temporal trend (percentage per year) in the percentage reduction (1981 – 2021)

However, TCs that passed through or close to these areas during this time period have had a significant impact. As a result, even though these regions have the greatest reductions in the upper 10th percentile, the increasing tendency has declined over time.

D. Trends in Percentage Contribution of TCs

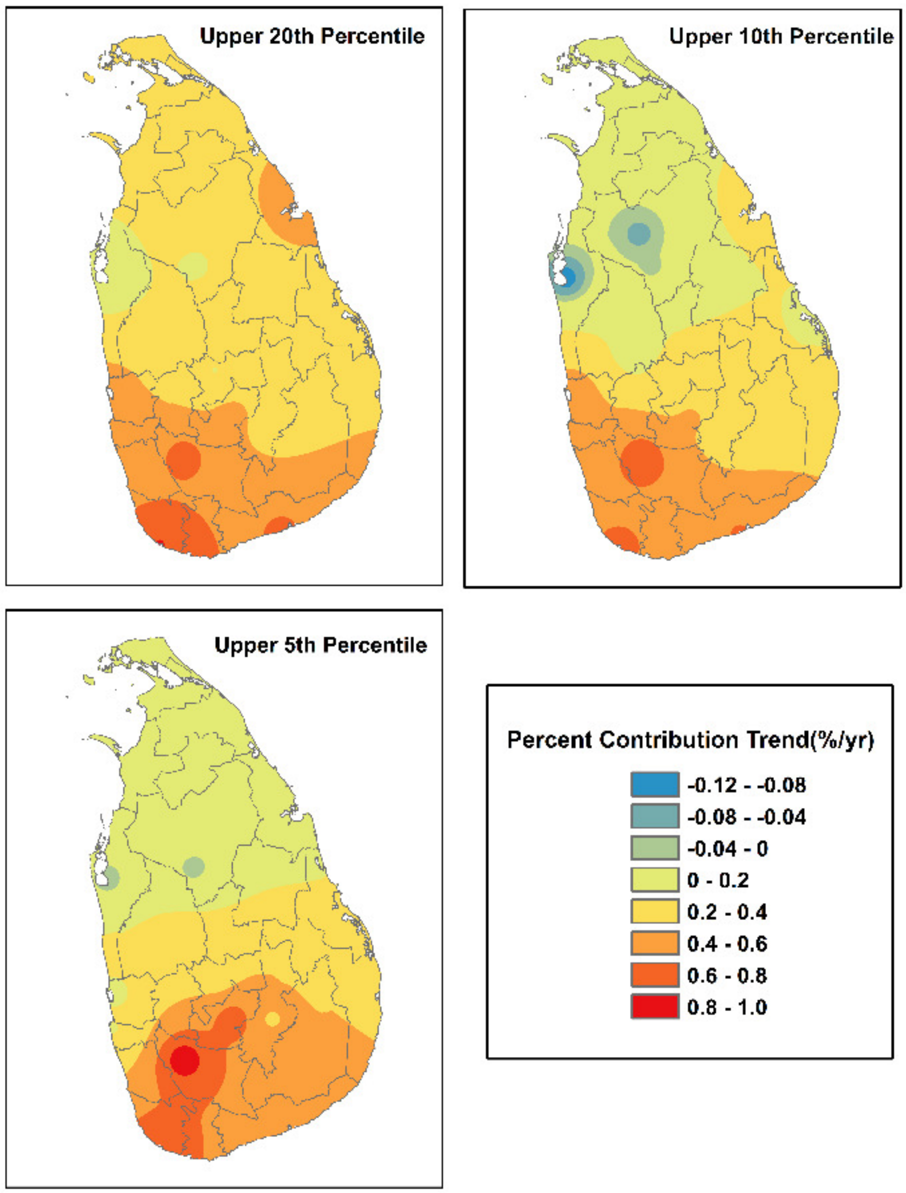

Figure 12: Temporal trend of the percentage contribution of TC precipitation to overall precipitation within the (a) upper 20th percentile, (b) 10th percentile, and (c) 5th percentile (1981 – 2021)

The final method applies the metric of the upper 20th, 10th, and 5th percentiles for the percentage contribution of TC precipitation to the overall extreme precipitation.Figures 12a– 12c show how the percent contribution has changed temporally at each of these percentiles. The gradations are consistent between the three percentiles, so direct comparisons can be made across maps. During the 1981–2021 record period, the contribution of TC precipitation to total extreme precipitation at each percentile has been increasing with the exception of some areas in North Western and North provinces.When comparing the three maps, the trend's size usually rises in western slope of the central hill's areas with increasing extreme precipitation. Using Sabaragamuwa province, Rathnapura as an example, there is a 6.6% per decade trend at the 20th percentile, a 7.4% per decade trend at the 10th percentile, and a 9.2% per decade trend at the 5th percentile.In general, this pattern of an increasing trend value is apparent across the western slope of the central hills in study region in moving from figures 12a and 12b (20th percentile to 10th percentile) and also from figures 12b to 12c (10th percentile to 5th percentile). However, even if there was a positive trend in other regions, as the percentile value increased, the trend size has slightly decreased.

