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FUTURE PROJECTION OF EXTREME RAINFALL OVER MALAYSIA USING HIGHRESMIP (CMIP6) DURING BOREAL WINTER AND SUMMER

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Abstract

Climate change is known to influence the behavior of extreme precipitation and bring detrimental effects such as extreme drought, heatwaves, flooding, and storm surge. This study aims to evaluate the capability of three High Resolution Model Intercomparison Project (HighResMIP) Coupled Model Intercomparison Project Phase 6 (CMIP6) models in simulating extreme precipitation. The best model will be used for future extreme rainfall projection in Malaysia. The three models that were utilised are CMCC-CM2-VHR4, FGOALS-F3-H and MRI-AGCM3-2-S. There are three extreme indices from Expert Team on Sector Specific Climate Indices (ET-SCI) were used for evaluation. Results showed that MRI-AGCM3-2-S was the most consistent model that is able to simulate the extreme indices compared to the other models. However, this model was not efficient in simulating rainfall at high topography areas. During December-January-February (DJF) season, the eastern region received more rainfall compared to that of western part. East Malaysia, east and central Sabah are wetter compared to the central of Sarawak. In contrast, June-July-August (JJA) season experiences widespread drying in most of the study areas. The future was projected to experience less dry days with intensified rainfall that occurred in short period of time. This study in line with Sustainable Development Goals (SDG) 13 which to limit and adapt in climate action. Early warning systems and adaptive strategies can be designed based on this thorough evaluation, contributing to a sustainable approach in addressing the challenges posed by climate extremes over Malaysia.

Keywords: extreme precipitation, climate model, Southeast Asia

Introduction

An extreme by meaning is significantly different from the average or usual pattern. According to (Hijioka et al. 2014; IPCC 2012), the region of Southeast Asia is the hotspot of global warming. In Malaysia, extreme weather has increased the number of extreme events lately (AFP 2022; MMD 2019) and this country is prone to any climate change impacts due to its geographical location such as drought, land slides, heatwaves, storm surges and flash flood. The number of rainfalls received in this country is influenced by monsoonal seasons, topography areas, climate variabilities and urban heat islands (Asmat et al. 2018; Salimun et al. 2014; Tan et al. 2021; Tangang et al. 2017; Tangang et al. 2008).

Detrimental events have affected various sectors such as socioeconomic development, politics, and disruption to normal services (Tan et al 2018). The extensive flooding in southern peninsular Malaysia from December 2006 to January 2007 forced over 200,000 evacuations, caused 16 fatalities, and incurred economic losses exceeding $500 million (Tangang et al. 2008). Recently, Malaysia has lost USD1.46 billion due to flooding that hit during December 2021, according to a statement by the

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Department of Statistics (DOSM) (Bernama 2022). The amount of rain fell in Klang on a day (18th December 2021) was equivalent to the national monthly average rainfall. The event has claimed 54 lives and more than 120000 peoples were evacuated. Warmer climate may alter the atmospheric condition (IPCC 2012; Viceto et al. 2017) and intensified rainfall is expected to be occurred within a short period of time in the future (Fowler et al. 2021).

The High Resolution Model Intercomparison Project (HighResMIP) was a MIP endorsed by CMIP6. It pioneered a multi-model approach to systematically study the effects of horizontal resolution, marking the first instance of such an application (Gutjahr et al. 2019; Kodama et al. 2021; Roberts et al. 2019). Some studies were using General Circulation Models (GCM) to investigate the characteristic and magnitude of extreme precipitation over Southeast Asia (Hariadi et al. 2022; Liang et al. 2022; Liang et al. 2021) which agreed an exponential increase in trend of both precipitation and temperature. The using of higher resolution model helps analysing extreme precipitation well and provide more realistic spatial distribution pattern (Bador et al. 2020; Fu et al. 2022). Shared Socioeconomic Pathways (SSPs) are an integrated scenarios to support different research groups and assess the uncertainty in efforts to mitigate climate change and prepare for its impacts (O'neill et al. 2014). Using this framework helps in predicting the climate in future according to greenhouse gas emissions release.

Due to ambiguity in future climate, study on climate extremes using climate models is critical for early planning and mitigation. Few researches have been conducted in this country on climate uncertainties and their impact, but there are still significant gaps and unknown territory that require further investigation and attention. Thus, this study aimed to assess the accuracy of HighResMIP CMIP6 models in replicating historical extreme precipitation indices (1982-2014) in Malaysia. Additionally, this research also focuses to analyse anticipated changes in extreme precipitation over Malaysia under the high emission scenario SSP5-8.5 for future projections (2015-2050).

