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DEVELOPMENT OF REGIONAL CLIMATE MODEL (RCM) FOR CAMERON HIGHLANDS BASED ON REPRESENTATIVE CONCENTRATION PATHWAYS (RCP) 4.5 AND 8.5

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ABSTRACT

The development of the local climate is important for climate hazard assessment. Cameron Highlands (longitude from 101° 21' to 101° 30' and latitude from 4° 19' to 4° 37') were chosen as the study area for climate downscaling. This paper presents the work of downscaling techniques and regional climate model (RCM) development. The second-generation Canadian Earth System Model (CanESM2) based on representative concentration pathways (RCPs) 4.5 and 8.5 was applied to develop the local climate model for the 2020-2100 period. The climatic parameters chosen were temperature (maximum and minimum) and rainfall. The simulated RCMs are then analyzed using statistical reliability, including the Pearson correlation coefficient, linear regression, root mean square error (RMSE) and probability density function (PDF). The results showed that the simulated maximum and minimum temperatures and rainfall are most likely to follow the RCP8.5 scenario. The precipitation threshold for the occurrence of flash flood events was estimated using the intensity duration frequency (IDF) relationship generated by maximum precipitation. A return period of two years and four hours of rainfall duration is used for threshold estimation because the rainfall is convective. The daily rainfall threshold for flood occurrence is estimated to be 11.3 mm/hr.

Keywords: Statistical Downscaling, Temperature, Precipitation, Climate hazard assessment, Flash flood threshold.

INTRODUCTION

Climate change is a challenging environmental issue worldwide, and it has become serious in recent decades (Kouassi et al., 2013; Thabet, 2018; Choukrani et al., 2018; Remini, 2020, Assemian et al., 2021). Previous studies have proven that anthropogenic activities are the main contributor to climate change because they rapidly increase greenhouse gas concentrations in the atmosphere and disturb the energy balance (Wolff et al., 2020). Many studies have been conducted to study the response of the global climate to increasing greenhouse gas (GHG) concentrations by general circulation models (GCMs) (Tan and Loh, 2017). However, GCMs are not suitable for use in the study of local climate due to the coarse resolution of the models.

A statistical downscaling model (SDSM) was used in this study to downscale the GCM into a regional climate model (RCM) in the Cameron Highlands based on representative concentration pathways (RCPs) 4.5 and 8.5. It is a two-step process consisting of i) the development of statistical relationships between large-scale predictors and regional climate variables (predictands) and ii) the application of statistical relationships established to the output of GCMs to simulate local climate characteristics in the future (Wilby and Dawson, 2007). Downscaled RCMs with higher resolution could be used for climate impact assessments because they are able to realistically simulate regional climate features.

Among all natural disasters, floods are the most concerning disasters in tropical countries such as Malaysia. Floods in Malaysia are mainly monsoon floods and flash floods. Factors that cause monsoon floods are the seasonal wind flow patterns during the Southwest Monsoon and Northeast Monsoon and the local topographic features, whereas flash flood factors are the rainfall intensity and duration. Flash floods usually occur on smaller scales, such as areas with rapid development. They are extremely destructive and difficult to prepare because flash floods can occur within short periods, from minutes to hours (Buslima et al., 2018). Therefore, flood analysis should be considered in rapidly developing areas.

MATERIALS AND METHODS

Background of study area

Cameron Highlands (Fig. 1) is the smallest district of Pahang state in Peninsular Malaysia. The area is bounded between longitude from 101°21' to 101°30' and latitude from 4°19' to 4°37' with an average elevation of approximately 1829 m above sea level (Gasim et al., 2009). The income of Cameron Highlands is mainly dependent on agriculture because its tropical climate is suitable for planting highland crops, including vegetables (50%), tea (40%), flowers (7%) and fruits (2%) (Aminuddin et al., 2005). Cameron Highlands cover an area of approximately 710 km^2 with a total population of approximately 35000 (CHDC, 2016).

