IOP Conference Series: Earth and Environmental Science

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To cite this article: H Hamid *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1347** 012013

Rainfall projection using CIMP6 models of extreme area in Johor

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Abstract. This paper explores the impact of climate change on rainfall patterns, particularly extreme intensity, in Johor, Malaysia. The study focuses on addressing uncertainties in climate change projections by selecting suitable Global Climate Models (GCMs) based on location and topography. Four CMIP6 models (GFDL-ESM4, IPSL-CM6A-LR, MIROC6, and MRI-ESM2-0) were chosen for analysis. The research employs statistical downscaling, using historical observed data (1988-2020) and GCM output data, with a bias correction through linear scaling. The performance of the GCMs is assessed using various metrics including Root Mean Square Error (RMSE), Coefficient of Determination (R2), Percentage of Bias (Pbias), and Nash-Sutcliffe Efficiency (NSE). The IPSL-CM6A model is identified as the most suitable for rainfall projection in Johor. Under the severe climate scenario (SSP5-8.5), the analysis indicates increasing rainfall intensity in January from 2025 to 2054, notably at the Pusat Pertanian Endau station with a significant 50% increment. However, for the projected period 2055 to 2084, most stations experience a decrease in rainfall from January to June, with the Ladang Sg. Plentong station showing the largest reduction of about 40% in January. Conversely, the latter half of the year shows increased rainfall for all stations. The Mann-Kendall Test method highlights a significant decreasing trend in rainfall across all stations from 2025 to 2084 under the SSP5-8.5 scenario. This suggests that without mitigation efforts, the area will likely experience decreasing rainfall intensity due to the effects of climate change.

1. Introduction

Although it is impossible to forecast future advances in scientific knowledge, the value of future observational monitoring can be estimated [1]. Impact of the awareness of climate change, scientists and researchers were developed mathematical models, General Circular Models (GCMs) that capable to represent physical process of atmosphere and ocean in response of increasing greenhouse emission. The divergence of the GCMs from their ensemble mean is used in most of the techniques and existing techniques have the primary flaw of underestimating or overestimating the uncertainty in projections, particularly in catastrophic weather occurrences [2]. Thus, the selection of more suitable GCMs based on location and topography can be considered as effective way in order reducing the uncertainty in climate change projection.

The Coupled Model Intercomparison Project (CMIP) was created to investigate and evaluate climate simulations produced by coupled ocean–atmosphere–cryosphere–land GCMs. There are many of CMIP phases that had established by World Climate Research Programme (WCRP) from CMIP1 until the latest one which is CMIP6. The climate sensitivity range in the CMIP6 models evaluated in this report is wider than in CMIP5 models, and the Assessment Report 6 (AR6) estimated extremely probable range is based on numerous lines of evidence. The increased CMIP6 climate sensitivity values compared to CMIP5 can be attributed to 20% stronger amplifying cloud feedback in CMIP6 [3]. The trend of development and adaptation shown in earlier CMIP stages is continued in CMIP6 by the overview from the study in respect to CMIP6 have large resolution and more accurate in climate scenarios [4].

There were some previous studies to support the methodology of this study, by using statistical downscaling in climate change modelling. From a study of [5] a combination of global and regional climate models, statistical downscaling approaches, and a process-based distributed hydrologic model were used to simulate the basin hydrologic response to climatic forcings in a reference (1971–2000) and future (2041–2070) era. The other studies also used statistical downscaling for other climate projection. The effectiveness of the Penman–Monteith (P–M) model and statistically downscaled global climate model (GCM) forecasts in forecasting daily reference evapotranspiration (ET) at six meteorological stations in Canada was examined and measured [6].

Since 1977, increasingly frequent warm phase occurrences of the El Nino Southern Oscillation (ENSO) have been recorded. This behavior, particularly the prolonged warm period from 1990 to mid-1995, was unprecedented in the previous 120 years and had a substantial impact on rainfall in Malaysia [7]. It indicated that the increment of temperature was affected on reduction of water availability and became worst during dry months. The objectives of this study; to forecast long-term rainfall due to climate change under three (3) different range of scenarios in shared socio-economic pathways (SSP) and; to examine the long-term future rainfall trends corresponding to the climate change scenarios using statistical analyses.