Materials and Methods

Malaysia is geographically demarcated into Peninsular and East Malaysia. This study broadens its geographical scope between specific coordinates, ranging between 0.5° S - 8° N latitudes and 98°E - 120°E longitudes. The daily precipitation data spanning from 1982 to 2014 were sourced from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data for observational purposes. This study exclusively analyses conditions during boreal summer (JJA) and boreal winter (DJF).

Three CMIP6-HighResMIP GCMs simulation for SSP5-8.5 scenario were used with horizontal resolution 25 km for the period of 2015 to 2050 (Table 1). Data is available at (https://esgf-node.llnl.gov/search/cmip6). This emphasizes the study focus on a comprehensive examination of climate patterns and projections within the specified geographic parameters using the selected climate simulation model.

Table 1: Institute and model names of CMIP6-HighResMIP GCMs used

Institute	Model	Shortform
Meteorological Research Institute (Japan)	MRI-AGCM3-2-S	MRI
Chinese Academy of Sciences Flexible Global Ocean-Atmosphere-Land System Model	FGOALS-f3-H	FGOALS
Centro Euro – Meiterraneo sui Cambiamenti Climatici	CMCC-CM2-VHR4	CMCC

Precipitation Extreme Indices

Table 2 showed three extreme indices used in this study, namely Consecutive Dry Days (CDD), R50mm, and Rx1day from Expert Team on Sector-Specific Climate Indices (ET-SCI) (Zhang et al. 2011). The indices can be categorised into three categories, i.e. duration, frequency and intensity indicators. Generally, CDD measures the maximum length of dry spell which it measures the length of non-rainy days. A rainy day is defined by receiving at least 1 mm of rainfall per day. Next, R50mm represents the frequency of extreme precipitation, meaning the number of days experiencing rainfall greater than 50 mm within a particular time frame. For Rx1day, the index represents maximum of daily rainfall and used as intensity indicator.

Table 2: List of ET-SCI precipitation extreme indices used in this study (Source: Zhang et al. (2011)

Index	Name	Description	Units	Indicator
CDD	Consecutive dry days	Highest number of consecutive days when precipitation < 1 mm	days	Duration
R50mm	Number of extreme precipitation days	Annual count when precipitation ≥ 50 mm	days	Frequency
Rx1day	Max 1 day precipitation amount	Monthly and annual maximum 1 day precipitation	mm	Intensity

Statistical analysis

GCM were ranked based on their ability to capture the intricate spatial patterns of precipitation using the Taylor Skill Score (TSS) (Taylor 2001). This statistical analysis diagram serves as a critical tool for conducting a comprehensive comparison between the precipitation patterns simulated by models and the observed data. The result represents the ability of the model to point out the observed spatial distribution of extreme indices in Malaysia.

Results and Discussion

Historical trend of rainfall extreme indices over Malaysia

All models were able to simulate well CDD in both seasons. The northern part of Peninsular Malaysia experienced more dry days (Figure 1a, c) compared to East Malaysia. Historically in Malaysia, the duration of dry days mostly occurred on the northern part of peninsular during DJF. During this season, east coast Peninsular experienced less day of CDD due to receiving large amount of rainfall during northeast monsoon season (Figure 1a). Two different climate zone occurred on the east coast and west coast part of the Peninsular due to Titiwangsa mountains (Wong et al. 2016).

