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Comparative assessment on climate prediction from CMIP5 and CMIP6 models over Hulu Terengganu, Malaysia

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Comparative assessment on climate prediction from CMIP5 and CMIP6 models over Hulu Terengganu, Malaysia

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Abstract. The uncertainties of climate change in the future year cause the contribution factors and greenhouse gasses (GHGs) effects on the local climates need to be revised. The development of new climate scenarios in the 6th Coupled Model Intercomparison Project (CMIP6) is consistent with the technological exploration and increment of GHGs dispersion compared to the consideration factors in CMIP5. The purpose of this study was to compare the performance of CMIP5 (based on Representative Concentration Pathways, RCPs) and CMIP6 (based on Shared Socioeconomic Pathways, SSPs) in simulating seasonal rainfall and estimating trends in Hulu Terengganu, Malaysia. The linear scaling (LS) method was used in this study to treat the gaps between observed and simulated results, and the climate trend was examined using the Mann-Kendall (MK) and Sen's Slope tests. The results show that the SSPs scenario outperforms the RCPs in simulating historical rainfall (2015-2020) by producing a higher r value and a smaller percentage difference. According to the MK test, there was no significant trend in projected rainfall across all scenarios (2020-2099). Based on Sen's Slope test, RCP 4.5 and RCP 8.5 show an increasing trend for all rainfall stations. However, all SSP scenarios show a declining trend in projected rainfall, with SSP1-2.6 producing the largest declining trend magnitude. In contrast, when compared to observed rainfall from the baseline period (1988-2017), the SSPs scenario indicates the potential for a greater increase in future annual rainfall projections than the RCPs scenario. All SSP scenarios show an increasing annual rainfall magnitude in 2040-2069 (Δ2050). However, the annual rainfall for SSP2-4.5 and SSP5-8.5 began to decrease in 2070-2099 (Δ2080). Meanwhile, RCP 2.6 has the greatest reduction in annual rainfall projections for both projected time periods when compared to other scenarios. It can be concluded that although all SSPs scenarios show a declining trend in projected rainfall from 2020 to 2099, the total annual rainfall projected for SSPs remains higher than RCPs in Δ2050 and Δ2080 periods.

1. Introduction

Climate change is considered to be one of the biggest threats and challenges confronting humanity and nature today. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), each degree of global warming is likely to increase global mean precipitation by 1% to 3% [1]. A warmer climate increases the moisture content of the atmosphere, which feeds into weather systems, making wet events wetter. Mild climate-related disasters, such as floods and droughts, have recently occurred in Malaysia, causing significant socioeconomic impacts as well as the incidence of landslides due to excessive rainfall and strong winds, which happened in hilly areas and caused minimal damage [2]. Furthermore, the observed rainfall record for the last 40 years shows a major increasing trend in annual total precipitation over Peninsular Malaysia [3]. Hence, future rainfall data projections with climate change impact are seen as necessary to provide a better understanding and long-term planning for the infrastructure system.

The majority of researchers worldwide use General Circulation Models (GCM) projections to study future climate change. The GCM has been shown to behave well when simulating climate change, making it an essential tool for examining how climate systems interact as well as a prominent tool for predicting future climate change [4]. However, due to a lack of proper model descriptions of the physical processes driving climate scenarios and climate systems, most GCM models incorporate a high level of uncertainty [5]. Several GCMs have been developed in recent decades. As a next step, the latest sixth phase of the Coupled Model Intercomparison Project (CMIP6) has been released, with improvements over previous CMIPs such as finer spatial resolution and additional Earth system processes and components such as ice sheets [6].

The primary distinction between CMIP6 and CMIP5 is the future scenario, where CMIP5 projections are available based on 2100 radiative forcing values for four greenhouse gas (GHG) concentration pathways known as Representative Concentration Pathways (RCPs). In contrast, CMIP6 employs shared socioeconomic pathways (SSPs) with the CMIP5 scenario (RCPs) premises [7]. SSPs account for mitigation and adaptation to diverse challenges in our society and allow researchers to evaluate the impact of these challenges' responses compared to RCPs. Besides, SSPs make assumptions about the global population, access to education, economic growth, urbanisation, technological developments, and other drivers of demand, such as lifestyle changes. The CMIP6 is made up of five (5) different narratives developed for SSPs, with SSP1 and SSP5 focusing on potential futures of green or fossil-fueled growth, SSP3 and SSP4 dealing with high inequality between or within countries, and SSP2 considered as an intermediate condition among all scenarios.

The purpose of this study was to compare the performance of CMIP5 and CMIP6 in simulating seasonal rainfall as well as trend estimation in Hulu Terengganu, Malaysia, using the Mann-Kendall (MK) and Sen's Slope tests. Both CMIP models were obtained from modelling centers at the Meteorological Research Institute (MRI), Ibaraki, Japan. The linear scaling method of bias correction was applied to the grid-based climate model data for local observed rainfall stations in order to predict the future rainfall projection with consideration of climate change impact. This method is based on the difference between monthly observed and simulated historical rainfall values. These differences are then applied to the simulated climate data from GCM models to obtain bias-corrected climate variables [8].

2. Study Area

Hulu Terengganu is located at 5° 05′ N and 102° 45′ E in the Terengganu State of Peninsular Malaysia. It covers nine townships totaling 387,462.60 hectares. Hulu Terengganu is surrounded by Kelantan and Pahang, which is home to Malaysia's oldest tropical rainforest, Taman Negara Malaysia. Furthermore, it is situated in Malaysia's Central Forest Spine region, turning the district into an environmentally sensitive area, with 99% of the land remaining undeveloped [9]. Figure 1 shows the location of the selected rainfall stations in Hulu Terengganu.