2. Study Area

Johor is located in the southern part of Peninsular Malaysia with the total land area is 19,102 km^2. The study area also located in an equatorial climate location with rain from Northeast monsoon occurred starts from November to March, and Southwest monsoon occurs from March to August. It also experiences humid tropical climate and the average rainfall about 2,000 – 2,500 mm distribution along the year. For this study, five (5) stations were selected as shown in Figure 1. All stations receive high rainfall that represent in Table 1.

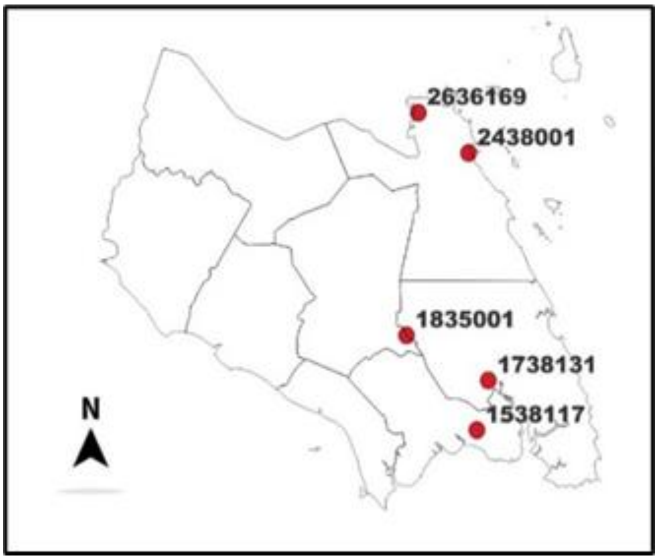


Figure 1. Locations of the study area.

Table 1. Coordinate of the stations and the total rainfall based on observed historical data from 1988 to 2020.

Station No.	Station ID	Station Name	Coordinate		Total Rainfall 1988-2020 (mm/yr)
			Latitude	Longitude	
1	2636169	Pusat Pertanian Endau	2.6097	103.6306	3301.46
2	2438001	Stor JPS Batu Tiga	2.4736	103.8139	2570.26
3	1538117	Ladang Sg. Plentong	1.5347	103.8444	2561.63
4	1835001	Ladang Pekan Layang-Layang	1.8556	103.5875	2550.34
5	1738131	Ladang Getah Malaya	1.7028	103.8861	2546.61

3. Methodology

Daily historical rainfall data, from year 1988 until 2017 was obtained from the Department of Irrigation and Drainage (DID). Missing daily data for each station are identified. It is essential to treat the missing historical data to perform effectively rainfall analysis afterward. The Inverse Distance Weighting (IDW) method was applied to fill the gap of the missing rainfall data records. In this method, the weight for each station is assumed to be inversely proportional to its squared distance of the target station from the neighboring station with available data as in Equation 1.

$$p_x = \frac{\sum_{i=1}^{m} \frac{1}{d_i^2} p_i}{\sum_{i=1}^{m} \frac{1}{d_i^2}} \quad (1)$$

Where, px is the estimate for the target station X, pi is the rainfall values of rain gauges used for estimation and m is the number of surrounding stations.

General Circulation Model (GCM) data can be downloaded at official website of World Climate Research Programme (WCRP) under Coupled Model Intercomparison Project Phase 6 (CMIP6). Out of many GCMs available in CMIP6, four (4) GCMs were initially selected as their consist of daily historical data (1988-2014) and daily future projections (2025-2084) for SSP5-8.5 which is high emission scenario. All the GCMs selected is using variant label “r1i1p1f1” as it is global attribute data, precipitation as variable parameter, and daily as the frequency. Label “r1i1p1f1” refers to a specific experiment configuration within the CMIP6 model run: the first realization with the first set of initial conditions, physics parameterizations, and external forcing conditions. Table 2 represents the GCMs initially selected.

