Projections of extreme precipitation events under climate change scenarios in Mahaweli River Basin of Sri Lanka

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The future changes in rainfall pattern in the Mahaweli River Basin of Sri Lanka using three general circulation models under two representative concentration pathways were assessed. The projections showed that consecutive dry days will decrease, consecutive wet days and annual total precipitation in wet days will increase, the monthly maximum consecutive five-day precipitation will generally decrease, and annual rainfall will increase except for the first inter-monsoon. The projections of the heavy rainfall varied according to the time periods and climate zones. The present results can help policy makers to optimize the use of water resources considering future climate change.

Keywords: Bias correction, climate change, extreme precipitation, GCMs, rainfall, RCPs.

CLIMATE change along with population growth will increase water shortage in many regions of the world in future compared to the past[1]. Precipitation patterns in different parts of Asia are characterized by strong variability with both increasing and decreasing trends observed during different seasons[2]. Another challenge facing society due to climate change is the changes in extreme weather and climatic events which are highly destructive due to its impact on human lives, economy and natural ecosystems despite being rare and mostly short-duration in nature[3]. The Intergovernmental Panel on Climate Change (IPCC) reported that the economic losses from climate-related disasters have increased over years, and the fatality rates and economic loss expressed as a proportion of gross domestic product are higher in developing countries[4]. Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions would become more intense and more frequent by the end of this century[5]. As a result, the quantity of runoff of a river basin can vary rapidly resulting in flood and prolonged drought. Such extreme events would be difficult to predict in advance if the future patterns of rainfall are not well understood. This situation can cause severe hardships in Asia as a large proportion of the population have water-dependent livelihoods and are highly vulnerable due to poverty and poor infrastructure. Therefore, projection of future precipitation patterns under different climate change scenarios is crucial for sustainable water resource management at a basin scale[6].

Sri Lanka has experienced several impacts of climate change including increasing temperature[7] and increasing variability of rainfall, and the country is located in one of the most vulnerable regions of the world[8]. Several studies have dealt with the rainfall patterns in Sri Lanka and a majority of them are based on historical records. Eriyagama *et al.*[9] indicated that the mean annual rainfall over Sri Lanka has been decreasing in the past 57 years at ~7 mm/year. Jayatillake *et al.*[10] noted an overall decrease of 7% in the average annual rainfall from the period 1931–60 to 1961–90. But, there exists a wide disparity in the magnitude of changes during different seasons of rainfall. A trend analysis, which utilized 100 years of rainfall records of 15 meteorological stations, identified a statistically significant increasing trend (3.15 mm/year) at Colombo and decreasing trends at Nuwara Eliya (4.87 mm/year) and Kandy (2.88 mm/year)[11]. In another study, Wickramagamage[12] found a negative trend in the southwest monsoon season throughout the country, and the main cause for these recent changes is reported to be the weakening of the southwest monsoon circulation parameters caused by global warming.

The selection of Mahaweli Basin as the study area was due to its strong connection with the country's economy resulting from its contribution to various economic sectors such as domestic and industrial water supplies, agriculture and hydropower. The diversions from the Mahaweli River benefit five river basins in the dry zone, and the present development plans would add five more dry zone river basins to the list[13]. A good understanding of future seasonal rainfall pattern is important for the sustainability of future development projects, to ensure optimum utilization of rainfall and to avoid flood and mitigate drought.

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There are a few studies on future rainfall patterns in the Mahaweli River Basin carried out with different methodologies instead of prediction using different GCMs. Withanachchi *et al.*[14] reported that the upstream areas of the Mahaweli River Basin experience high fluctuations of precipitation with further declining rainfall. A reduction of 16.6% rainfall in the upper catchment areas of the Mahaweli River Basin is predicted by 2025 (ref. 15). However, most studies dealt with observed changes of rainfall. To the best of our knowledge, General Circulation Models (GCMs)-based studies on future rainfall projections at the basin scale are limited.

The present study attempts to project future rainfall in the Mahaweli River Basin (MRB) of Sri Lanka up to the year 2095 using three selected Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs for two Representative Concentration Pathway (RCP) scenarios of RCP4.5 and RCP8.5. The temporal and spatial variation of rainfall based on projected annual and seasonal values of rainfall in different climatic zones of the basin were described and the patterns in extreme precipitation events in the basin for the future were analysed. The present findings are expected to provide valuable insights for decision makers, water managers and designers to manage basin water efficiently and to be well prepared for mitigation and adaptation strategies to face extreme events. Furthermore, studies on climate change impact on extreme precipitation events could be incorporated into vulnerability and risk (due to climate change) studies in the basin, which influences social, economic and political development of the country in a sustainable manner.

Study area

Sri Lanka with its tropical monsoonal climate and weather pattern is influenced by meteorological conditions in the Bay of Bengal. The rainfall, controlled by monsoonal wind regime, is the only form of precipitation the country receives. It experiences four major rainfall seasons: two monsoon and two inter-monsoon periods. The first inter-monsoon begins in March and lasts till April. The country experiences southwest monsoon from May to September followed by the second inter-monsoon from October to November and the northeast monsoon from December to February[11].

Sri Lanka is divided into three climatic zones based on rainfall: wet zone (WZ), intermediate zone (IZ) and dry zone (DZ). The average annual rainfall in WZ is >2500 mm and that in IZ is between 1750 and 2500 mm, whereas the DZ receives <1750 mm rainfall. The average temperature in the basin varies from 24°C to 28°C (ref. 16). A major portion of the rainfall in DZ is during the northeast monsoon period. There are two seasons of cultivation in reference to the rainfall pattern in the DZ: *Maha* or major season from October to March and *Yala* or minor season from April to September.

This study was conducted in MRB of Sri Lanka. Mahaweli River flows across all three climatic zones and across 7 out of 25 administrative districts of Sri Lanka. It starts in the central mountains at an elevation of 2440 m amsl and flows down to Koddiyar Bay at the East coast of the island. Figure 1 shows the elevaion map of the basin dividing it into three climatic zones.

The annual river flow is about 21% of the surface water resources of the country[17]. The Mahaweli River is the largest river in terms of watershed area, surface water resources and length. In 2011, the production of rice (Binomial name – *Oryza sativa* L.) and other field crops from the Mahaweli benefited areas was 789,231 tonnes and 340,778 tonnes respectively, and a total generation of hydropower was around 1975 GWh annually (about 49% of national hydropower)[18]. Accordingly, MRB is strongly connected with the country's economy because of its contribution to many sectors such as domestic and industrial water supply, agriculture, hydropower and environment. The population of the basin was 3,197,650 in 2012 (ref. 19). Generally, the population is high in the WZ and IZs. Kandy, the second most populous city in the country, is also located in the upper reaches of the basin.

Data and methodology

Observed rainfall data

A total of five rainfall stations from each of the three climatic zones was selected resulting in a total of 15 rainfall stations. The location of the stations, elevation data and the average annual rainfall of each station are presented in Table 1 and Figure 2.