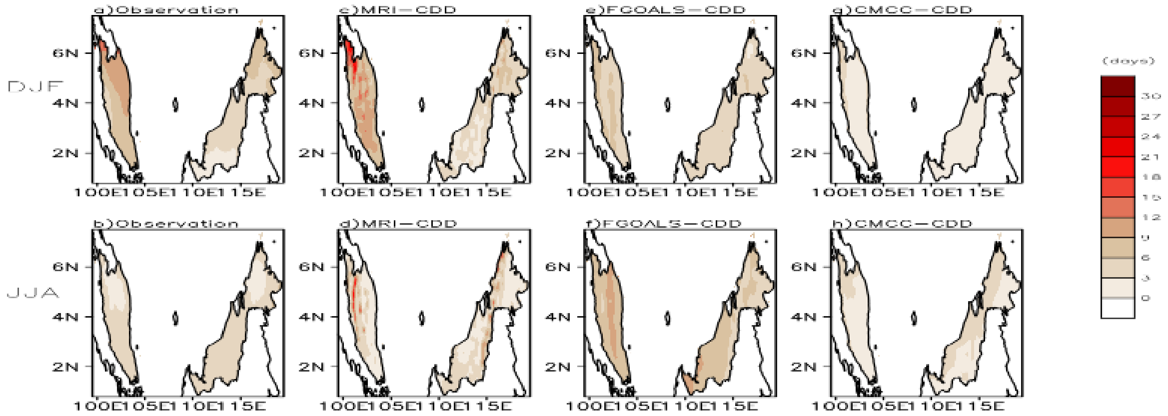

Figure 1: Spatial distribution of consecutive dry days (CDD) over Malaysia during historical period (1982-2014). Observed data from CHIRPS followed by MRI, FGOALS and CMCC of HighResMIP CMIP6 GCM. The first row represents boreal winter, DJF and second row for boreal summer, JJA. Unit: days

The whole Malaysia encountered dry condition during JJA (Figure 1b). MRI model simulated high numbers of dry days over some areas of Peninsular and Sabah (Figure 1d). FGOALS model tend to simulate more CDD (Figure 1f) compared to CMCC model (Figure 1h).

Overall, MRI model is aligning closely with observations in DJF (Figure 1c) and showed the ability to recognise higher terrain area (Titiwangsa mountains) compared to other models that underestimate the duration and spatial pattern of the CDD during DJF season. Meanwhile, CMCC excels in simulating CDD during JJA season (Figure 1h). Result is supported by statistical analysis of CDD index (Figure 2). During DJF, highest correlation showed by MRI model compared to CMCC and FGOALS (Figure 2a). Also, both FGOALS and CMCC are having less RMSE and STD. During JJA, all models performed poorly in simulating the index, with correlations close to zero (Figure 2b). The model which is closest to the observation is CMCC.

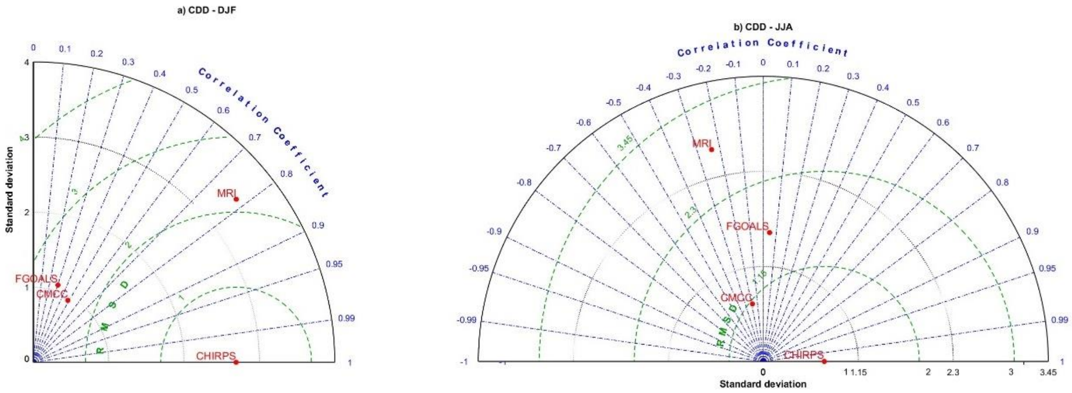

Figure 2: Taylor diagram of extreme index, Consecutive Dry Days (CDD) between the observation and the simulation of HighResMIP CMIP6 GCM during the historical day (1982-2014). First column represents DJF, and the second column represents JJA.

Figure 3 depicted the number of extreme precipitation days (R50mm) index. In general, all models are able to simulate R50mm index for both seasons. High intensity of precipitation historically occurred over the east coast of the Peninsular and northern part of Sabah during DJF (Figure 3a), while the limited number of days witnessed extreme rainfall during JJA (Figure 3b). MRI model showed the most reasonable day of R50mm, but yet to pick up the high intensity over east coast and Sabah (Figure 3c). CMCC and FGOALS are also unable to simulate well R50mm index throughout DJF season (Figure 3e, g). The results are consistent with (Amiruddin et al. 2022), who found that a high resolution model was unable to replicate the amount of rainfall during the DJF. During JJA season, less number of R50mm over the region thus indicates less extreme precipitation days happened during 1982 to 2014 period (Figure 3b, d, f, h).