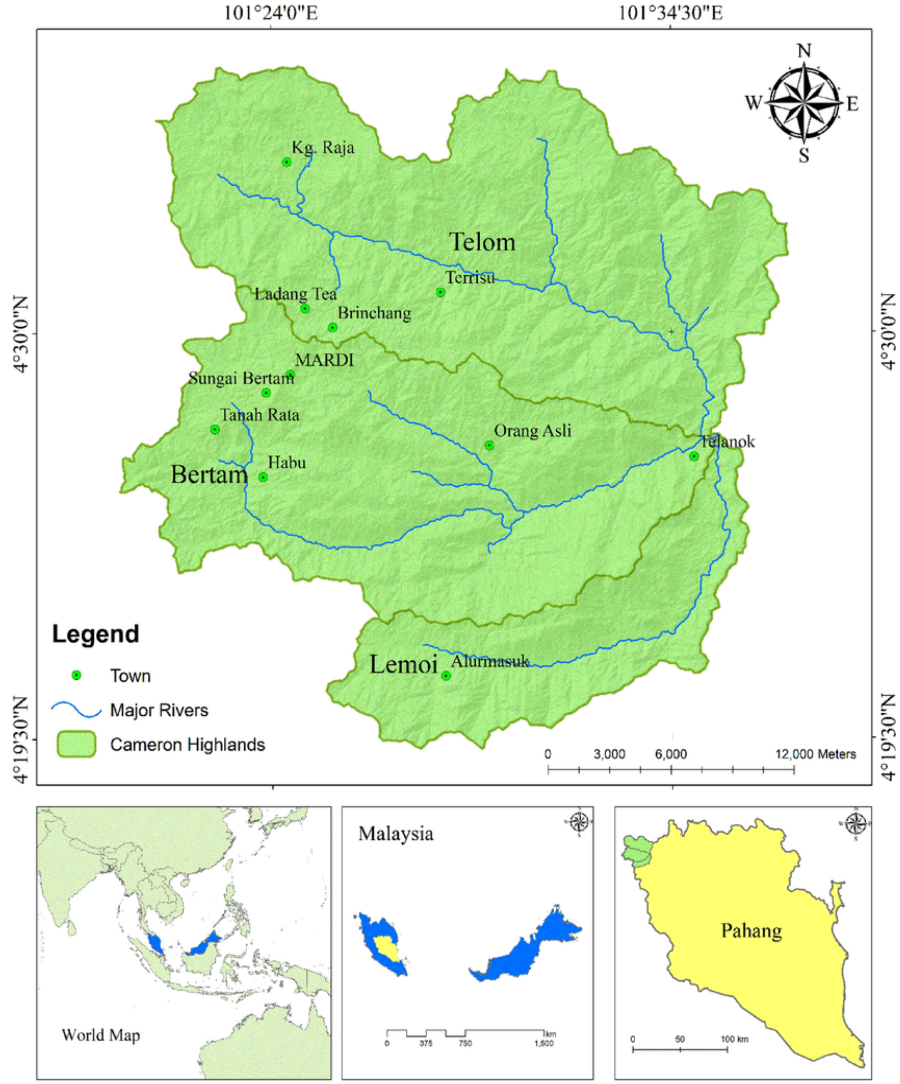

Figure 1: Location of Cameron Highlands (Nasidi et al., 2021)

According to the Malaysian Meteorological Department (MMD), the average temperature of the area is 19.4 °C, ranging from 15.0 °C to 25.4 °C (MMD, 2014). The average monthly rainfall is recorded as 230.9 mm, with maximum and minimum daily rainfall of 463.2 mm and 80.6 mm, respectively. The highest number of rainy days recorded in a month is 29 days (MetMalaysia, 2013). The recent severe flood recorded in the Cameron Highlands was a mud flood in October 2013 when excess water was released from the Sultan Abu Bakar Dam in Ringlet following continuous heavy rain. The flood caused three deaths, and approximately 80 houses were swept away (Baharuddin et al., 1996). In November of the next year, another mud flood occurred again in the same area. The flood swept away more than 20 houses in Ringlet town, Ringlet new village, Kampung Ulu Merah Ringlet and Bertam Valley, which were submerged in knee-deep flood waters. Three people died by heavy downpours, and approximately 90 victims from 28 families were evacuated (Kaur, 2013).

Figure 2: CanESM2 GCM data (Government of Canada, 2021).