IV. SUMMARYAND CONCLUSIONS

Used a variety of metrics to understand how tropical cyclones contribute to extreme rainfall in the Sri Lanka.A brief summary of the unique findings from each approach is shown in Table 2.

Implemented several metrics of extreme precipitation to determine how TCs contribute to the overall extreme precipitation in Sri Lanka. Each of those metrics provided fresh insight into the main purpose of the study, including the analysis of the top wettest days, the frequency of extreme days, variations in the top tenth percentile, and trend in the percentage of TC rainfall that contributes to total extreme rainfall. However, same spatial patterns of extreme precipitation were consistently displayed by all metrics. Furthermore, every one of these methods demonstrated that the intensity and frequency of extreme tropical cyclone (TCs) in the districts of Colombo, Galle, Katunayake, and Rathnapura was rising rapidly. Eastern, Northern, North-Central and North-Western Provinces indicate a higher contribution of TC rainfall to the overall heavy rainfall in this study period, but the frequency of TC extreme rainfall events in those regions does not show an increase in the annual trend.Prior research indicates that dynamic rainfall trends with both increasing and decreasing patterns in Sri Lanka.However, total precipitation in the Sri Lanka has gone largely unchanged since1981, this study's period of record. Another researcher displayed the annual rainfall trend, demonstrating a declining tendency in the western and an increasing trend in the eastern parts of the country.As a result, no significant change in extreme precipitation was observed during this period, and the extent to which TCs influence trends in extreme precipitation could not be determined.

Many indicators show that over time, precipitation from TCs has contributed to overall heavy precipitation, and it has varied from region to region.Western, Central, Southern and Sabaragamuwa Provinces showed positive trends in contribution of 5% - 10% per decade.Both the frequency and magnitude of extreme TC events were consistently found.While the frequency of extreme TC events has increased with an annual trend of 0.2662, all extreme events have increased over time with an annual trend of 2.205.All extreme rainfall events and TC extreme events exhibit a positive trend in frequency, although the frequency and magnitude of all extreme rainfall events have increased more quickly than the frequency and magnitude of TC extreme events in overall Sri Lanka.Furthermore, tropical cyclone-related precipitation has been accounted for agreaterpercentage of the overall

Table 2. Summary of Results from Each Metric Used to Examine Extreme Precipitation

Extreme Precipitation Metric	**Major Findings**
Top 10 wettest days	TCs are responsible for the top 10 wettest days over land and coastal areas in the dry and semiarid regions rather than the wet region of the island. The number of TC days comprising the top 10 wettest days of the year has statistically equal and non-significant declining pattern with a slope of 0.15 days yearly. The TC contribution to the top 10 is higher when it is formed close to Sri Lanka or having a projected path along or when it is formed close to the Eastern coast of Sri Lanka.
Frequency of extreme precipitation days	Maps showing the frequency of extreme events from all events show broad regional patterns, but maps of TC extreme events show storm-track patterns The frequency of extreme TC events has increased rapidly in Colombo, Galle, Katunayake and Rathnapura districts over the period of record Between 18% and 22% of the extreme precipitation events that have occurred from the east through the north to the northwest coast and in the nearby inland areas have been caused by TCs.
Top percentile of precipitation days	The western slopes of the island's central highlands have a stronger tendency in the top 10th percentile of average rainfall for TCs days, and the eastern and southeastern coastal regions also exhibit a notable increase than overall extreme rainfall. The upper 10th percentile value would decrease by 5% – 9% if TC precipitation days were removed.
Trends in percentage contribution of TCs	The contribution of TC precipitation to overall extreme precipitation has been increasing in some areas in the island. The contribution of TC precipitation to overall extreme precipitation increases more rapidly for the western slope of the central hills as the definition of ‘‘extreme’’ becomes stricter.

extreme precipitation that has occurred over the past few decades in the east, north, northwest coast, and adjacent inland areas.Our results are comparable to those of [10].His research has verified, by the use of historical records, the direction of approach and/or impact on the coastline, that 17 out of the 22 cyclones had an effect on the east coast of Sri Lanka, three on the west coast, and one on each of the north and south coasts of the island.

This study's results are based on some assumptions. Our estimations are likely the highest impact that TCs could have to excessive precipitation because our technique takes precipitation into account when a TC turns extratropical and merges with a front.This strategy could be improved by creating an objective method for identifying the source of a station's precipitation.Our research suggests that TC contributions may need to be considered more accurately in extreme precipitation estimates.

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