Table 2. GCMs that selected for initial study.

No.	GCMs	Institution	Resolution (Long × Lat)
1	GFDL_ESM4	NOAA Geophysical Fluid Dynamics Laboratory (NOAA GFDL), USA	1.0˚ × 1.3˚
2	IPSL-CM6A-LR	Institution Pierre Simon Laplace, Paris	2.5˚ × 2.5˚
3	MIROC6	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies (MIROC), Japan	1.4˚ × 1.4˚
4	MRI-ESM2-0	Meteorological Research Institute, Japan	1.1˚ × 1.1˚

The idea of downscaling is to translate the information which is the climate data from GCMs to local and regional scales since GCMs typically provide data over very large grid points which are about 100-300 km. In order to get the climate data for each rainfall station, statistical downscaling method was applied to GCMs by using software Microsoft R Open version 4.0.2.

Comparison between projected raw GCM data and observation data mostly consists of biases resulted from the differences due to mean and variability between them. The gap must be filled before further analysis and a bias correction which is Linear Scaling (LS) methods was applied for this study. The bias correction can be used as calibration method for the models to overcome the uncertainty. LS method is widely used and proven the most accurate method beside maintain the reliability of the results after treatment. The Equation 2 is used as bias correction treatment.

$$P_{cor,m,d} = P_{raw,m,d} \times \frac{\mu(P_{obs,m})}{\mu(P_{raw,m})} \quad (2)$$

Where, $P_{cor,m,d}$ is the corrected precipitation on the d^{th} day of m^{th} month, $P_{raw,m,d}$ is the raw precipitation on the d^{th} day of m^{th} month, and μ is the mean value of observed or raw precipitation at given month m.

Four statistical metrics were used to evaluate the performance of the GCMs in year 2015 until 2017 based on availability historical data of the five stations. The projected GCMs data and rainfall at different grid points were compared in respect to Root Mean Squared Error (RMSE), Coefficient of Determination (R^2), Percentage of Bias (Pbias), and Nash-Sutcliffe Efficiency (NSE). Because a GCM might exhibit varying degrees of under or overestimation of a climatic variable, ranking the GCMs with different statistical assessment outcomes for different time periods is a difficult process. Thus, CP was utilized to combine the historical evaluation results of GCMs in order to rank them for each time frame. The CP calculates the distance (Lcp) between each GCM and an ideal value or frontier, then ranks the GCMs based on this distance. Lcp is calculated as in Equation 3.

$$L_{cp} = \left[\sum_{j=1}^{z} \left| x_j - x_j^{*} \right| \right]^{\frac{1}{p}} \quad (3)$$

Where, z is the number of evaluation metrics used, x_j is the normalized value of metric j obtained for a certain GCM, x_j* is the normalized ideal value of metric j, and p is the parameter (1 for linear, 2 for squared Euclidean distance measure)

The Lcp can be any positive number, however a low Lcp as zero reflects how near a GCMs rainfall simulation is to historical data value and the results were used to rank the GCMs in rainfall projection from 2025 until 2084. Lcp results which scored the lowest value were given the first rank and the highest value were given the last rank.

4. Result and Analysis

Evaluation of GCMs by using statistical analysis was done of this study. The projected GCMs data and observed rainfall at different grid points were compared for year 2015-2017 as validation process. After Lcp was calculated for each station, IPSL-CM6A for Ladang Getah Malaya, Stor JPS Batu Tiga, Ladang Sg. Plentong, and Ladang Pekan Layang-Layang station had lowest values compared to other models. Thus, from the rank in CP, IPSL-CM6A model was selected for GCM model in rainfall projection for 2025 until 2084 for the study area.