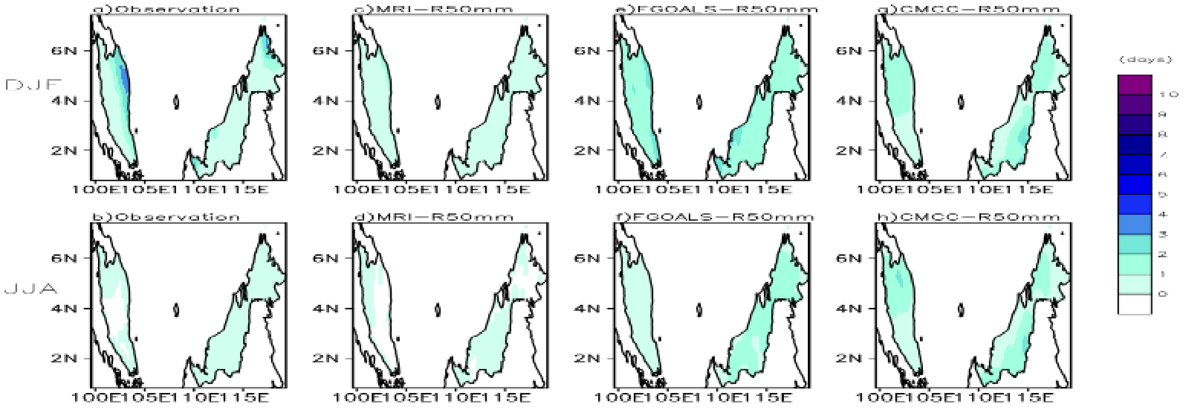

Figure 3: Spatial distribution of number of extreme precipitation days (R50mm) over Malaysia during historical period (1982-2014). Observed data from CHIRPS followed by MRI, FGOALS and CMCC of HighResMIP CMIP6 GCM. The first row represents boreal winter, DJF and second row for boreal summer, JJA. Unit: days

Even MRI model could not simulate the extreme rainfall patterns, but it can consider as the most reasonable model for R50mm index for both season (Figure 4). Figure 4a showed that MRI model has the highest correlation and low STD and RMSE whereas FGOALS and CMCC both has correlation value near to 0, high value of STD and RMSE (Figure 4a). Different conditions during JJA, although FGOALS model has the highest correlation (0.4), however MRI model is lower in STD and it RMSE is close to 0 (Figure 4b) thus making this model reasonable in evaluating the R50mm index.

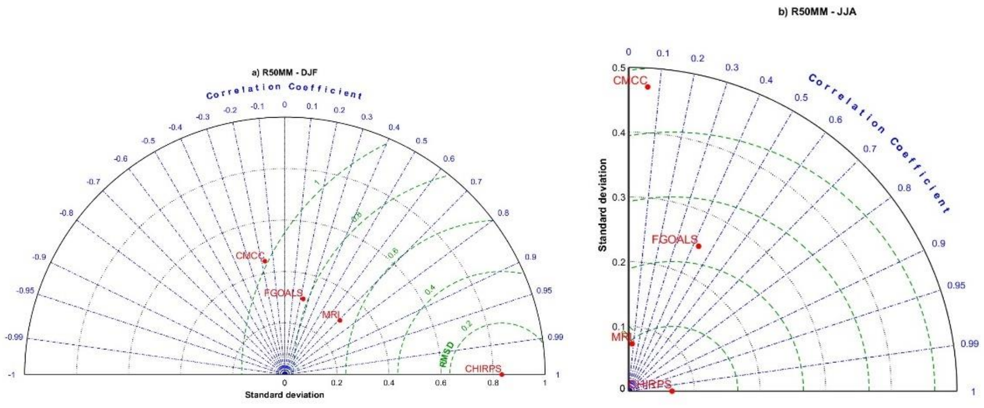

Figure 4: Taylor diagram of number of extreme precipitation days (R50mm) indices between the observation and the simulation of HighResMIP CMIP6 GCM during the historical day (1982-2014). First column represents DJF, and the second column represents JJA.