A period of 30 years from 1971 to 2000 was selected as the baseline period for the study. Selecting a 30-year average has been the standard practice in obtaining climate normals for over a century[20]. Daily precipitation data for this period for the selected 15 rainfall stations were collected from the Meteorological Department of Sri Lanka. The Normal Ratio Method, a classical technique of estimating missing rainfall data, was used to fill the missing records in the historical dataset. This method was earlier used in the basin and proved to provide more realistic and acceptable results compared to the Aerial Precipitation Ratio Method[21,22]. According to the Normal Ratio Method, the missing precipitation is represented as

$$P_x = \frac{1}{n}\sum_{i=1}^{i=n}\frac{N_x}{N_i}P_i, \quad (1)$$

where P_x is missing precipitation record at the interpolation station x, P_i the precipitation for the same period for the same storm at the ith station of a group of nearby stations, N_x the normal annual precipitation (mean of 30 years of annual precipitation data) value for the x station

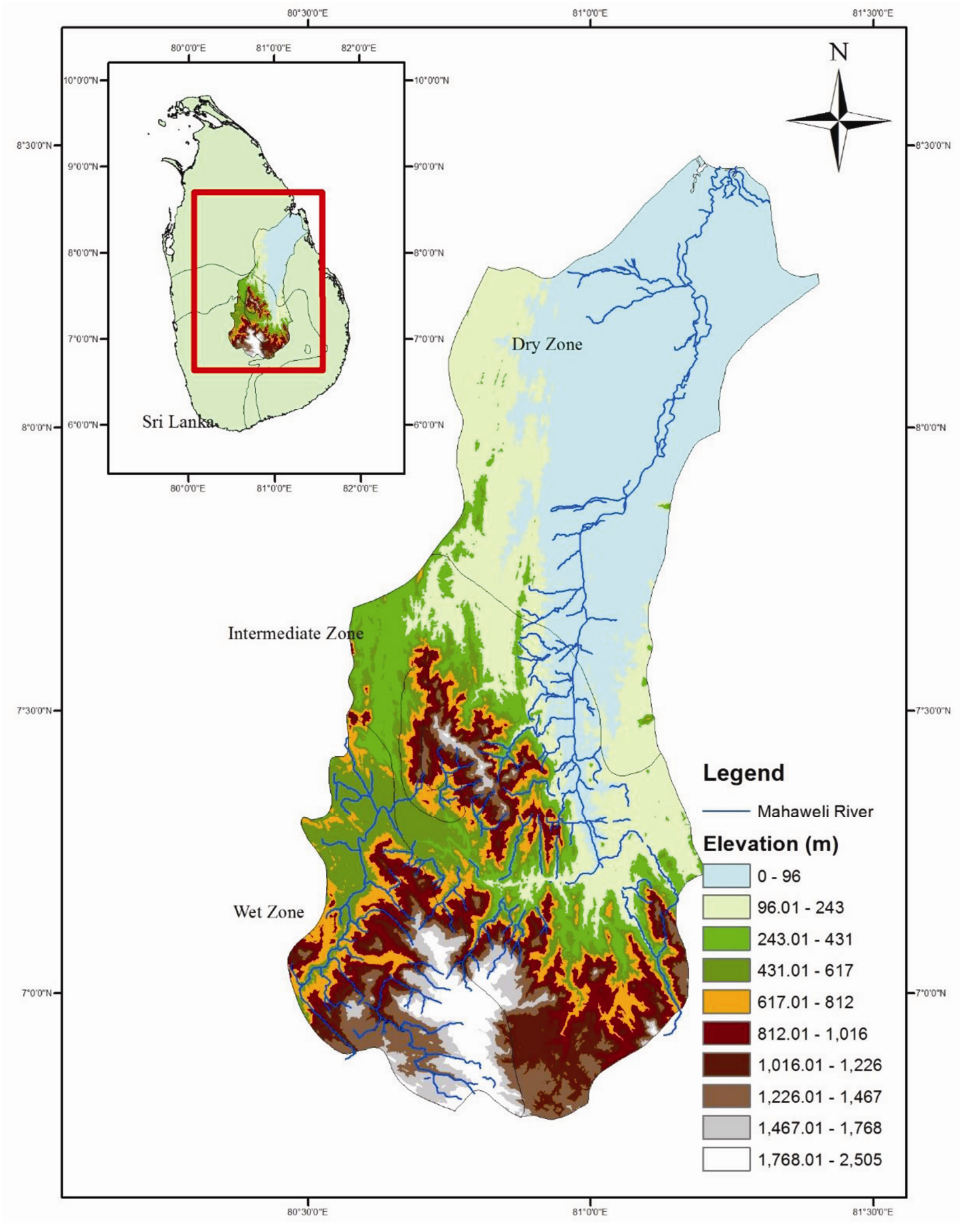

Figure 1. Location of the Mahaweli River Basin in Sri Lanka and its altitudinal variation range.

and N_i is the normal annual precipitation value for the ith station.

Future rainfall data

Data for the historical run (1971–2000) and future rainfall data (2006–2095) under two selected RCP scenarios were downloaded for three GCMs for each station. The most appropriate GCM for a given climate scenario construction was selected following the criteria outlined by Smith and Hulme[23] who suggested that vintage, resolution, validity and representativeness of the results should be considered while selecting a suitable GCM for a particular study. The following three GCMs were selected for this study (Table 2).

RCP2.6 is a 'peak-and-decline' scenario; its radiative forcing level first reaches a value ~3.1 W/m^2 by mid-century and returns to 2.6 W/m^2 by 2100. In order to reach such radiative forcing levels, greenhouse gas (GHG) emissions are reduced substantially over time[24]. RCP4.5 is a mitigation scenario, the transformations in the energy system, land use, and the global economy required to achieve this target are not possible without explicit action to mitigate GHG emissions[25]. RCP6.0 is a stabilization scenario in which the total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for

Table 1. Selected rainfall stations in the Mahaweli River Basin, Sri Lanka

Climatic zone	ID	Rainfall station	Location: Latitude (°)	Location: Longitude (°)	Elevation (m)	Average annual rainfall (mm)
Wet zone	01	Katugastota	7.3	80.6	445	1850
	02	Galaha (new forest)	7.1	80.7	1182	2519
	03	Nawalapitiya	7.1	80.5	715	3032
	04	Seetha Eliya	6.9	80.8	1801	1970
	05	Bopaththalawa	6.8	80.7	1700	2112
Intermediate zone	06	Dyrabba	6.9	80.9	1658	1658
	07	Kobonella	7.3	80.8	920	3230
	08	Woodside Estate	7.6	80.8	1093	1979
	09	Narangalla	7.1	81.0	380	2545
	10	Nalanda	7.7	80.6	364	1550
Dry zone	11	Trincomalee	8.6	81.2	3	1644
	12	Polonnaruwa	7.9	81.0	70	1665
	13	Bakamuna	7.8	80.8	192	1680
	14	Hingurakgoda	8.0	80.9	73	1504
	15	Kantale	8.4	81.0	76	1599