Historical data from 1988 to 2017 and projected data using IPSL-CM6A-LR model under SSP5-8.5 were compared as shown in Figure 2. Both data were clustered monthly and high intensity of rainfall usually happens in between October until March impacted from Northeast Monsoon that originating in China and the north Pacific. Pusat Pertanian Endau station and Stor JPS Batu Tiga station illustrated clearly that projected data and historical data area followed the rainfall pattern that high intensity on November until January. However, the rainfall pattern for other stations is inconsistent and had uncertainty along the year.

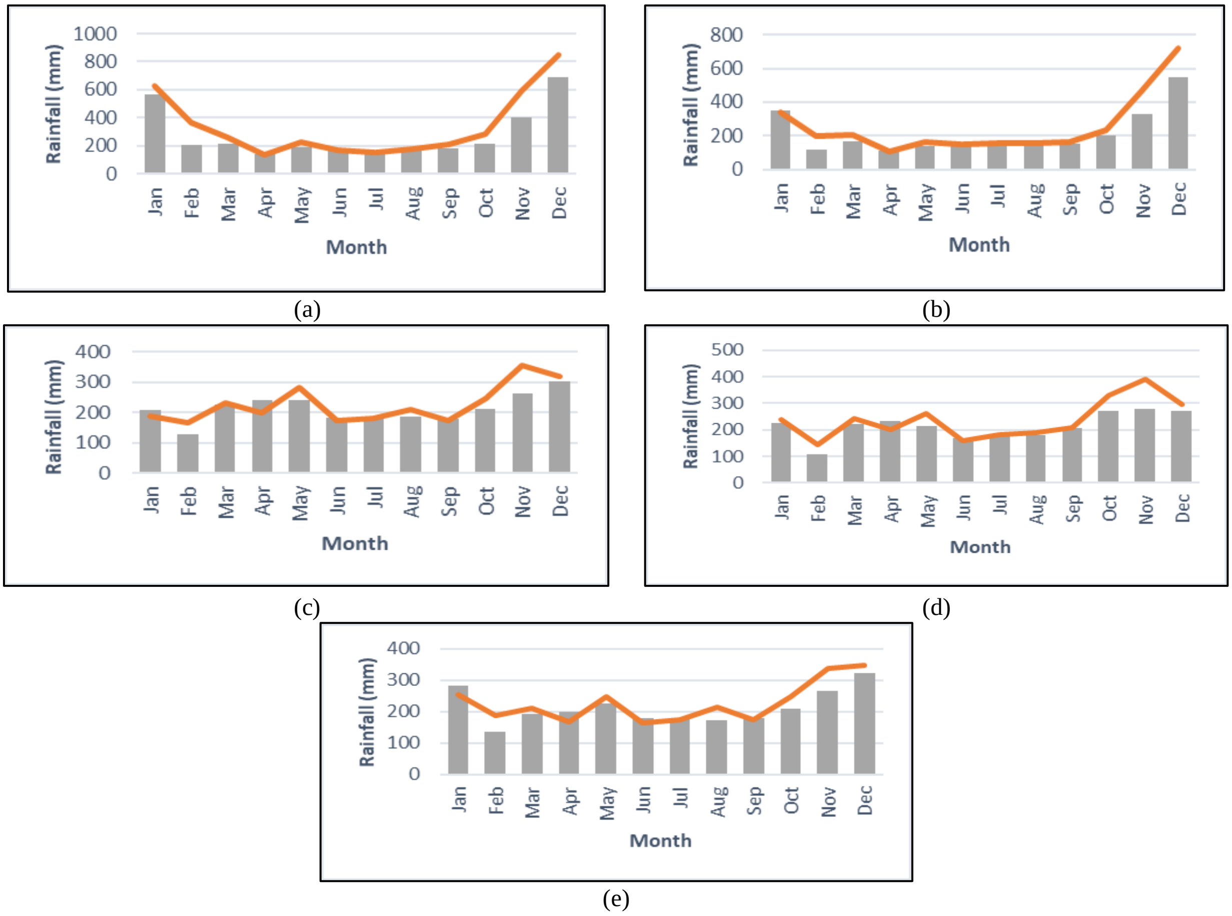
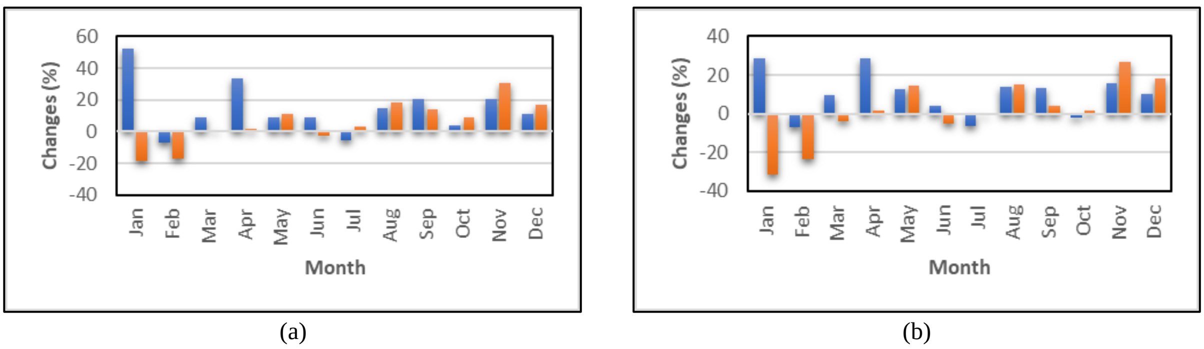