Rx1day index (Figure 5) represents total maximum precipitation in millimeter. Intensed rainfall occurred on east Peninsular, north Sabah and west Sarawak during DJF as showed in observation spatial distribution pattern (Figure 5a) but less rainfall is seen during JJA (Figure 5b). There is significant different on the east coast and west coast Peninsular during DJF (Figure 5a) which the presence of high terrain separates its condition thus creating a climate zone (Wong et al. 2016). All three models are able to simulate however both FGOALS and CMCC seems to overestimate the index as compared to that of observation (Figure 5e, f, g, h). After all, MRI model is the most reasonable model to simulate Rx1day index well (Figure 5c, d).

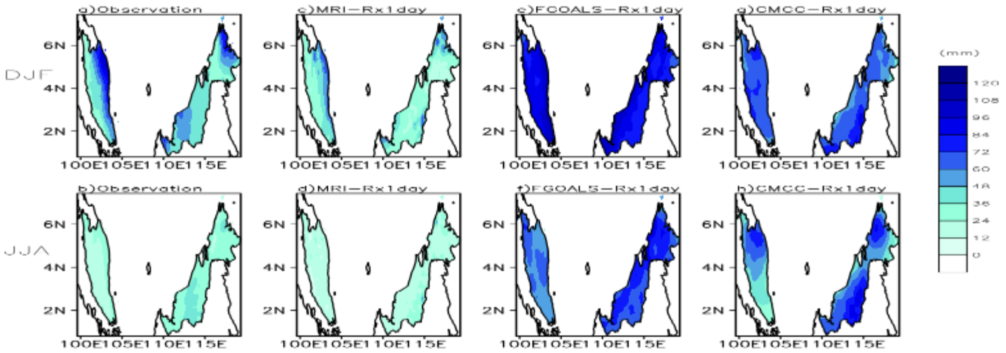

Figure 5: Spatial distribution of maximum daily precipitation amount (Rx1day) over Malaysia during historical period (1982-2014). Observed data from CHIRPS followed by MRI, FGOALS and CMCC of HighResMIP CMIP6 GCM. The first row represents boreal winter, DJF and second row for boreal summer, JJA. Unit: mm

The statistical analysis of Rx1day index agree that MRI model has the ability to perform well for both seasons (Figure 6).

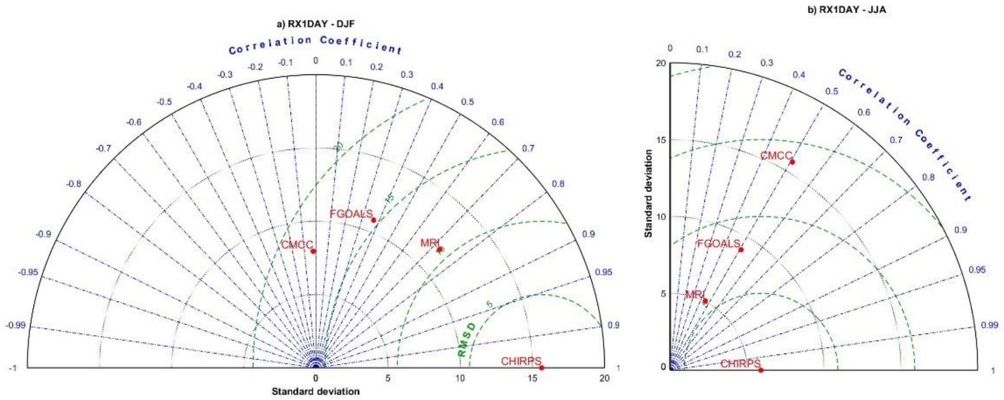

Figure 6: Spatial distribution by Taylor diagram of maximum daily precipitation amount (Rx1day) indices between the observation and the simulation of HighResMIP CMIP6 GCM during the historical day (1982-2014). First column represents DJF, and the second column represents JJA.

In conclusion, no models are good enough to simulate the spatial pattern especially the R50mm index over the east coast Peninsular and Sabah. However, for CDD and Rx1day indices, MRI model generally perform better compared to the others. It also has the capability to simulate the influence of topography ranges.

A simplified result is shown in Table 3 below. In general, MRI model is the most consistence model in simulating extreme precipitation indices during DJF and JJA. Except for CDD index which CMCC model has the lowest STD and RMSE compared to other models during JJA.