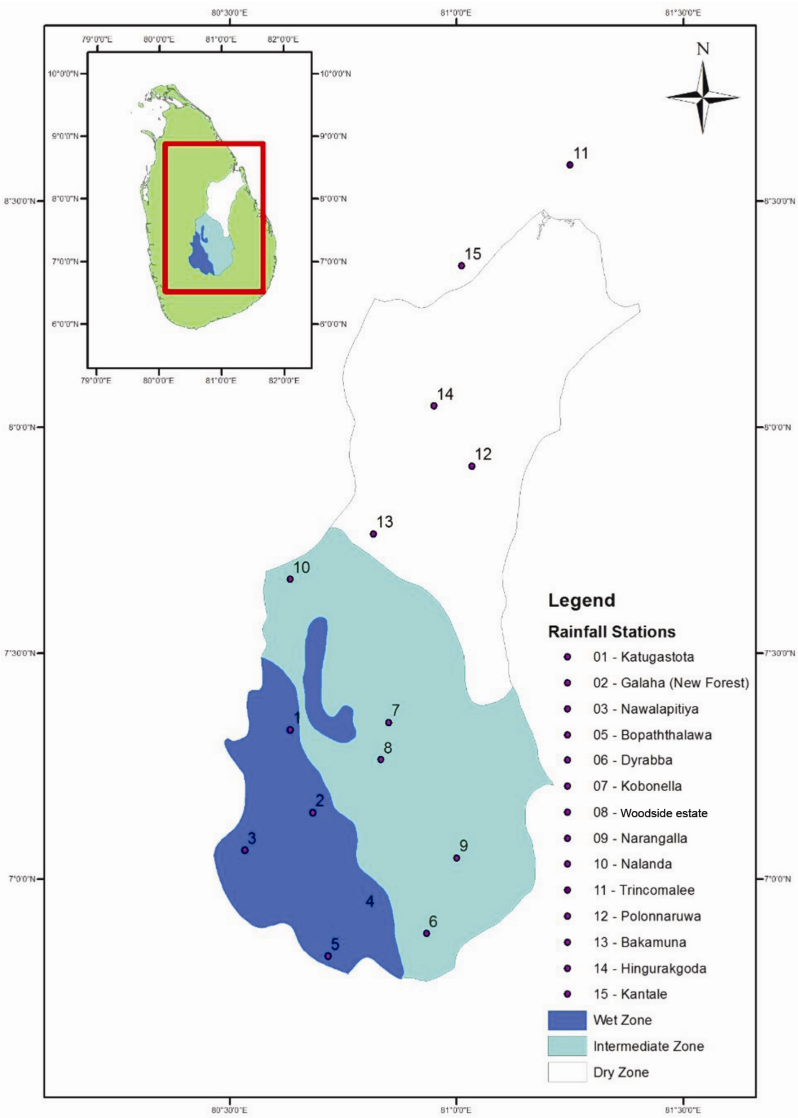

Figure 2. Distribution of rainfall stations in Mahaweli River Basin, Sri Lanka.

Table 2. General circulation models (GCMs) used in the present study

			Atmosphere		Ocean	
Model	Research institute	Vintage	Resolution	Number of vertical levels	Resolution	Number of vertical levels
BCC-CSM1.1	Beijing Climate Center, China Meteorological Administration	2011	2.8125° × 2.8125°	26	1°	40
MIROC5	University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	2010	1.40625° × 1.40625°	40	1°	50
CCSM4	US National Centre for Atmospheric Research	2010	0.9° × 1.25°	27	1.4°	60

Source: Flato *et al.*[33].

reducing greenhouse gas emissions[26,27]. RCP8.5 is a socio-economic development pathway characterized by slow rates of economic development with limited convergence across regions, a rapidly rising population to comparatively high levels and relatively slow pace of technological change[28].

For this study RCP4.5 and RCP8.5 were selected. Sri Lanka being a developing country, RCP2.6 can be considered to have lesser relevance. As it is always better to be aware of the worst-case scenario RCP8.5 was selected; therefore, the combination of RCP4.5 (a stabilization and a mitigation scenario) and RCP8.5 was selected. Daily historical precipitation data and future precipitation data for both RCP4.5 and RCP8.5 were downloaded in a netCDF format and extracted using ArcGIS.

Bias correction

There are several methods available for bias correction, ranging from simple linear scale approaches to sophisticated distribution mapping approaches. Some evaluations found that quantile mapping is one of the best-performing methods[29,30]. Because quantile mapping offers a good combination of accuracy and robustness, this method was used in this study. In this method, the distribution function of simulated data is shifted using a transfer function to match with that of the observed data. *R* software can perform quantile mapping bias correction on the raw data simulated from GCMs by writing a simple program using *R* language. *R* studio is equipped with a qmap package for this purpose and the 'fitQmap' and 'doQmap' functions were utilized. The 'fitQmap' function identifies the parameters of different quantile mapping methods, whereas the 'doQmap' function performs quantile mapping using parameters identified earlier[31]. The Bernoulli–Gamma distribution was used to represent the rainfall distribution. Here the probability distribution function is defined as

$$g(x) = \begin{cases} \pi * \gamma(x), & x > 0 \\ 1-\pi, & x \le 0 \end{cases}, \tag{2}$$

where $\gamma(x)$ is the probability density function of the gamma distribution, π the probability of non-zero event.

The cumulative distribution function (CDF) used in Bernoulli–Gamma distribution is

$$G(x) = \begin{cases} 1-\pi+\pi * \tau(x), & x > 0 \\ 1-\pi, & x \le 0, \end{cases} \tag{3}$$

Here $\tau(x)$ is the CDF of the gamma distribution. The inverse CDF or quantile function is defined as given below for this type of distribution

$$G^{-1}(p) = \begin{cases} \Gamma^{-1}\left(\dfrac{p-1+\pi}{\pi}\right) & \text{if } \pi > 1-p \\ 0 & \text{if } p \le 1-p. \end{cases} \tag{4}$$

where Γ^{-1} (p) is the inverse CDF of the gamma distribution and p is the probability[31].

Model calibration and validation

Statistical analysis was conducted to justify the use of the selected three GCMs for projection of future rainfall for the study area. For this purpose, statistical parameters such as coefficient of determination (R^2) and root mean square error (RMSE) were calculated for monthly rainfall distribution of both raw GCM data and data after bias correction against the observed data. R^2 and RMSE were calculated using the following equations, where higher R^2 and lower RMSE indicate better correlation.

$$\text{Coefficient of determination, } R^2 = \left(\frac{\text{cov}\,XY}{S_x S_y}\right)^2, \quad (5)$$

where

$$\text{cov}\,XY = \frac{\sum_{i=1}^{n}((X_i - \bar{X})(Y_i - \bar{Y}))}{(n-1)},$$

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}},$$

$$S_y = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}{n-1}},$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}, \quad (6)$$

where x is the observed data and y is the raw GCM data or bias corrected GCM data. Spatial averaging of the projected rainfall values for each climate zone of the basin was conducted using Thiessen Polygon method in ArcGIS. The projections and the observed data of all the stations in the respective climatic zones were averaged over the particular climatic zone by giving it a weighted value.

Indices of precipitation extremes

There are a number of indices of precipitation extremes which can be used to represent the observed and future data in a more meaningful and useful manner by analysis and comparison of time series, means, extremes and trends. Therefore, five indices were selected to represent a variety of important rainfall characteristics (Table 3).

The RClimDex software[32] was used to calculate the above mentioned precipitation indices at each station for the baseline, and 2020s (2006–2035), 2050s (2036–2065) and 2080s (2066–2095) under the two RCPs (ensemble mean of the three GCMs was used for the future rainfall).

Results and discussion

Performance evaluation of bias correction

Precipitation data were observed to have high variability with respect to both space and time. In most of the stations, the R^2 values increased after bias correction. According to the radar diagrams (Figure 3), the improvement in the correlation was less in WZ compared to DZ and IZ. The correlation of raw GCM simulations with the observed data was very low. Therefore, a high correlation ($r > 0.6$) cannot be expected for results after bias correction. This could be due to the poor quality of observed data. RMSE decreased in many stations after bias correction. The reduction of RMSE in MIROC5 GCM was less compared to the other two GCMs. Among the three GCMs, BCC-CSM1.1 performed better followed by CCSM4 and MIROC5. Statistical analysis was carried out to justify the use of the three selected GCMs for projection of the future rainfall of the study area. The overall results of the statistical analysis suggested that bias correction helped improve the correlation of GCM data to the observed data.

The three selected GCMs were observed to project an increase in rainfall compared to the baseline period in all the three future periods under both RCPs. Therefore, the ensemble mean of the three GCMs was used for the rest of the analysis.

Annual rainfall projections

The mean annual rainfall of the three climatic zones in MRB for the baseline and the three future periods under the two RCP scenarios is presented in Table 4. The IZ is observed to receive the highest rainfall for the three future periods. In general, a continuous increase in average annual rainfall is projected.

The change of future annual rainfall scenarios compared to baseline was analysed and the results are shown in Figure 4. In the 2020s, both scenarios project an increase in annual rainfall for the entire basin, except in a small portion of WZ, which will experience <0.6% decrease under RCP4.5. In 2020s, the DZ is observed to experience the highest positive anomaly (18–20%) and the least in WZ (4–8%). In the 2050s, the entire basin is projected to experience an increase in annual rainfall. Compared to 2020s, there is a further increase under RCP4.5, whereas a decreased positive anomaly is projected under RCP8.5. In 2080s, the greatest percentage increase is projected for the entire basin under both scenarios. This is about 36–37% in DZ, 25–28% in IZ and 18–22% in WZ. Therefore, RCP4.5 projects a continuously increasing rainfall from the near-future to the far-future and the positive anomaly is highest in DZ and lowest in WZ. Both scenarios project the highest positive anomaly in the far-future.