Data collection

The GCM used was the second-generation Canadian Earth System Model (CanESM2) (Fig. 2), which could be retrieved online via the website of the government of Canada. The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data (predictors) were downloaded together with the GCM. Secondary data were used as predictands and for climate hazard assessment for the study area. Furthermore, flood reports for Cameron Highlands were obtained from the Department of Irrigation and Drainage for climate hazard assessment. Data and information collected from relevant departments and institutions are tabulated in Table 1.

Table 1: Sources of secondary data

Department	Specification of data and information
CanESM2	An atmosphere-ocean general circulation model, associated with 26 predictors. It was downscaled to Regional Climate Model (RCM) based on station data obtained from Malaysian Meteorological Department (MMD).
Malaysian Meteorological Department (MMD)	Daily climate data such as maximum temperature and minimum temperature in degree Celsius (°C) 1983 to 2018, daily rainfall amount in millimeters (mm) from 1983 to 2015. It was used to select the CanESM2 predictors used for downscaling work.
Drainage and Irrigation Department (DID) of Cameron Highlands	Flood events record for Cameron Highlands. Information such as rainfall intensity and rainfall depth were obtained from the record.

In this study, the maximum temperature (Tmax), minimum temperature (Tmin) and rainfall were downscaled based on GCM-CanESM2. Statistical downscaling model (SDSM) version 4.2 was used for the downscaling work. Treated data were subjected to quality control to ensure that there were no missing data or suspect values. The defective daily observed data of maximum and minimum temperature were calculated as 0.09% with the longest of three consecutive days. The defective data were treated and replaced by the average temperature of the corresponding month. For daily observed data of rainfall, 0.7% of data were recorded as trace values in which the rainfall amount was less than 0.1 mm. Trace values were treated as no rainfall on particular days. Screening variables were required to eliminate irrelevant predictors before model calibration. A calibrated model was used to generate the historical RCM and projected RCM in the weather generator and scenario generator functions, respectively. The downscaled RCM period was 2006-2100 based on RCP 4.5 and 8.5. Historical RCM could be used to replace the missing observed data, whereas projected RCM was used to study the future climate trend and then further used for climate hazard assessment. Finally, the RCMs generated could be analyzed in summary statistics according to the period desired, and the results were briefly presented in the comparison results function by a line graph or bar chart. The experimental setup for statistical downscaling (SDSM) works was followed as shown in Table 2.

Since the future climate generated from Scenario Generator could not be generated for Day 29th of February in the leap year, assumptions were made to treat the dataset in February of every leap year (2006-2100). For the maximum and minimum temperatures, the 29th of February was replaced by the average temperature one day before and after. It was assumed that the temperature did not significantly vary throughout the year. Based on the MMD rainfall record, January-March was recorded as the driest period, and it was assumed that there was zero rainfall for that particular day.

Table 2: List of settings/advanced settings adjusted during downscaling work

Parameters	Temperature	Rainfall
	Calibrate Model	
Threshold	0	1
Model Transformation	None	Fourth Root
Optimization Algorithm	Dual Simplex	Ordinary Least Square
Process	Unconditional	Conditional
	Scenario Generator	
Year Length	365 (GCM)	365 (GCM)

Reliability assessment

Pearson correlation and linear regression are used to establish a relationship between the observed data and generated RCM. The r value of the Pearson correlation coefficient can be classified as $0.2 \leq |r|$ as a weak relationship, $0.4 \leq |r|$ as a moderate relationship, $0.6 \leq |r|$ as a strong relationship, and $0.8 \leq |r|$ as a very strong relationship (Campbell, 2013). Linear regression is the square of the r value, which can be obtained by plotting a scatter plot. A value closer to 1.0 indicates a stronger relationship, and a value closer to zero indicates a weak relationship between the observed data and generated RCM. The root mean square error (RMSE) is used to calculate the difference between the observed data and the downscaled RCM (Sreehari and Pradeep Ghantasala, 2019). A probability density function (PDF) curve is generated by using the mean and standard deviation, and values closer to the observation are chosen as the local climate model (Bartlett, 2018). Overall, the simulated model was chosen based on the level of correlations to the observation parameters.