Table 3: Summary of model efficiency performance based on extreme index analysis over Malaysia for the years 1982 – 2014 using Taylor Skill Score

Model	Season	Extreme Indices		
		CDD	R50mm	Rx1day
MRI	DJF	/	/	/
	JJA		/	/
FGOALS	DJF			
	JJA			
CMCC	DJF			
	JJA	/		

In general, MRI model can perform well in calculating most of extreme precipitation indices over this region during boreal summer and boreal winter. Thus, this model is selected to simulate extreme rainfall in future projection.

Future projection and changes

The spatial distribution of the changes in precipitation extreme indices for different season based on SSP5-8.5 scenario is presented below. Only MRI model will be used for future projection due to its ability to simulate extreme precipitation better compared to the other two models.

During DJF, a decrease in CDD occurred on the northern part of the Peninsular and few small places over the region (Figure 7a). Only small part of east coast Peninsular and few places over Sarawak showed increases in day. Compared to historical analysis (Figure 1a), the rainy conditions during this season over east coast of Peninsular will decrease due to the increasing number of CDD in the future. For JJA, some places showed increases while some areas showed decreases of CDD (Figure 7b). Only small areas showed more decreases of CDD. In general, CDD is projected to decrease during DJF over this region meanwhile some areas will facing drier and wetter conditions during JJA. Previous study has showed that Maritime Continent (MC) is projected to increase 60% in CDD at the end of 21st century (2081-2100) under RCP8.5 (Supari et al. 2020).

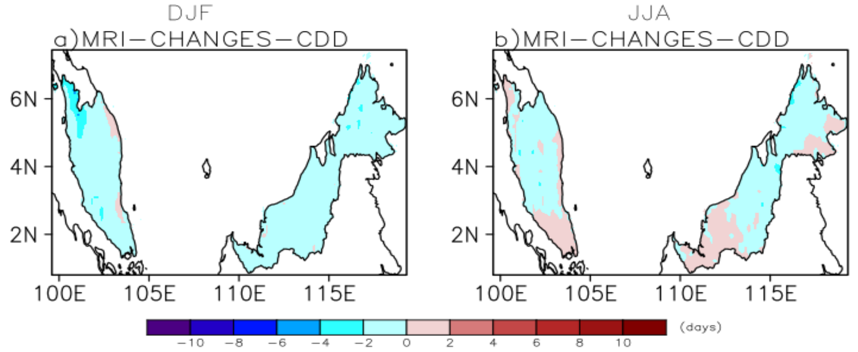

Figure 7: The projected changes of extreme index, CDD at the near century (2015-2050) relative to the present day under SSP5-8.5 scenarios for (a) DJF and (b) JJA using MRI model. Unit: days

For the number of extreme precipitation days, R50mm projected that some areas are wet and some areas are dry for both seasons (Figure 8a, b). The east coast part of the Peninsular which usually receive rainfall during DJF will experience less frequency of days receiving rainfall more than 50 mm. Rainfall is projected to decrease ~20 - 40% during boreal winter and increase during summer months over Malaysia (Loh et al. 2016) according to The Providing Regional Climates for Impacts Studies (PRECIS) model.

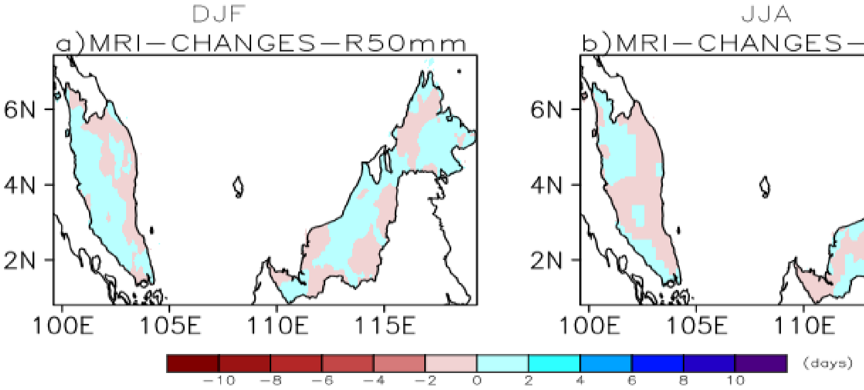

Figure 8: The projected changes of number of extreme precipitation days, (R50mm) relative to the present day under SSP5-8.5 scenarios for (a) DJF and (b) JJA. Unit: days

This in line with Clausius-Clayperon relation, which stated that the increment of precipitation up to 7% per degree warming temperature. Elevated surface temperatures stimulate intensified rainfall, illustrating the interconnected dynamics between temperature shifts and increased precipitation according to this fundamental thermodynamic principle. (Utsumi et al. 2011; Wasko et al. 2018).