Seasonal rainfall projections

The baseline and projected future mean seasonal rainfall for the basin under the two RCP scenarios are provided in Table 5. Variation of future changes in seasonal rainfall across space in the basin compared to the baseline was also analysed under the two scenarios (Figure 5).

It is evident from Figure 5 and Table 5 that the mean seasonal rainfall is decreasing in the first inter-monsoon compared to the baseline for the basin in all time periods

Table 3. Precipitation indices used in the present study as recommended by the Expert Team on Climate Change Detection and Indices (ETCCDI)

Indicators	Notation	Unit	Definition
Consecutive dry days	CDD	Days	Maximum number of consecutive days with daily precipitation <1 mm
Consecutive wet days	CWD	Days	Maximum number of consecutive days with daily precipitation ≥1 mm
Annual total wet-day precipitation	PRCPTOT	Mm	Annual total precipitation in wet days (daily precipitation ≥1 mm)
Monthly maximum consecutive 5-day precipitation	Rx5day	Mm	Most intense rainfall event in 5 consecutive days for a given month
Medium-heavy rainfall days	R20mm	days	Annual count of days for precipitation >20 mm

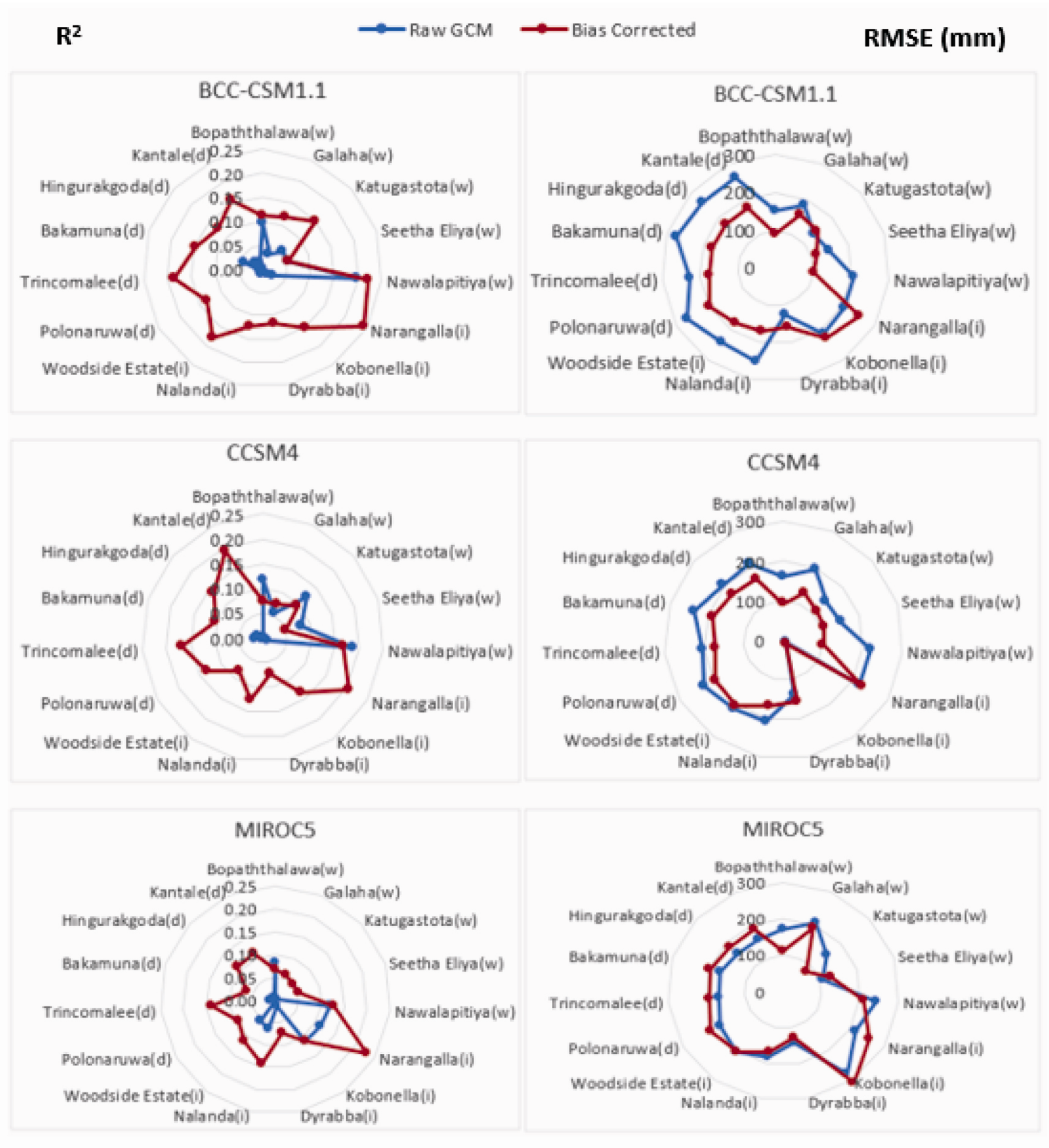

Figure 3. Comparison of coefficient of determination (R^2) and root mean square error (RMSE) before and after bias correction of the three GCMs (BCC-CSM1.1, CCSM4 and MIROC5).

Table 4. Mean annual rainfall (mm) of three climatic zones in Mahaweli River Basin for baseline and the three future periods under the two RCP scenarios

		RCP4.5			RCP8.5		
Climatic zone	Baseline	2020s	2050s	2080s	2020s	2050s	2080s
Wet zone	2332	2398	2515	2753	2579	2595	2849
Intermediate zone	2392	2661	2749	3026	2759	2707	3034
Dry zone	1511	1826	1853	2078	1800	1633	2077