The 33 years (1988 to 2020) of historical rainfall data from four (4) rainfall stations were acquired from the Department of Irrigation and Drainage (DID) of Malaysia as shown in Table 1. The selection of rainfall stations depends on the study location and the quality of the historical data with less than 10% missing value.

Figure 1. The location of the selected rainfall stations in Hulu Terengganu.

Table 1. List of selected rainfall stations in the study.

Station ID	Station Name	Latitude (N)	Longitude (E)
4929001	Kg. Embong Sekayu	04 57 10	102 58 00
4930038	Kg. Menerong	04 56 20	103 03 40
5029034	Kg. Dura	05 04 00	102 56 30
5128001	Sg. Gawi	05 08 35	102 50 40

3. Methodology

Figure 2 illustrates the methodology's flow chart. This study compares the performance of the CMIP5 GCM's MRI-CGCM3 and its updated model, the CMIP6 GCM's MRI-EMS2-0. In general, MRI-ESM2-0 has been improved considerably over previous models and is expected to perform better in many experiments. The atmospheric vertical resolution is now 80 layers, up from 48 layers in its predecessor. As MRI-ESM2-0 accumulates various improvements concerning clouds, such as a new stratocumulus cloud scheme that resulted in a remarkable reduction in errors in longwave, shortwave, and net radiation at the top of the atmosphere [10], the resulting errors are sufficiently small compared to those in previous models.

In this study, three CMIP5 projections, RCP 2.6 (low emission scenario), RCP 4.5 (intermediate emission scenario), and RCP 8.5 (high emission scenario), are compared to their equivalent radiative forcing in CMIP6, SSP1-2.6, SSP2-4.5, and SSP5-8.5. The model output was obtained from the open-access platform https://esgf-node.llnl.gov. This website provides historical and future monthly rainfall projections. Table 2 contains a detailed description of the models. To make the evaluation process easier, the r1i1p1 variant model for CMIP5 and r1i1p1f1 variant model for CMIP6 were chosen.

Table 2. Detailed descriptions of the CMIP5 and CMIP6 GCM models used in this study.

Institution/Country	Abbreviation		Model	Resolution
Meteorological Research Institute, Ibaraki, Japan.	MRI	CMIP5	MRI-CGCM3	1.10° x 1.10°
		CMIP6	MRI-ESM2-0	1.12° x 1.12°

GCMs perform well in simulating observed data on a large scale, but they still have some bias that must be corrected when studying it on a local scale [8]. For this study, the linear scaling (LS) method is used to correct the biases of the GCM. LS is the most straightforward bias correction technique employed in several studies. It adjusts the GCM mean value to be in perfect agreement with the rainfall observation data. The LS method computes a consistent corrected factor based on the difference between original GCM data and observations [11]. However, this method can only be applied correctly if the monthly mean values are included. The LS equation is expressed in equation (1) as follows:

$$P_{his}(d)^* = P_{his}(d) \times [\mu_m (P_{obs}(d)) / \mu_m (P_{his}(d))] \quad (1)$$

where, d = daily, μ_m = monthly mean, * = bias corrected value, *his* = GCM history simulation data and *obs* = observed rainfall data.

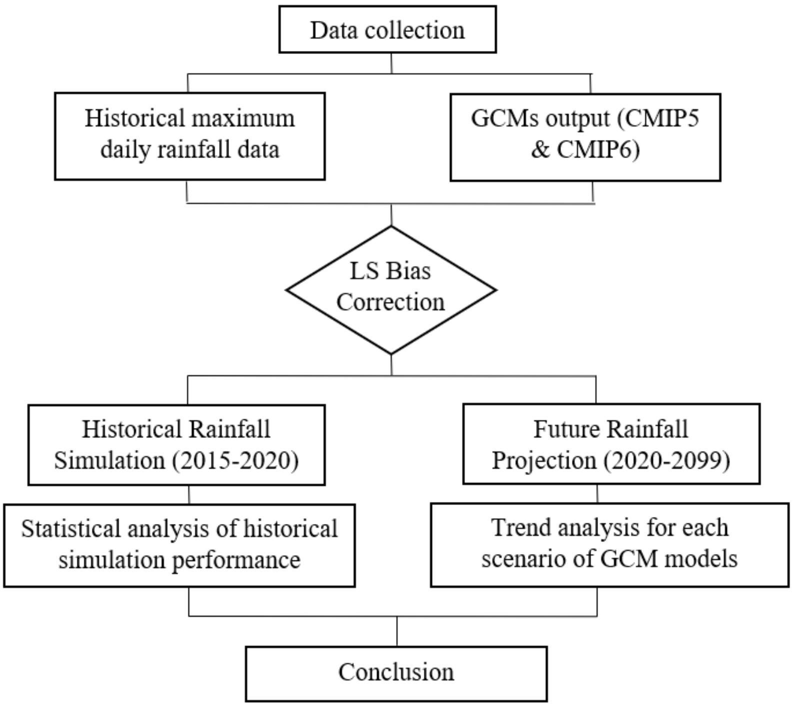


Figure 2. Flow chart of the study

The performance of two CMIPs models in simulated historical rainfall (2015 to 2020) was analysed statistically in terms of percentage difference (% difference) and Pearson's correlation (r). Lesser values of % difference with higher r indicated that the models performed well. This is an important process for determining which of the models is reliable and compatible with actual climate conditions. The percentage difference is calculated as:

$$\% \text{ Difference} = \frac{(x-y)}{(x+y)/2} \text{ x } 100\% \quad (2)$$

The Pearson's correlation, r is calculated as:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (3)$$