Figure 2. Comparison of observed historical data 1988-2020 (bar chart) and projected GCM data 2015-2020 (line chart) for (a)Pusat Pertanian Endau, (b)Stor JPS Batu Tiga, (c)Ladang Sg. Plentong, (d)Ladang Pekan Layang-Layang, and (e)Ladang Getah Malaya station.

In order to analyze the projected data more specifically, the percentage of changes were calculated and the graphs are plotted as Figure 3 for all stations. Same goes to comparison of historical and projected data, the changes are analyzed by divided into 2 clusters, (2025-2054) and (2055-2084) to give consistency of the analysis.



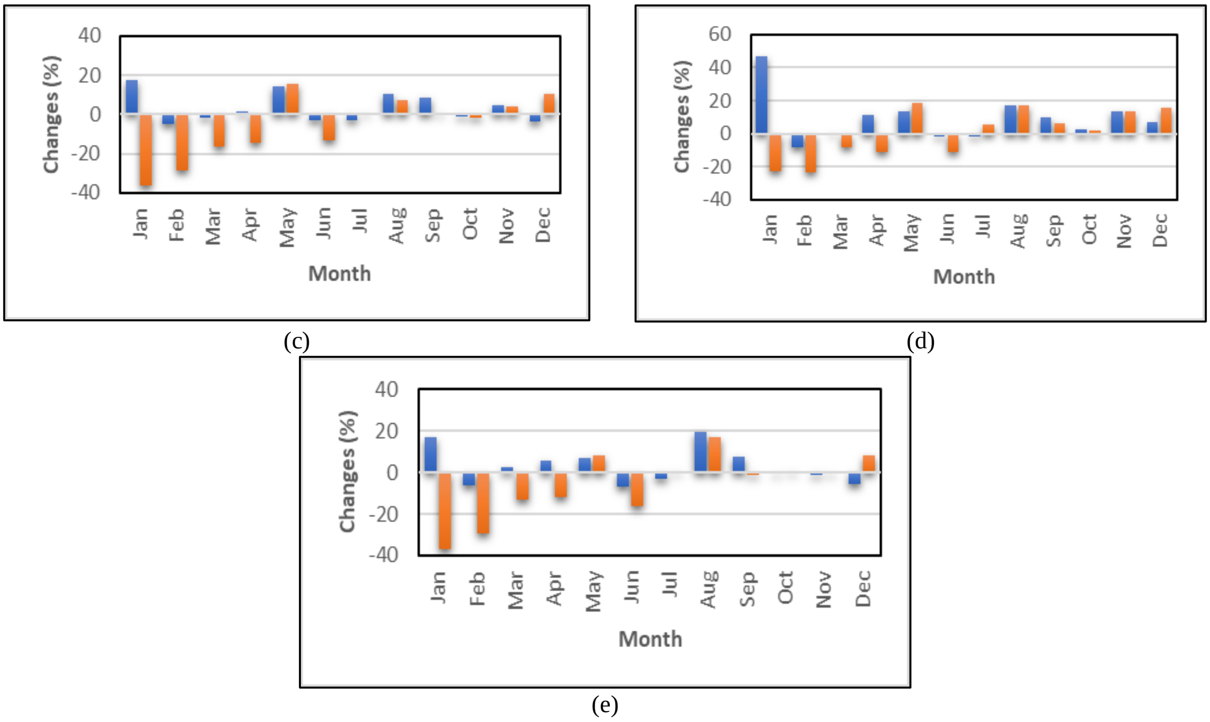


Figure 3. Percentage of changes of observed historical data 1988-2020, GCM projected data 2025-2054(blue bar) and 2055-2084(orange bar) for (a)Pusat Pertanian Endau, (b)Stor JPS Batu Tiga, (c)Ladang Sg. Plentong, (d)Ladang Pekan Layang-Layang, and (e)Ladang Getah Malaya station.

For period 2025 until 2054, the rainfall intensity for most of the stations will be increasing in January and Pusat Pertanian Endau station had largest changes about 50% in increment of rainfall. For projected data 2055 until 2084, majority stations had decrement of rainfall from January to June. Ladang Sg. Plentong station had largest changes about 40% decrement of rainfall on January. However, there were increase in rainfall from July to December for all stations along the year.

The projected data using IPSL-CM6A-LR model under SSP5-8.5 for year 2025 until 2084 for each station are tested with Mann-Kendal test method to identify the significancy trend of the projected rainfall as shown in Table 3. Based on the result, all stations illustrated with significant decrement of rainfall trend based on the negative value and less than -1.645 of the Z value with confident level of 95%. In indicated that, under worst scenario (SSP5-8.5), rainfall intensity will be less from year to year after projected using the model.