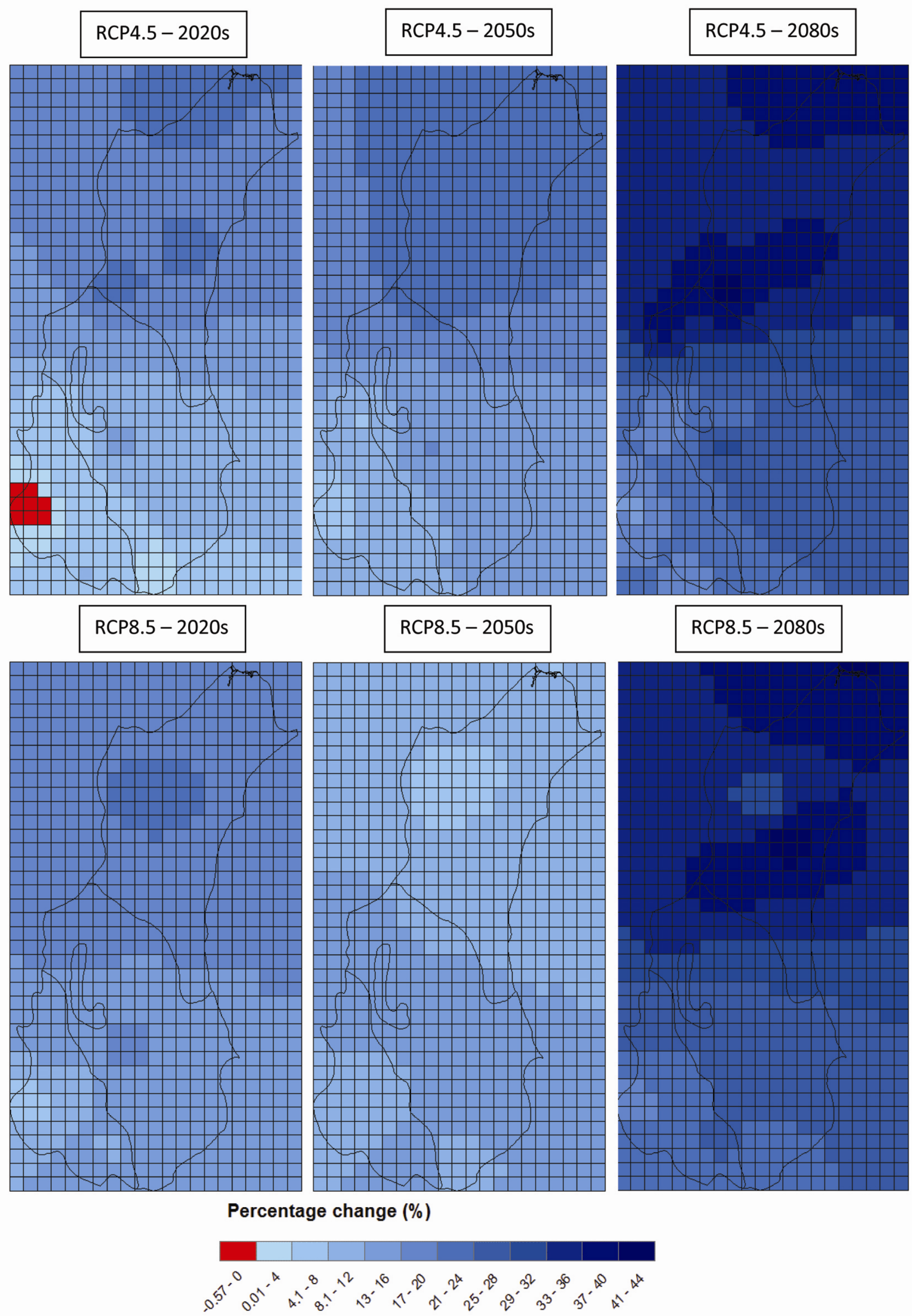

Figure 4. Percentage of change in the mean annual rainfall compared to the baseline (1971–2000) in 2020s, 2050s and 2080s under the RCP4.5 and RCP8.5 scenarios.

Table 5. Mean seasonal rainfall (mm) of the three climatic zones in MRB, Sri Lanka for the baseline and the three future periods under the two RCP scenarios

			RCP4.5			RCP8.5		
Climatic zone	Season	Baseline	2020s	2050s	2080s	2020s	2050s	2080s
Wet zone	First inter-monsoon	298	219	255	275	218	212	229
	Southwest monsoon	1059	1005	1072	1151	1052	1207	1206
	Second inter-monsoon	606	637	685	756	670	728	858
	Northeast monsoon	378	552	497	578	508	449	560
Intermediate zone	First inter-monsoon	328	220	278	285	237	224	246
	Southwest monsoon	535	557	628	668	649	724	719
	Second inter-monsoon	679	741	784	836	787	819	931
	Northeast monsoon	855	1142	1059	1237	1085	940	1137
Dry zone	First inter-monsoon	150	122	150	162	116	97	147
	Southwest monsoon	281	269	365	445	331	390	480
	Second inter-monsoon	492	535	571	606	523	546	683
	Northeast monsoon	597	900	767	865	830	600	767

under both scenarios, except in 2080s in DZ where there is about 10% increase under RCP4.5. Although there is a decrease in the first inter-monsoon rainfall, the maximum expected difference is about 100 mm. The change in percentage (negative anomaly) is observed to be highest in 2020s, which can be high as –20 to –40% in WZ and IZ and lowest in 2080s (about –10% change in WZ and IZ or even up to 10% increase in DZ) under RCP4.5. Therefore, it is clear that the negative anomaly will be more severe in WZ and IZ under the RCP4.5 scenario. But under RCP8.5, the negative anomaly is highest in 2050s (in the range of –30 to –40%) in DZ and a large part of IZ. The lowest negative anomaly is projected in DZ (about 10%) in 2080s under this scenario.

The southwest monsoon is projected to increase compared to the baseline period, except in 2020s under RCP4.5 where it decreases by about 10% for a large area of the basin (Figure 5). Positive anomaly is generally observed to be increasing continuously from the near-future to the far-future under both scenarios for the entire basin. The WZ in general will have a low increase in rainfall (1–20%) compared to IZ and DZ during the southwest monsoon period. In 2080s, DZ is projected to receive 50–60% more rainfall under RCP4.5 and 60–90% under RCP8.5.

It can be seen that there is no significant variation in percentage increase of the second inter-monsoon rainfall across space (Figure 5). Up to 10%, 10–20%, 20–30% increase respectively, is observed in the 2020s, 2050s and 2080s under RCP4.5. In general, RCP8.5 has projected a greater increase compared to RCP4.5. Overall, the second inter-monsoon rainfall in the future will continuously increase compared to the baseline period from the near-future to the far-future for the entire basin in general as projected by both the RCP scenarios.

The entire basin is subjected to an increase in the northeast monsoon rainfall in future compared to baseline period (Figure 5). The positive anomaly will be lowest in 2050s under both RCPs (maximum of 30–40% increase in WZ under RCP4.5), while it is comparatively higher in 2020s and 2080s for the entire basin (as high as 80–90% in WZ in 2080s under RCP4.5). The results show that there will be a substantial increase in the northeast monsoon rainfall in the DZ (between 230 and 300 mm) in the near-future. The northeast monsoon rainfall will also increase in WZ and IZ, which will flow down to DZ.

In summary, the monsoonal rainfall is projected to increase until 2080s in the southwest monsoon, second inter-monsoon and northeast monsoon, under both RCPs, but will decrease in the first inter-monsoon.

Change of precipitation extremes

The output from RClimdex software was used to prepare box and whisker plots to observe the inter-annual variability of each precipitation index.

Consecutive dry days: The DZ with 61 consecutive dry days (CDD) in the baseline period will experience a 40–60% decrease in CDD under both RCPs (Figure 6). CDD will continue to remain higher in DZ compared to other zones in the future under both RCPs. In all climate zones and under both RCPs, future CDD is projected to be lower than that of the baseline.

The basin experienced a high variability in CDD in the baseline period, and the highest variability of 91 CDD is evident in DZ under both RCPs. The variability is predicted to be reduced by 40–80% under both scenarios together with the number of CDD in the future periods. However, the variability in DZ will remain higher than that in the WZ and IZ.

Consecutive wet days: The WZ has experienced a 5% higher consecutive wet days (CWD) compared to