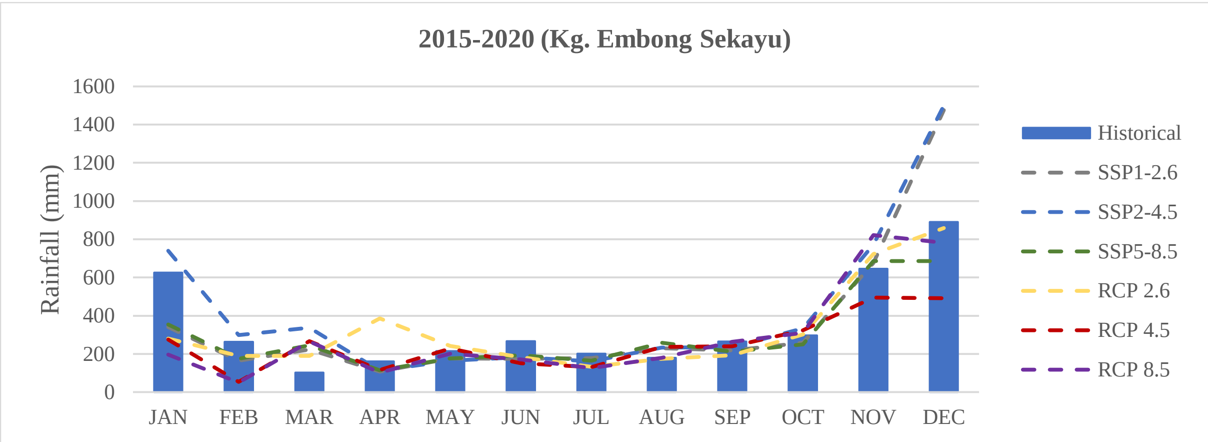
where, x = modelled data, y = historical data, $\bar{x}$ = mean of modelled data and $\bar{y}$ = mean of historical data.

Meanwhile, two (2) statistical tools, the Mann-Kendall (MK) trend test and the Sen's Slope test, have been used to determine whether there are any significant trends in future rainfall projections (2020 to 2099). Trend analysis is considered a very useful tool for hydrological management because hydrological variables such as precipitation provide information on the possibility and tendency of future climate changes, as suggested by the World Meteorological Organization (WMO). Future annual rainfall projections using two CMIP models are also compared to the historical period (1988 to 2017) to assess potential future climate change in Hulu Terengganu. The analysis was performed for three different scenarios for each CMIP in order to provide a detailed understanding of future climate prediction. For a more detailed comparison, the results of future projections were presented in two (2) different projected time periods, 2040–2069 (Δ2050) and 2070–2099 (Δ2080).

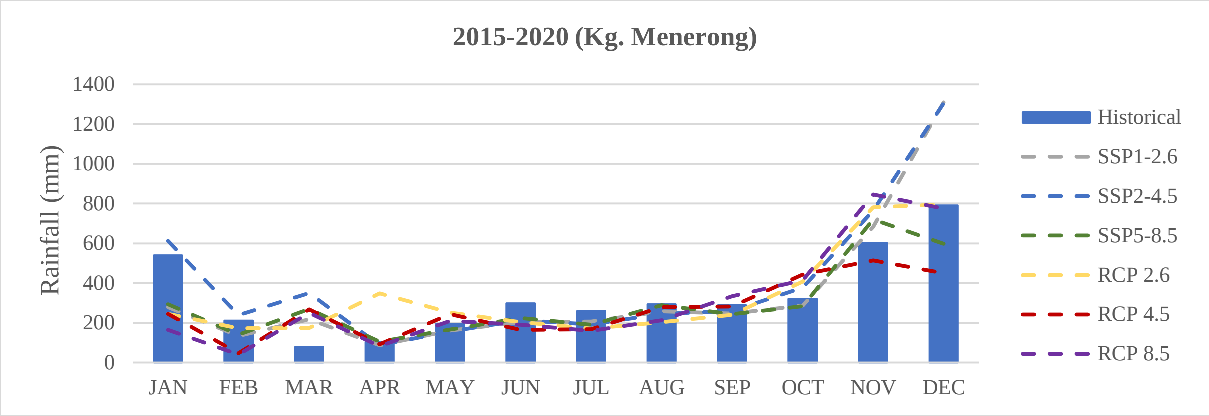
4. Result and Discussion

4.1. Performances in Simulating Historical Rainfall

Figure 3 (a-d) shows the comparison of annual monthly simulated historical rainfall using both CMIPs models and the observed historical record for all rainfall stations. The rainfall data ranged from 2015 to 2020 (6 years). The annual monthly simulated rainfall pattern was consistent with the observed rainfall pattern, albeit with overestimated/underestimated monthly simulated results, which could be attributed to the short data frames, which were not suitable for long-term analysis. Then, the performance of simulated results was evaluated using statistical analyses in terms of percentage difference (% difference) and Pearson's correlation (r), as shown in Table 3. In general, the SSPs scenario from the CMIP6 model produced more convincing results than the RCPs scenario from the CMIP5. All SSPs scenarios show the lowest percentage difference for all rainfall stations and indicate better performance in simulating historical rainfall by producing a higher r value that is close to 1.0.