Rainfall intensity-duration-frequency (IDF) relationship

In this study, the only data available for flood threshold prediction are the daily rainfall of the Cameron Highlands. Therefore, daily rainfall data from Cameron Highlands from 1983 to 2016 were used in the analysis. First, the maximum daily rainfall from each year was extracted. Then, the maximum annual rainfall was used to estimate various rainfall durations using an empirical reduction formula including 5 minutes, 10 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, 6 hours, 12 hours and 24 hours (Rasel and Islam 2019). The equation used for short duration rainfall estimation is as follows:

$$P_t = P_{24} \sqrt[3]{\frac{t}{24}} \tag{1}$$

where P_t is the rainfall depth in mm at duration t in hours, P_{24} is the daily rainfall in mm and t is the duration of rainfall in hours for which the rainfall depth is needed.

The estimated rainfall depths were converted into rainfall intensity by dividing by their corresponding rainfall duration. Then, the sample mean and standard deviation for the estimated rainfall intensity at different durations were calculated using the following equations:

$$P_{ave} = \frac{1}{n} \sum_{i=1}^{n} P_i \tag{2}$$

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(P_i - P_{ave} \right)^2} \tag{3}$$

where P_{ave} is the average rainfall corresponding to a specific rainfall duration, P_i is the estimated rainfall intensity of an individual year and n represents the number of years.

The Gumbel extreme value type I distribution is used in the study of maximum extreme precipitation. The frequency of rainfall for each rainfall duration with a specified return period (T), including 2 years, 5 years, 10 years, 50 years and 100 years, was calculated by the following equation:

$$P_T = P_{ave} + K_T\, S \tag{4}$$

where P_T is the frequency of rainfall in mm and K_T is the Gumbel frequency factor. K_T can be calculated by applying the following equations:

$$K_T = -\frac{\sqrt{6}}{\pi} \left(0.5772 + \ln \ln \left[\frac{T}{T-1} \right] \right)^{-1} \tag{5}$$

where T is the specified return period in years.

Estimation of flood threshold

The flood threshold is estimated by using the IDF generated by the annual maximum rainfall. According to the National Oceanic and Atmospheric Administration (NOAA), flooding that begins within six hours of heavy rainfall is considered a flash flood (NOAA, 2021). However, according to the Department of Irrigation and Drainage, rainfall in Malaysia is convective, and therefore, flash floods can occur within four hours (DID, 2021). When the rainfall duration is known, then the rainfall intensity and rainfall depth can be calculated using equations of different return periods.

RESULTS AND DISCUSSION

Based on multiple regression analysis, different sets of NCEP/NCAR predictors were shortlisted, as shown Table 3. These selected predictors have no statistically significant difference ($p < 0.05$) with station data, which is suitable for RCM development. The RCM (2006-2100) based on RCP4.5 and 8.5 was developed for Tmin, Tmax and precipitation. As shown in Table 4, the reliability test outcomes show that the downscaled RCMs of T_{max} have a strong relationship ($r = 0.633$, $R^2 = 0.400$) in RCP 4.5 and a moderate relationship ($r = 0.598$, $R^2 = 0.357$) in RCP 8.5 with the observed data.

For T_{min}, both the downscaled models in RCP 4.5 ($r = 0.585$, $R^2 = 0.342$) and RCP 8.5 ($r= 0.578$, $R^2 = 0.334$) have a moderate relationship with the observed data. For precipitation, both the downscaled models in RCP 4.5 ($r = 0.515$, $R^2 = 0.265$) and RCP 8.5 ($r = 0.523$, $R^2 = 0.274$) have a moderate relationship with the observed data. In addition, the downscaled model for T_{max} has a smaller RMSE (0.694 °C) in RCP 4.5, whereas for T_{min} (0.583 °C) and rainfall (102.0 mm), a smaller RMSE appears in RCP 8.5.