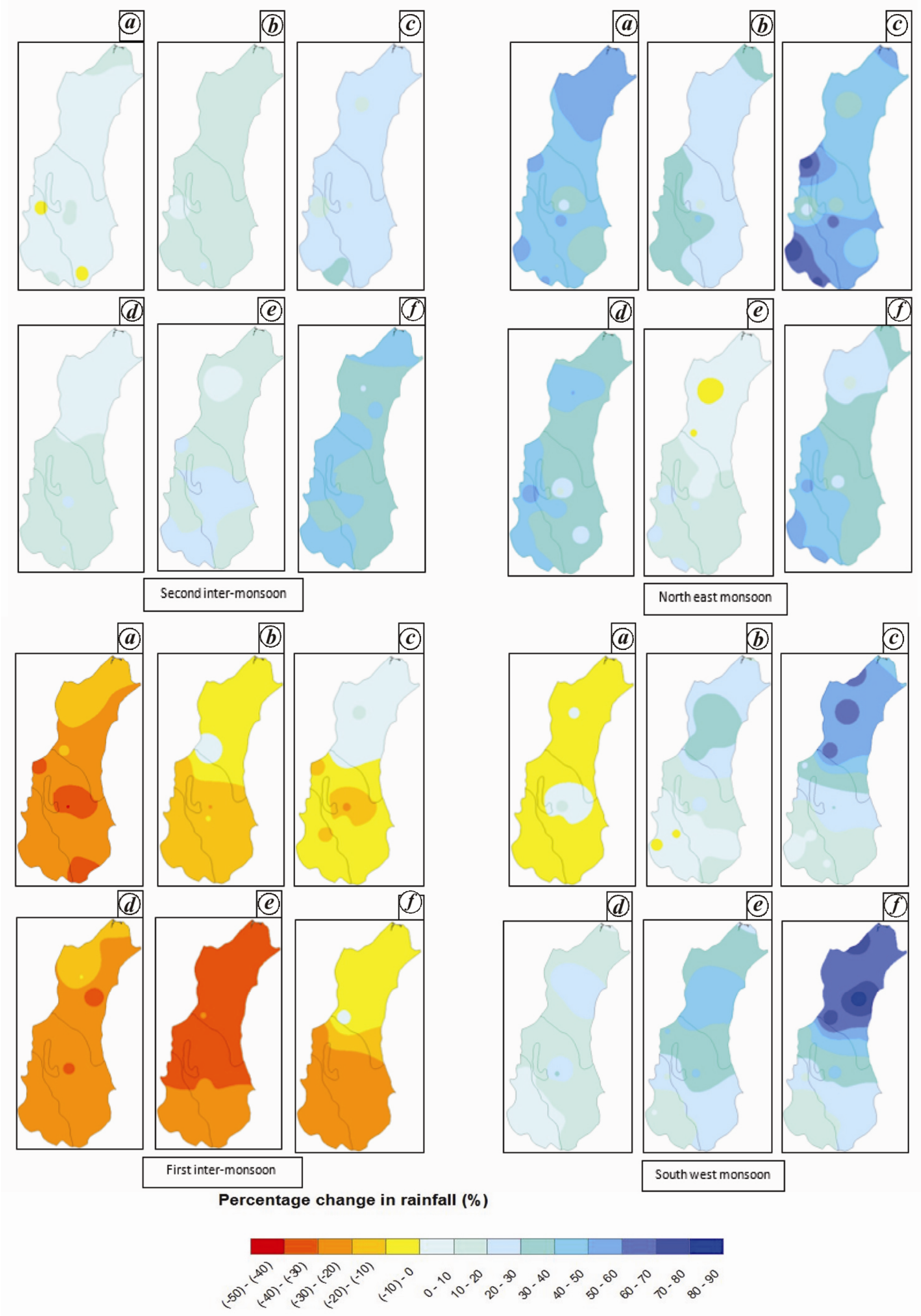

Figure 5. Percentage change in the mean first inter-monsoon, southwest monsoon, second inter-monsoon and northeast monsoon rainfall in MRB, Sri Lanka, compared to the respective baseline (1970–2000) values. ***a***, RCP4.5-2020s; ***b***, RCP4.5-2050s; ***c***, RCP4.5-2080s; ***d***, RCP8.5-2020s; ***e***, RCP8.5-2050s; ***f***, RCP8.5- 2080s.

IZ during the baseline period (Figure 7). The IZ is observed to have the highest CWD in future under both RCPs, except in 2050s under RCP8.5 when WZ has a higher value of 92 CWD. The DZ of the basin is observed to have the lowest CWD in the baseline and in the future periods under both the RCPs.

In the baseline period, the CWD shows a high variability in WZ (41 CWD) compared to the rest of the basin (Figure 7). The variability of CWD is increased by 240–270% for the future throughout the whole basin. Under RCP4.5, CWD is projected to increase from 2020s to 2080s in a continuous manner, but no such pattern can be observed under RCP8.5.

Total wet day precipitation: For all the three climatic zones, a wetter climate is expected with a 15–35%

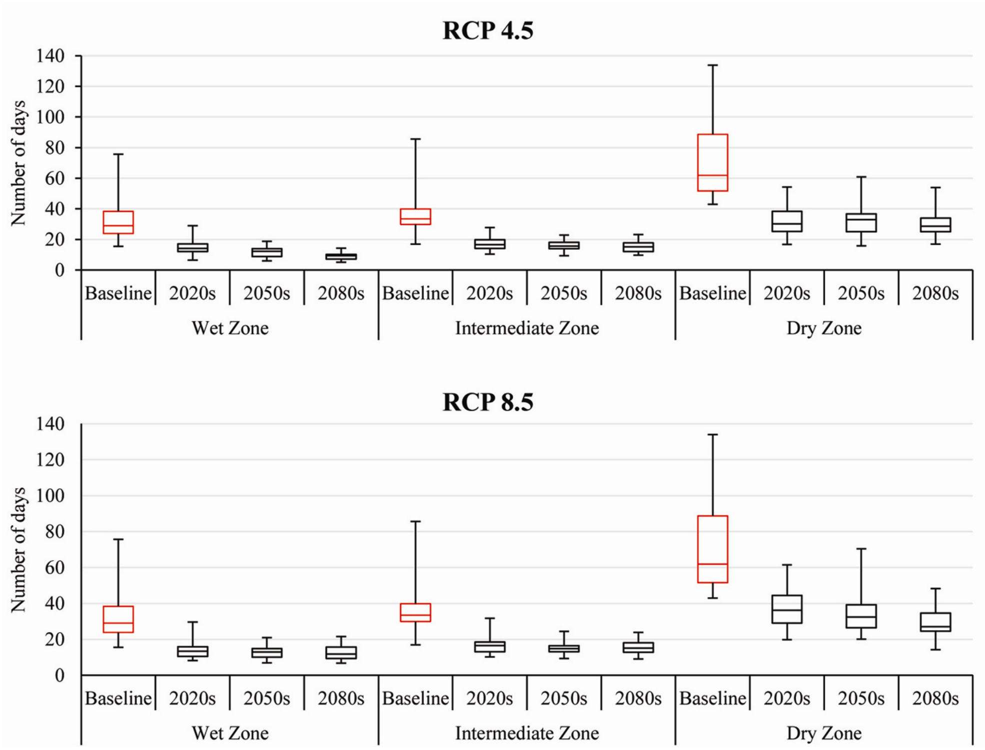

Figure 6. Inter-annual variability of CDD in MRB, Sri Lanka, in the baseline and future periods (whiskers – maximum and minimum, box ends – 25th and 75th percentiles and solid middle bar – median).