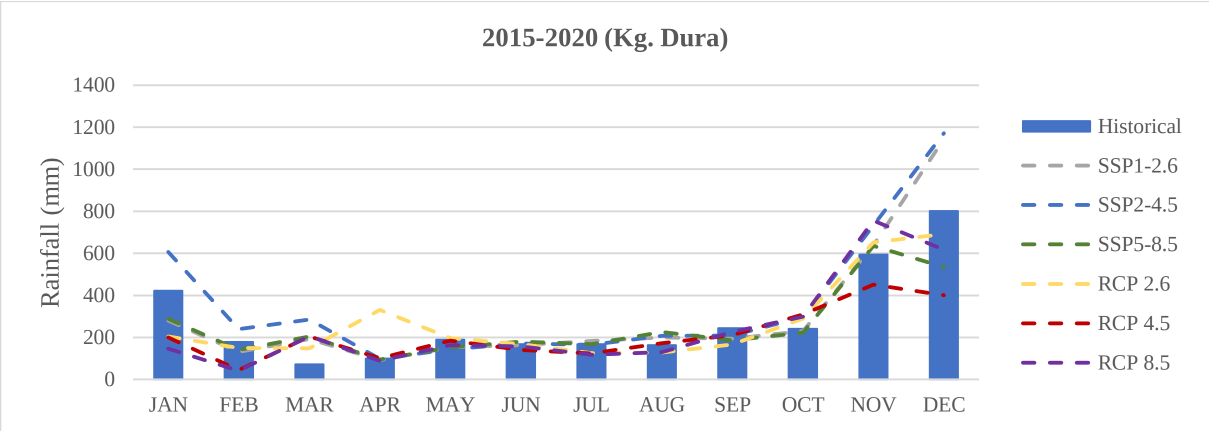


(a)

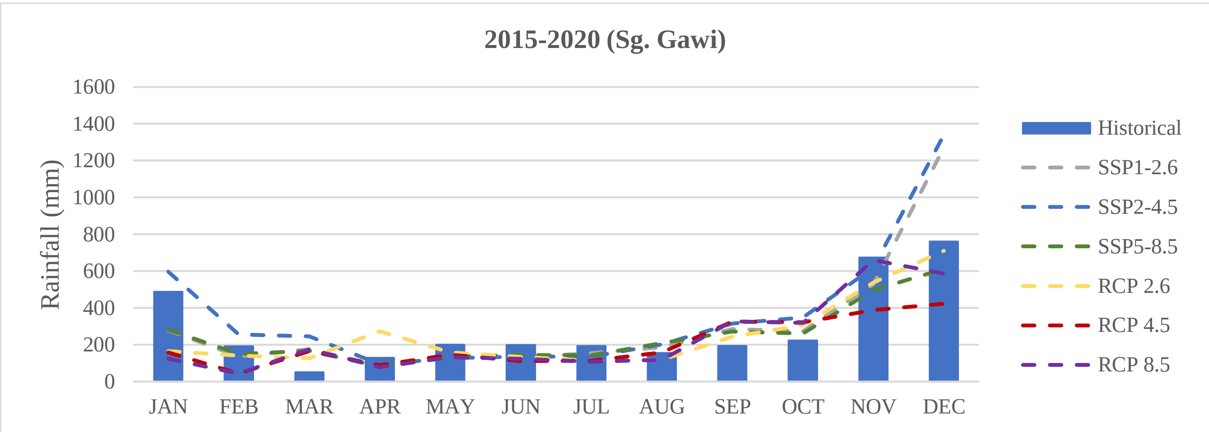


(b)

Figure 3(a-b). Comparison between historical simulated rainfall and observed historical record



(c)



(d)

Figure 3(c-d). Comparison between historical simulated rainfall (c) and observed historical record (d)

Table 3. Statistical analysis for performances of CMIP6 and CMIP5 model

Rainfall Station	Scenario	Percentage Differences, %	Pearson's correlation (r)
Kg. Embong Sekayu	SSP1-2.6	33.8	0.9
	SSP2-4.5	31.2	0.9
	SSP5-8.5	32.7	0.9
	RCP 2.6	32.6	0.8
	RCP 4.5	46.9	0.8
	RCP 8.5	42.6	0.8
Kg. Menerong	SSP1-2.6	33.3	0.9
	SSP2-4.5	31.0	0.9
	SSP5-8.5	29.9	0.8
	RCP 2.6	40.7	0.8
	RCP 4.5	46.2	0.7
	RCP 8.5	47.9	0.8
Kg. Dura	SSP1-2.6	24.3	0.9
	SSP2-4.5	28.0	1.0
	SSP5-8.5	25.3	0.9
	RCP 2.6	33.6	0.9
	RCP 4.5	40.1	0.8
	RCP 8.5	40.5	0.8
Sg. Gawi	SSP1-2.6	40.6	0.8
	SSP2-4.5	42.4	0.9
	SSP5-8.5	38.2	0.9
	RCP 2.6	42.4	0.8
	RCP 4.5	58.9	0.7
	RCP 8.5	57.2	0.8

The findings demonstrate that the CMIP6 models' rainfall simulation biases are lower than those of the CMIP5, indicating that CMIP6 has improved in terms of bias reduction for local-scale studies. Wang et al. (2021) compared precipitation downscaling results and observational data for the Hanjiang River Basin (HRB) in China using CMIP5 and CMIP6 multi-model ensemble (MME) [12]. They discovered that certain biases in the downscaled GCM precipitation simulation remained. However, CMIP6-MME data shows lower simulation biases than CMIP5-MME data, indicating that CMIP6 has improved in terms of reducing precipitation bias. Rivera & Arnould (2020) also looked into the ability of CMIP6 precipitation simulation historical runs to capture the temporal patterns observed over southwestern South America [13]. The results show that most CMIP6 models adequately captured the primary features of regional precipitation.