Table 3: Predictors selected for T_{max}, T_{min} and precipitation

Parameters	Predictors	Description
Maximum Temperature, Tmax	p8zhgl	850hPa Divergence of true wind
	prcpgl	Total Precipitation
	s500gl	500hPa Specific humidity
	s850gl	850hPa Specific humidity
	shumgl	1000hPa Specific humidity
Minimum Temperature, Tmin.	p1_fgl	1000hPa Wind speed
	p8_fgl	850hPa Wind speed
	tempgl	Air temperature at 2 m
Precipitation	p8zhgl	850hPa Divergence of true wind
	prcpgl	Total Precipitation
	s500gl	500hPa Specific humidity
	s850gl	850hPa Specific humidity
	humgl	1000hPa Specific humidity

Table 4: Results summary of reliability tests

Parameters	T_{max} (°C)		T_{min} (°C)		Rainfall (mm)	
RCP	4.5	8.5	4.5	8.5	4.5	8.5
Pearson Correlation Coefficient (r)	0.633	0.598	0.585	0.578	0.515	0.523
Linear Regression (R^2)	0.400	0.357	0.342	0.334	0.265	0.274
RMSE	0.694	0.756	0.585	0.583	102.1	102.0

The probability density function shows a slight shift to the right with a higher monthly average of T_{max} in the Cameron Highlands, and RCP 4.5 has a standard deviation closer to the observed T_{max} (Fig. 3). In addition, T_{min} and rainfall shifted to the left with lower monthly averages (Fig. 4 and Fig. 5). RCP 8.5 of both parameters has a closer standard deviation to the observed standard deviation compared to RCP 4.5. The strength of the relationships of the Pearson correlation coefficient are categorized as weak: $0.2 \leq |r| < 0.4$; moderate: $0.41 \leq |r| < 0.6$; strong: $0.61 \leq |r| < 0.8$ and very strong: $0.81 \leq |r|$. All reliability tests show that RCP 4.5 has a relationship and is better fitted to the observed data. For T_{min} and precipitation, the RCP 4.5 models have r values slightly higher than those of the RCP 8.5 model. However, the simulated models are both categorized as having a moderate relationship ($0.4 \leq r < 0.6$). However, a smaller RMSE and closer mean and standard deviation to the observed data are found in the RCP 8.5 model. Therefore, the RCP 8.5 scenario is selected for the T_{max}, T_{min} and rainfall models (2006-2100).

The downscaled models are satisfactory since the trend is similar to the observed data in most of the months except September for T_{max} and January and November for rainfall (Figs. 6 to 8). The selected model for each parameter is compared for the period from 2006 to 2015, as shown in Fig. 9. The trend shows that rainfall increases with temperature. The future climate for T_{max}, T_{min} and rainfall is projected based on RCP 8.5 (Figs. 10 to 12), and the changes in 2100 were estimated using equations as shown in the respective Figures. T_{max} and T_{min} are estimated to increase by 0.90 °C and 0.10 °C, respectively. However, annual precipitation is not very different (+34.2 mm) but shows an increasing trend in 2100 compared to 2020.