Table 3. Result of Mann-Kendal test

Station No.	Station ID	Station Name	Z-value
1	2636169	Pusat Pertanian Endau	-2.26
2	2438001	Stor JPS Batu Tiga	-2.75
3	1538117	Ladang Sg. Plentong	-3.76
4	1835001	Ladang Pekan Layang-Layang	-2.46
5	1738131	Ladang Getah Malaya	-3.76

5. Conclusion

Finding from this study, there are many models that had been used in Coupled Model Intercomparison Project Phase 6 (CMIP6) that reported from Assessment Report 6 (AR6). To identify the most suitable and less uncertainty of predicted model is by downscaling method depending on the availability of historical data. In order to reduce the uncertainty of model, bias correction is applied act as calibration

IOP Conf. Series: Earth and Environmental Science **1347** (2024) 012013 doi:10.1088/1755-1315/1347/1/012013

method before procced to next analysis process. In Johor, IPSL-CM6A-LR is more suitable to use than GFDL-ESM4, MIROC6, and MRI-ESM2-0 for projection of rainfall data. Projected data by using IPSSL-CM6A-LR under SSP5-8.5 for all stations shown significantly decreasing rainfall trend for year 2025 to 2084. It indicated that, by the effect of climate change and not taking any mitigation to overcome the problem, the area that usually received more rainfall will be affected with less rain intensity for future. Extreme phenomenon like drought also can be occurred if the climate change became worst. Perhaps, this study will provide information to stakeholders such as the government agency for making decision related to water resource monitoring and development. It will help the government in management and planning the next steps to overcome the problem in future.

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Acknowledgments

This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2020/WAB02/UTHM/02/8).