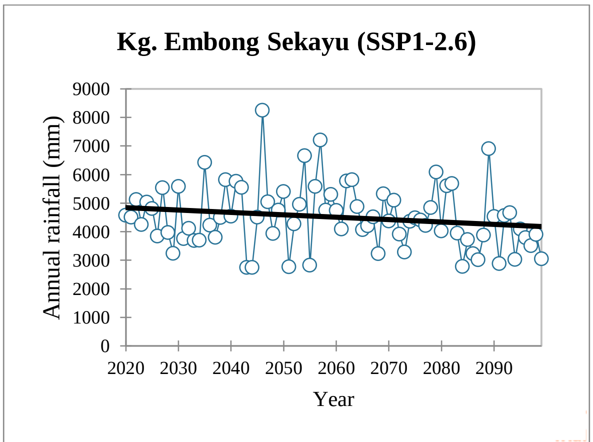
4.2. Trend Analysis of Projected Rainfall

The statistical analysis, Mann-Kendall (MK) trend test, and Sen's Slope test were used to determine the trend of rainfall projection for each station (2020 to 2099). If the *p-value* (two-tailed test) is less than α (alpha) = 0.05 (5% level of significance), Null Hypothesis (H_o) is rejected. Rejecting H_o indicates that a significant trend in the time series was detected, whereas accepting H_o indicates that no significant trend was detected. Meanwhile, positive Sen's Slope test values indicate that rainfall indices are increasing and vice versa. The outcome from the annual rainfall trend analysis for each station is shown in Table 4. The results of the MK trend test show a non-significant trend was detected since the H_o was accepted for all rainfall stations and scenarios. The p-values computed for all stations are greater than the significant level, α of 0.05.

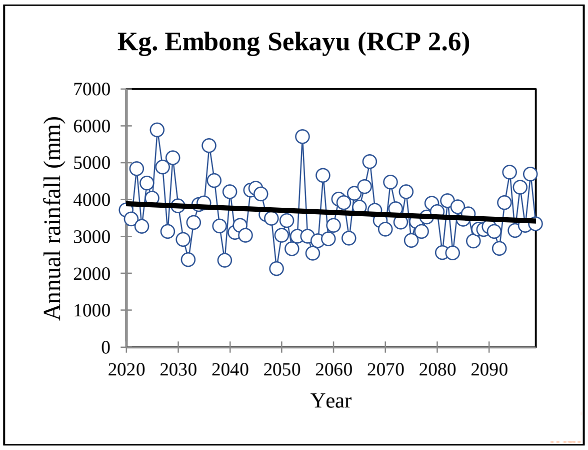
Table 4. Annual rainfall trend analysis for each station and scenario

Station	Scenario	Mann-Kendall Test				Sen's Slope test
		Kendall's Tau	p-value (two-tailed test)	Alpha, α	Test Interpretation	
Kg. Embong Sekayu	SSP1-2.6	-0.13	0.08	0.05	Accept H_o	-9.26
	SSP2-4.5	-0.12	0.12	0.05	Accept H_o	-7.00
	SSP5-8.5	-0.05	0.51	0.05	Accept H_o	-2.20
	RCP 2.6	-0.10	0.19	0.05	Accept H_o	-5.07
	RCP 4.5	0.08	0.31	0.05	Accept H_o	4.32
	RCP 8.5	0.04	0.60	0.05	Accept H_o	3.21
Kg. Menerong	SSP1-2.6	-0.12	0.10	0.05	Accept H_o	-7.71
	SSP2-4.5	-0.13	0.10	0.05	Accept H_o	-6.47
	SSP5-8.5	-0.02	0.85	0.05	Accept H_o	-0.86
	RCP 2.6	-0.09	0.22	0.05	Accept H_o	-4.49
	RCP 4.5	0.07	0.37	0.05	Accept H_o	3.46
	RCP 8.5	0.07	0.39	0.05	Accept H_o	4.66
Kg. Dura	SSP1-2.6	-0.14	0.07	0.05	Accept H_o	-7.71
	SSP2-4.5	-0.13	0.09	0.05	Accept H_o	-5.87
	SSP5-8.5	-0.05	0.54	0.05	Accept H_o	-2.38
	RCP 2.6	-0.08	0.28	0.05	Accept H_o	-3.68
	RCP 4.5	0.09	0.23	0.05	Accept H_o	4.20
	RCP 8.5	0.06	0.42	0.05	Accept H_o	3.68
Sg. Gawi	SSP1-2.6	-0.14	0.06	0.05	Accept H_o	-8.87
	SSP2-4.5	-0.13	0.08	0.05	Accept H_o	-7.17
	SSP5-8.5	-0.06	0.46	0.05	Accept H_o	-2.56
	RCP 2.6	-0.03	0.71	0.05	Accept H_o	-1.31
	RCP 4.5	0.10	0.20	0.05	Accept H_o	4.21
	RCP 8.5	0.08	0.32	0.05	Accept H_o	4.16

Based on Sen's Slope test, there is an increasing trend for RCP 4.5 and RCP 8.5 scenarios for all rainfall stations as shown in Table 4. However, the SSPs scenario shows a decreasing rainfall trend for all rainfall stations, with SSP1-2.6 producing the highest decreasing trend value. Figure 4 shows an example of trend analysis of annual rainfall data for Kg. Embong Sekayu, with a linear trend line plotted for the time period 2020 to 2099.