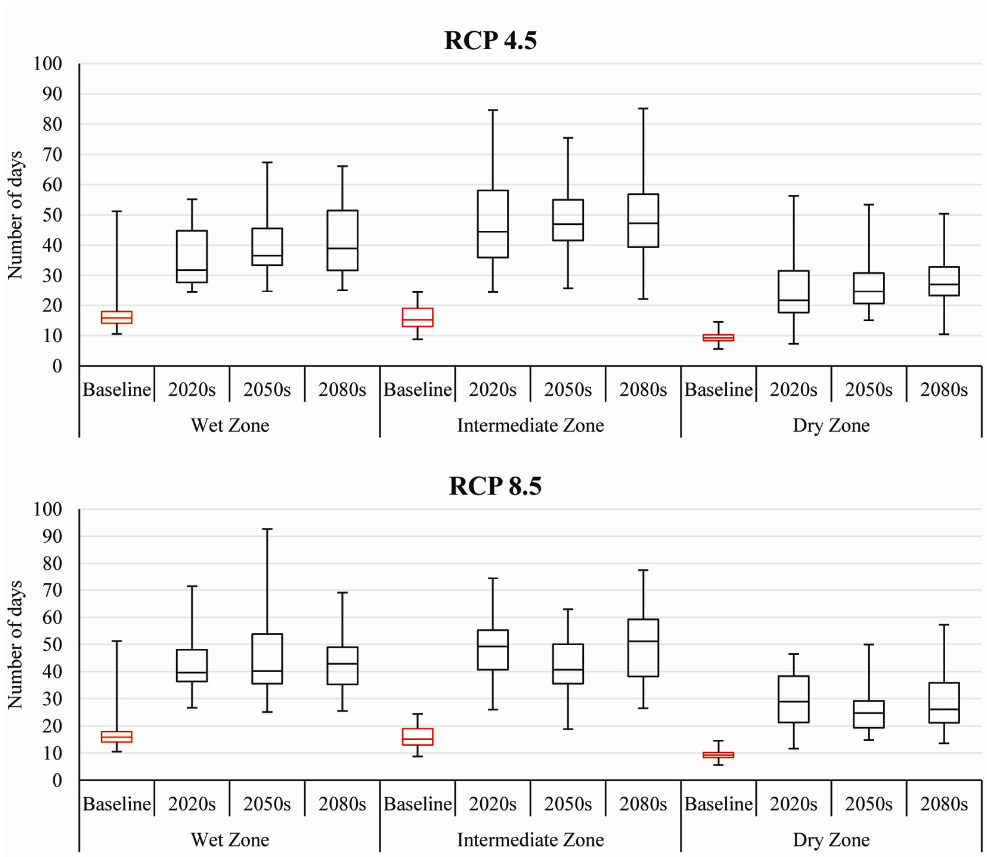

Figure 7. Inter-annual variability of CWD in MRB, Sri Lanka in the baseline and future periods (whiskers – maximum and minimum, box ends – 25th and 75th percentiles and solid middle bar – median).

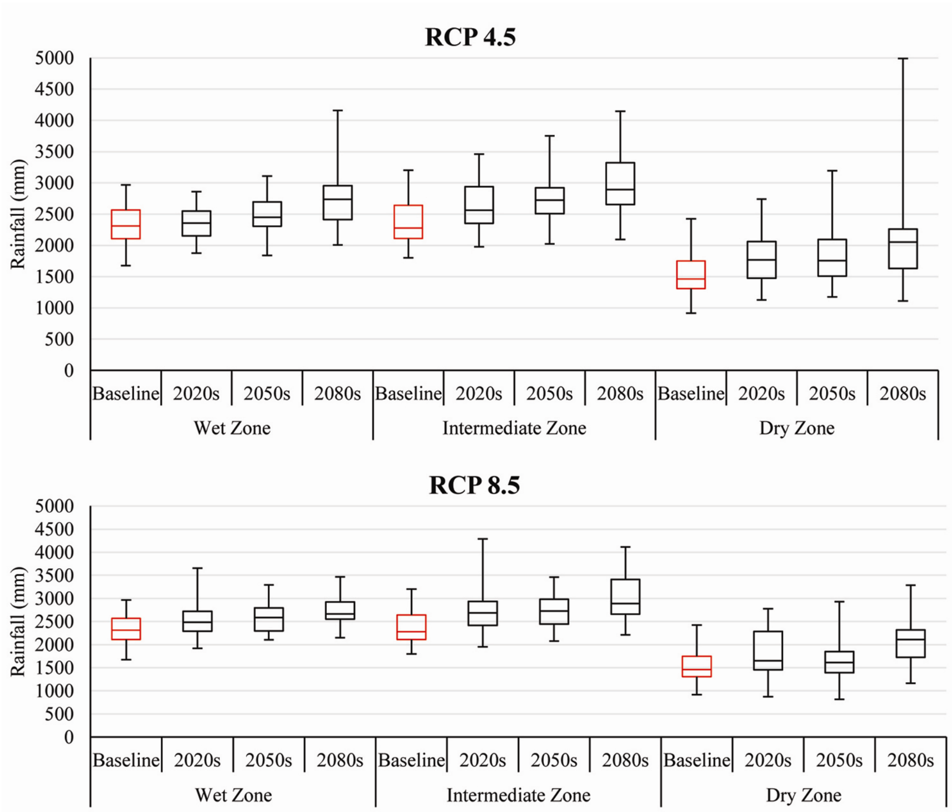

Figure 8. Inter-annual variability of total wet day precipitation (PRCPTOT) in MRB, Sri Lanka, in the baseline and future periods (whiskers – maximum and minimum, box ends – 25th and 75th percentiles and solid middle bar – median).

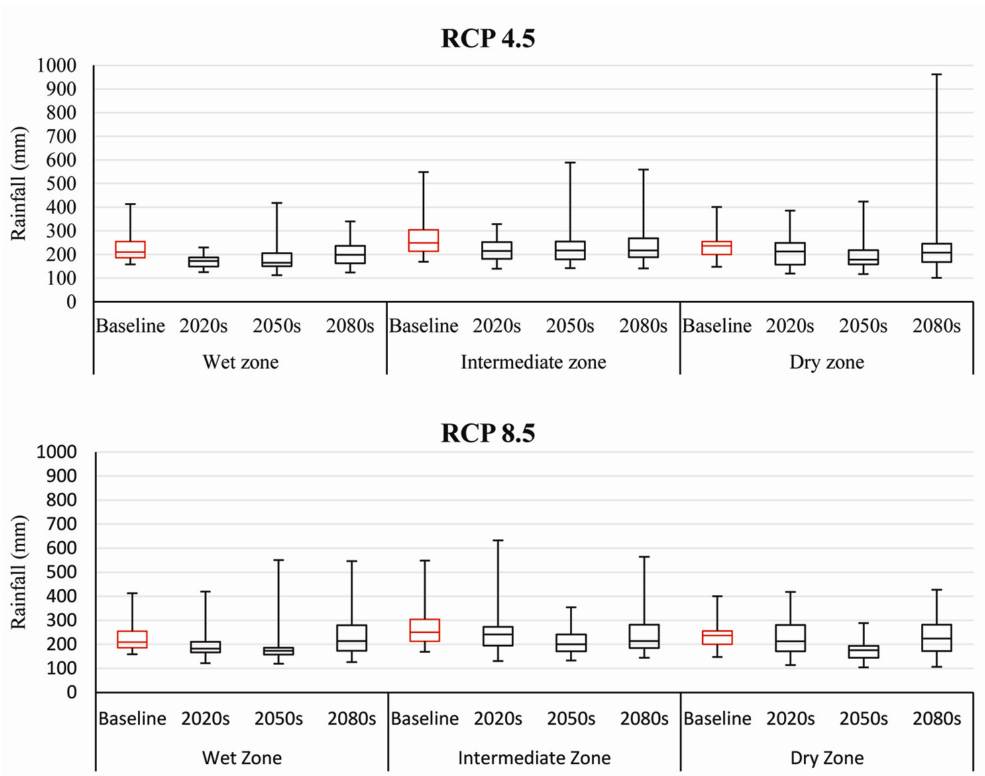

Figure 9. Inter-annual variability of consecutive five-day precipitation (R*x*5day) in MRB, Sri Lanka, in the baseline and future periods (whiskers – maximum and minimum, box ends – 25th and 75th percentiles and solid middle bar – median).