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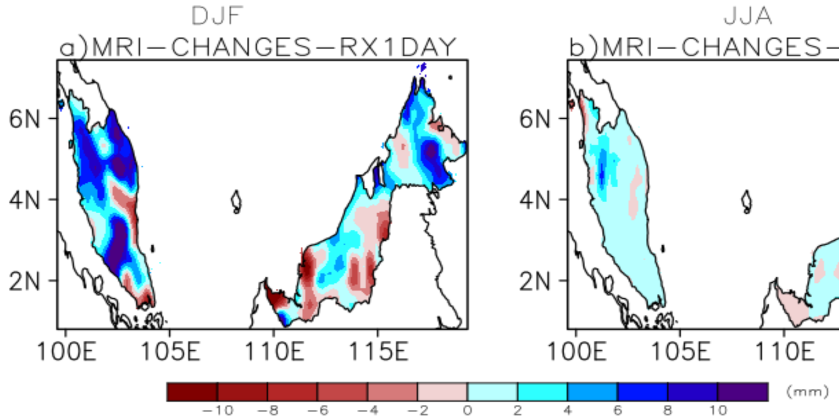

Figure 9: The projected changes of maximum one day precipitation amount, (Rx1day) relative to the present day under SSP5-8.5 scenarios for (a) DJF and (b) JJA. Unit: mm

The findings are consistent with previous study regarding the future concerns this country will encounter regardless of the scenario applied. There is higher probability of rainfall extreme occurring over the west coast of Peninsular during the autumn transitional monsoon period and early monsoon rainfall is expected to occur over East Malaysia (Kwan et al. 2013; Sa'adi et al. 2017). During the northeast monsoon, the whole entire Peninsular is projected to experience a notable rise in the extreme precipitation rate in future (Liang et al. 2022). This phenomenon may lead to future extreme events to happened for both hourly and 24 hours timescale (Abdul Halim et al. 2017). Study by Supari et al. (2020) over Southeast Asia agree on the significant changes on CDD during JJA and the increasing trend of R50mm and Rx1day extreme indices. Overall, the future is projected to have more frequent days of intensified rainfall which will occur within a short period of time.

Conclusion

This research focuses on simulating extreme rainfall distribution over Malaysia for historical climate (1982-2014) and projected future changes (2015-2050) using HighResMIP CMIP6 GCM under SSP5-8.5 scenario. The output derived from CMCC-CM2-VHR4, FGOALS-F3-H and MRI-AGCM3-2-S models was utilized to simulate three extreme precipitation indicators from ET-SCI, namely CDD, R50mm, and Rx1day. The Taylor Skill Score (TSS) statistical approach was applied to evaluate model performance against the observed data.

Generally, all three models are able to simulate the extreme indices during DJF and JJA. However, the MRI model had the most consistency in simulating all indices for both seasons. The statistical analysis complied with the assessment by showing a strong correlation, lower STD and RMSE, hence this model has been selected to generate projection for the future. Nevertheless, MRI model has struggle capturing extreme rainfall over east coast during DJF.

Robust changes are projected over this country. The duration (CDD) index is projected to decrease while R50mm (frequency) and Rx1day (intensity) showed increasing during DJF, thus concluded that a high intensity of rainfall will occur within short period of time during this season. In terms of JJA, future changes demonstrate drier weather throughout this period, which is opposite the pattern of the DJF season. The spatial distribution pattern of future projections indicated variations over this country, emphasizing that it will not be spared from the effects of climate change.

Future studies should include variables such as temperature, wind, omega, and relative humidity to have a better understanding of the mechanism driving climate change in this country. Furthermore, there are fewer publications on weather-related studies across East Malaysia (Sabah and Sarawak) than in the Peninsular. A full overview of this country is difficult to do due to lack of information, complex topography and effect varies depending on seasons. The utilization of higher resolution data for impact assessment studies should be expanded that covers the entire country.

The findings have the potential to improve our understanding of future climate change and the uncertainty surrounding this country. Integrated cooperation from all agencies is required to combat fluctuations and make this nation more resilient to climate change.

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Declaration of Interest Statement

The authors declare no conflict of interests.

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