(a)



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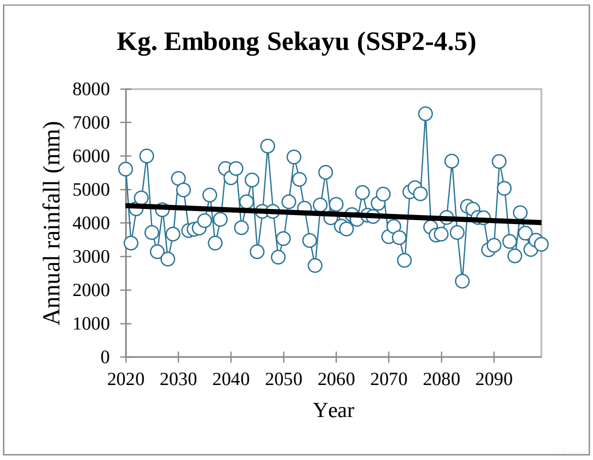

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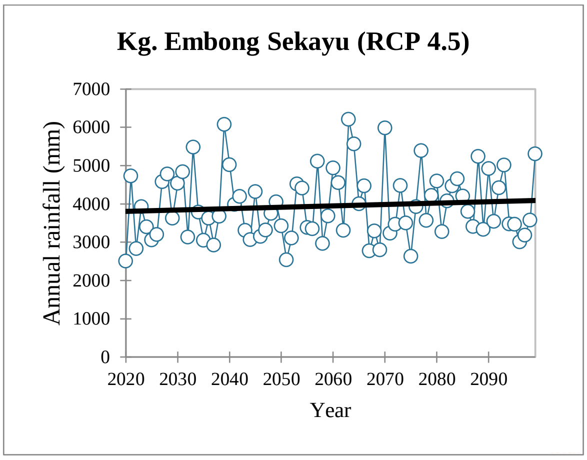
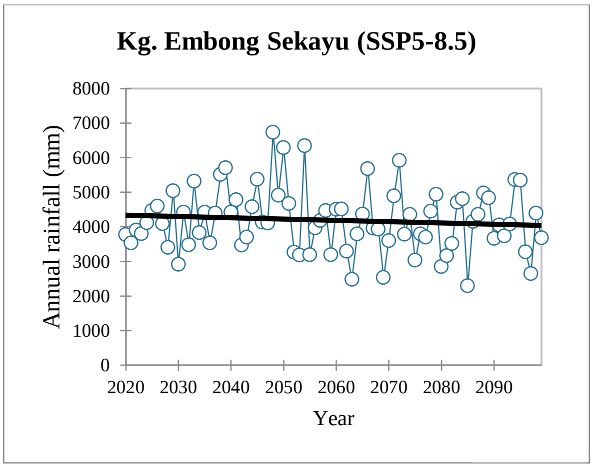


(d)

Figure 4(a-d). Trend analysis of annual rainfall for Kg. Embong Sekayu station



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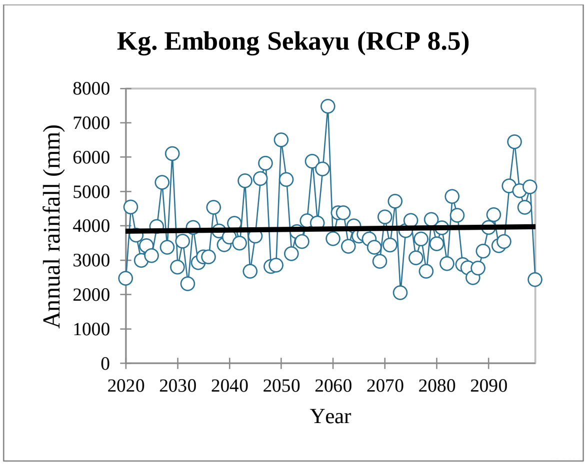
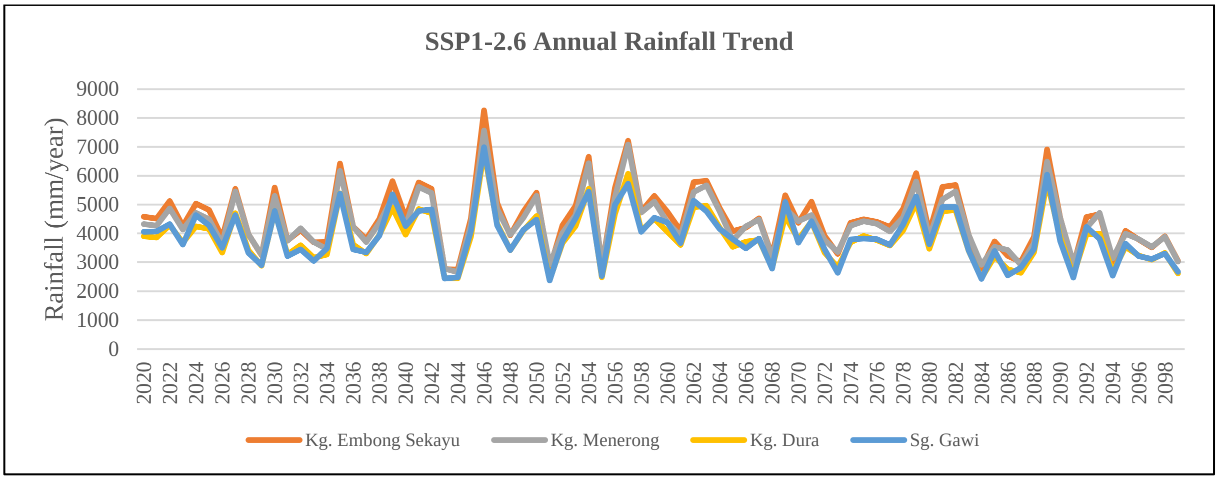


(f)

Figure 4(e-f). Trend analysis of annual rainfall for Kg. Embong Sekayu station

The rainfall trend from each scenario at their correspondence stations also has been compared as shown in Figure 5 (example for SSPs scenarios). The comparison shows that SSPs and RCPs predicted consistent future annual rainfall trends for different stations.