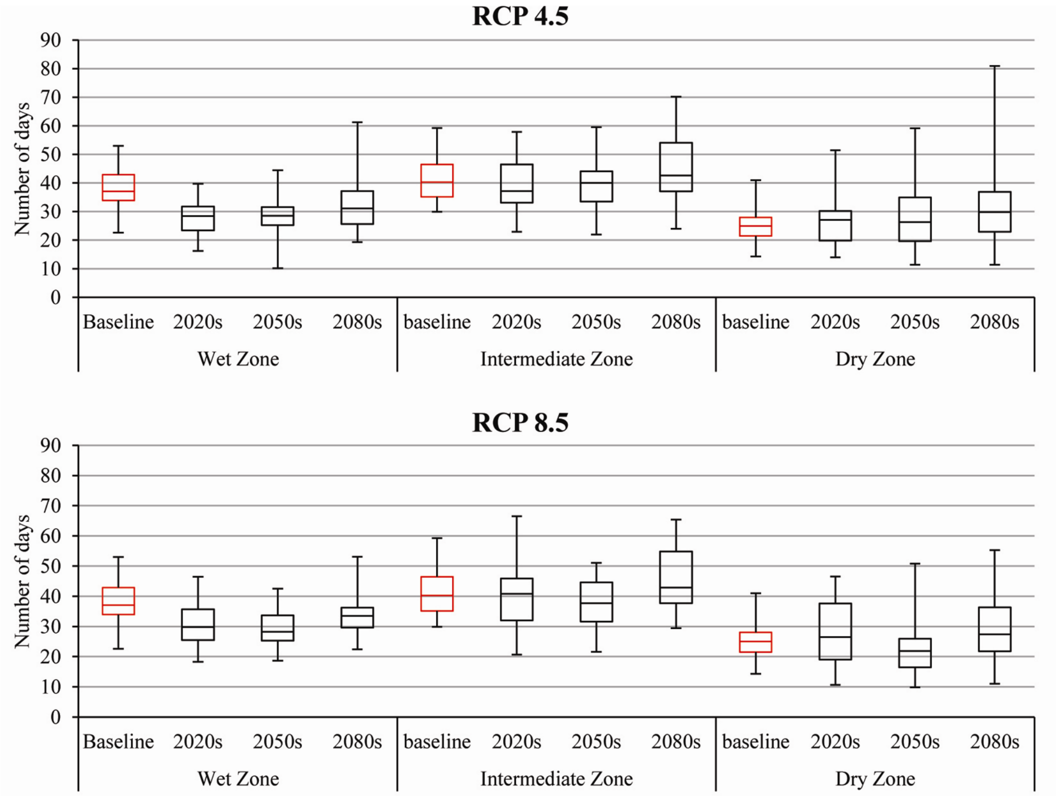

Figure 10. Inter-annual variability of annual count of days when precipitation >20 mm (R20mm) in MRB, Sri Lanka, in the baseline and future periods (whiskers – maximum and minimum, box ends – 25th and 75th percentiles and solid middle bar – median).

increase in rainy days in all the future periods under both scenarios. Total wet day precipitation (PRCPTOT) is high in WZ and IZ; the highest being in IZ and lowest in DZ for the baseline period and all the future periods under both scenarios (Figure 8). The highest PRCPTOT of 4988 mm is observed in DZ in the 2080s.

The variability is observed to be high in 2080s compared to other time periods, while it is the highest with 3878 mm in DZ. The variability of PRCPTOT during the baseline, 2020s and 2050s is generally similar in magnitude.

Consecutive five-day precipitation (Rx5day): For the entire basin the mean intensity of the maximum five day rainfall is observed to be lower than the baseline period in all time periods under both the RCPs (Figure 9). Under RCP4.5, for WZ and IZ, it is least in 2020s and increases by 5–10% till the end of the century, but is still lower than that of the baseline. The IZ and WZ have received the highest (548 mm) and the lowest (147 mm) R*x*5day respectively, during the baseline period, and in addition will be receiving the highest and the lowest R*x*5day respectively, in all future periods under both RCPs. It is observed that DZ will receive the highest Rx5day of 961 mm under the RCP4.5 scenario.

Under RCP4.5, the variability in R*x*5day is observed to be lowest in 2020s for the entire basin. The variability is observed to be continuously increasing in DZ and in 2080s where it has increased up to 860 mm, which is 240% increase compared to the baseline. In WZ and IZ, the variability increases in the 2050s, but slightly reduces in 2080s under RCP4.5. Under RCP8.5, the variability increases in the future, in WZ. In IZ, the variability increases in 2020s, reduces in 2050s and increases again in 2080s. The trends are similar in DZ compared with the baseline period.

Annual count of days when precipitation >20 mm (R20mm): IZ is observed to have experienced the highest extreme rainfall events (>20 mm), while DZ has experienced the lowest in the baseline period. This pattern is projected to remain the same in the future under both RCPs (Figure 10). Under both scenarios, the R20mm will decrease by 10–20% in WZ, and in IZ it will decrease in 2020s and 2050s by 5–10%, but will increase in 2080s by 3% compared to the baseline period. Under RCP4.5, R20mm in DZ continuously increases up to 30 days until 2080s, while it increases in 2020s and 2080s but decreases in 2050s under RCP8.5.

The variability will continuously increase from the baseline to 2080s in IZ and DZ of the basin under

RCP4.5 scenario. The variability is highest (69.5 days) in DZ in 2080s under RCP4.5. Similar pattern can be observed for DZ under RCP8.5, but no significant pattern can be observed in other cases.

Finally, it is important to consider the following. IZ is a narrow strip of land which lies between DZ and WZ of the island. When historical records are analysed, it can be seen that a considerable degree of rainfall pattern fluctuations took place in this region. Furthermore, changes to the rainfall isohyets predicted for the future can alter the current climatic zonal boundaries, i.e. parts of IZ could be lying in DZ or in WZ. As such, the land area currently demarcated as IZ (based on climate records of 1960–1990) can experience contrasting rainfall pattern changes during different time periods.

Conclusions

This study analysed the future rainfall patterns in the three climatic zones of the Mahaweli River Basin using three GCMs under the RCP4.5 and RCP8.5 scenarios. The annual rainfall is projected to be increased compared to the baseline in MRB and the highest and the lowest positive anomalies (percentage increase) are found in DZ and WZ areas of the basin respectively. The trend is generally continuous. Even though WZ should receive the highest rainfall by definition, results reveal that IZ sometimes will receive rainfall exceeding that of WZ in the future. This suggests the need to conduct more detailed studies covering the entire island to adjust the current demarcations of zones (which is based on 1960–1990 period).

The first inter-monsoon rainfall, which contributes the least to annual rainfall in the basin, is projected to decrease in the future period. The negative anomaly will be least in DZ of the basin. In general, an increase is projected for the southwest monsoon rainfall for the entire basin and the increase will be predominant in DZ. Both the second inter-monsoon and the northeast monsoon rainfall are projected to have been increased in the basin.

The DZ of the basin will experience the highest CDD in the future and for the entire basin the CDD is projected to decrease in the future compared to the baseline period. The variability of CDD is also projected to decrease. An increase in CWD is projected throughout the basin in the future period accompanied by an increase in variability. PRCPTOT is projected to increase with an increase in variability in the far-future. Both CWD and PRCPTOT will continue to be lowest in DZ compared to the rest of the basin. R*x*5day is projected to decrease in future for the entire basin, except in 2080s in DZ where it increases above the baseline value. Variability is observed to be lowest in the near future. R20mm will decrease in WZ, but will increase in DZ along with a general increase in variability. A clear trend cannot be observed for IZ.

In comparison, the likelihood of drought is less because the negative anomaly is small. In addition, CDD and CWD projections are also not in favour of drought. However, flood can be expected due to projected positive anomaly in the southwest monsoon, second inter-monsoon and southeast monsoon rainfall as well as an increase in CWD. The general decrease in R*x*5day is favourable for the basin since it reduces the possibilities for flash floods. Increasing variability in any of the indices analysed will pose a few problems to plan and manage water resources and sharing among various users.

The planned diversion projects of the basin discussed earlier would be sustainable in future due to the projected increase in water availability in the southwest monsoon, second inter-monsoon and northeast monsoon periods. The stream flow and in-basin storage during the first inter-monsoon would be mainly utilized for in-basin water needs and environmental flows due to the projected decrease in rainfall during this season. Results of the projected extreme rainfall events will assist in disaster preparedness planning in the basin. Likewise, the results of this study could be utilized by basin managers for sustainable planning of water resources and management. In addition, the results would provide information for the policy makers to optimize the use of water resources taking future climate change into account for crop production, hydropower generation and structural development that has long life.

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