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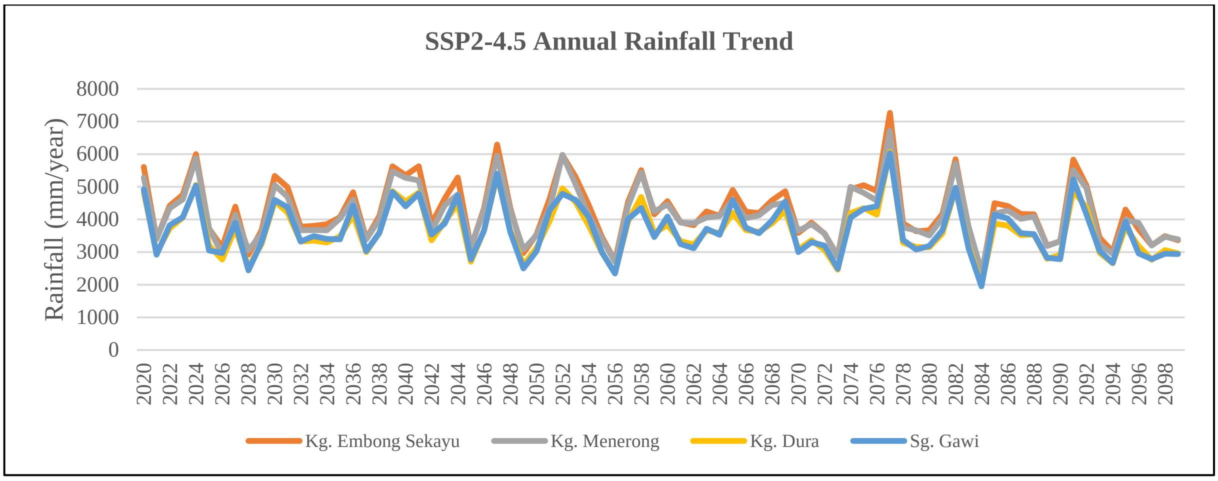

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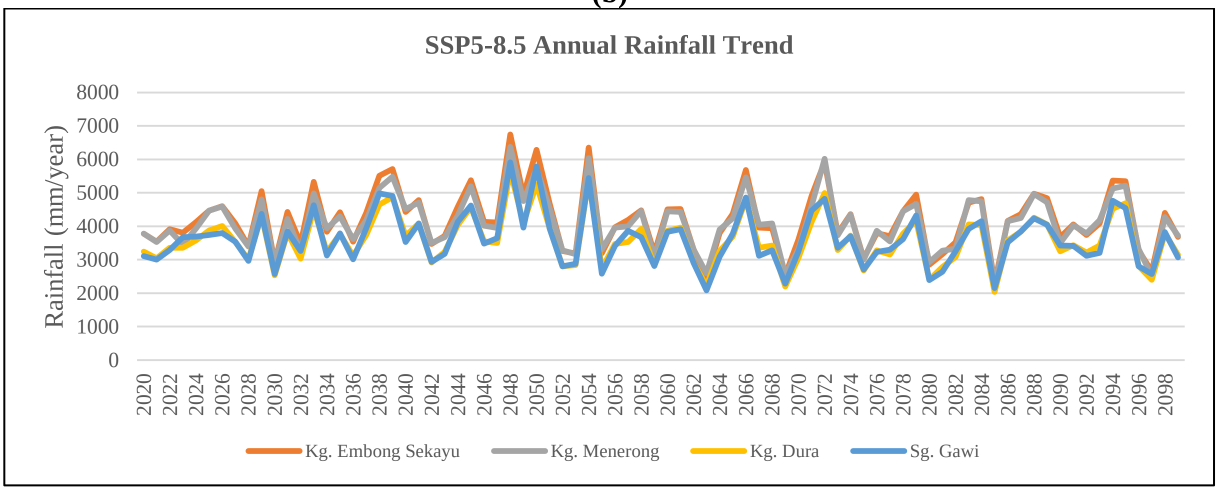

(c)

Figure 5. Comparison of future annual rainfall trend for SSPs scenario at different rainfall stations

4.3. Comparison of Annual Rainfall Projection

Figure 6 compares the future annual rainfall projection for both CMIPs scenarios for different projected time periods, 2040-2069 (Δ2050) and 2070-2099 (Δ2080), to the observed rainfall for the baseline period (1988-2017). According to the analysis, the SSPs scenario from the CMIP6's model, MRI-ESM2-0, indicates the possibility of a greater increase in rainfall magnitude in the future than CMIP5's model, MRI-CGCM3. Except for the Δ2080 projection for Kg. Menerong station, where RCP 4.5 projects the highest annual rainfall, SSP1-2.6 showed the highest annual rainfall projection for all rainfall stations and projected time periods. In fact, SSP1-2.6 had the highest increase in annual rainfall projection for all rainfall stations in Δ2050, with a 17% increase on average over the baseline period.

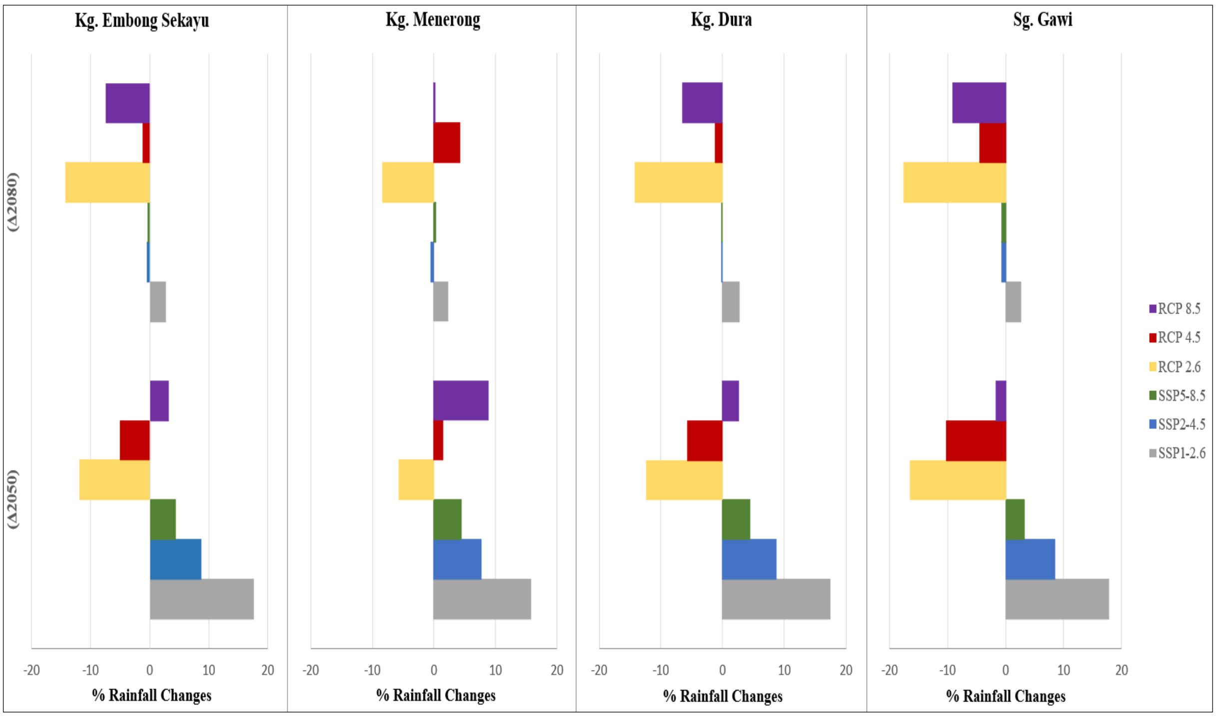

Figure 6. Comparison of annual rainfall projection with the baseline period (1988-2017)

SSP2-4.5 and SSP5-8.5 also show an increase in annual rainfall projections for all rainfall stations in Δ2050. However, the magnitude began to decrease in Δ2080. In contrast, RCP 2.6 from the CMIP5 scenario shows the greatest reduction in annual rainfall projection compared to other scenarios, with an 18% reduction predicted at the Sg. Gawi station in Δ2080. Meanwhile, RCP 4.5 and RCP 8.5 show inconsistent future annual rainfall patterns with increasing and decreasing annual rainfall in different projected time periods across all rainfall stations. In general, it can be concluded that although all SSPs scenarios show a declining trend in projected rainfall from 2020 to 2099, the total annual rainfall projected by SSPs scenarios was higher compared to RCPs in Δ2050 and Δ2080.

The increasing annual rainfall projections produced by the CMIP6 model are consistent with previous studies. Nashwan & Shahid (2022) used the CMIP6 multimodel ensemble to study future precipitation changes in Egypt [14]. The results revealed an increase in annual precipitation of up to 54%, mostly in the north, indicating a possible increase in flood and hydrological hazard susceptibility. Tan et al. (2021) discovered that annual precipitation is projected to increase by 6.9% by the 2021-2050 period in the study of hydrological extremes and responses to climate change in the Kelantan River Basin based on CMIP6 experiments, particularly during the early phase of the Northeast Monsoon in December [15]. Furthermore, Hong et al. (2021) investigated the change of extreme precipitation in the Philippines using CMIP6 multi-model ensemble projections and found that the relative rise of the 20-year return value of the annual maximum daily precipitation from the past to the year 2100 will be about 8.5% in the SSP2-4.5 and 17% in the SSP5-8.5, in the spatial median [16].

5. Conclusions

This study compares the performance of CMIP5 (based on Representative Concentration Pathways, RCPs) and CMIP6 (based on Shared Socioeconomic Pathways, SSPs) in simulating seasonal rainfall and estimating trends in Hulu Terengganu, Malaysia. From the analysis, the SSPs scenario produced more convincing results than the RCPs as they show the lowest percentage difference for all rainfall stations in simulating historical rainfall and indicate better performance by producing a higher Pearson's correlation (r) value that is close to 1.0. It is also demonstrated that the CMIP6 models' rainfall simulation biases are lower than those of the CMIP5, indicating that CMIP6 has improved in terms of bias reduction for local-scale studies.

Furthermore, despite the fact that all SSPs scenarios show a decreasing trend in projected rainfall from 2020 to 2099, the total future annual rainfall projected by SSPs scenarios was higher than RCPs in Δ2050 and Δ2080 when compared to the baseline period (1988-2017). As matter of fact, SSP1-2.6 had the highest increase in annual rainfall projection with a 17% on average for all rainfall stations in Δ2050. Meanwhile, RCP 2.6 shows the greatest reduction in annual rainfall projection compared to other scenarios, with an 18% reduction predicted at the Sg. Gawi station in Δ2080.

It can be suggested that future climate modelling should consider the increased availability of GCMs from both CMIPs, as well as the ability to compare model iterations. Besides, more emphasis should be placed on the development of high-resolution regional climate models in the future. Heavy rainfall can have serious consequences for people, communities, infrastructure, and natural ecosystems. In addressing the impact of climate change due to more frequent extreme rainfall events, governments and authorities should more securely and carefully prepare the proper infrastructure systems and guidelines to prevent critical damage, such as loss of life and properties from flooding and landslides events.

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