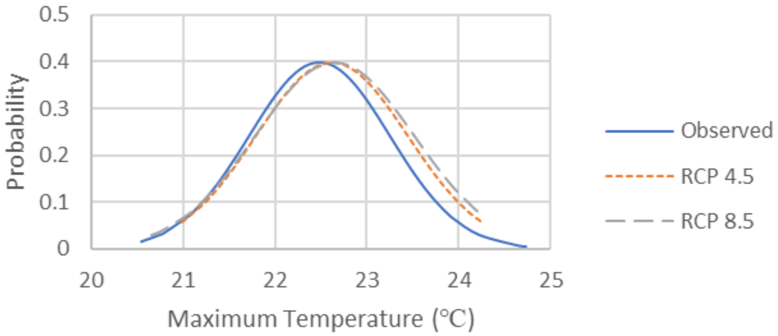

Figure 3: Probability density function of RCPs and observed maximum temperature

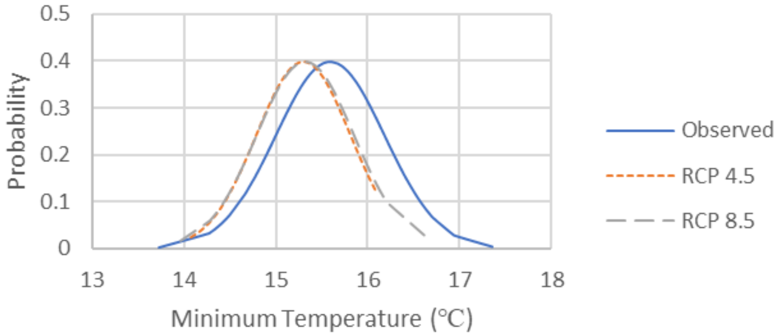

Figure 4: Probability density function of RCPs and observed minimum temperature

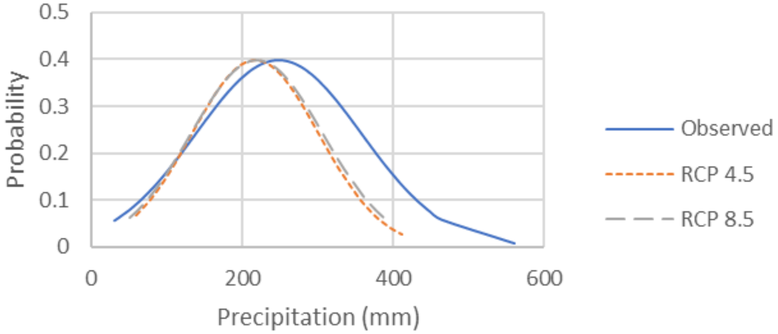

Figure 5: Probability density function of RCPs and observed precipitation

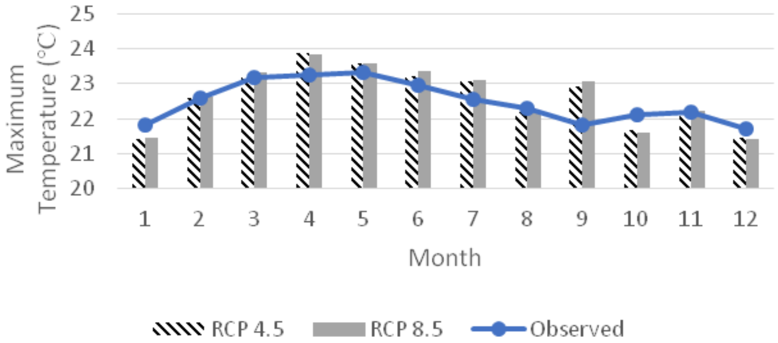

Figure 6: Monthly average from 2006 to 2018 for maximum temperature

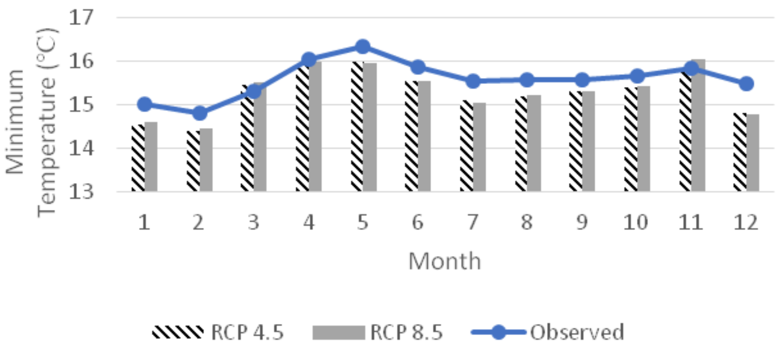

Figure 7: Monthly average from 2006 to 2018 for minimum temperature

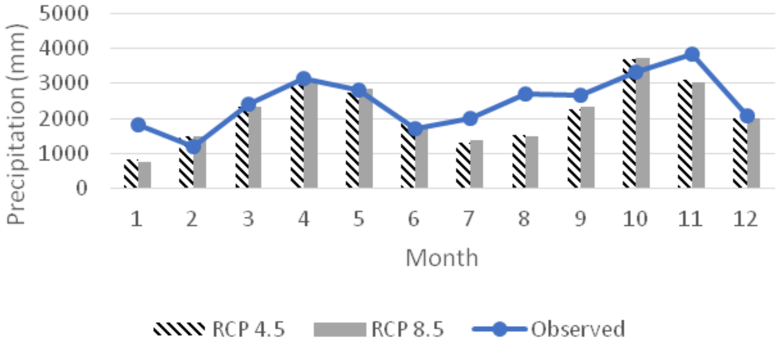

Figure 8: Monthly average from 2006 to 2015 for rainfall

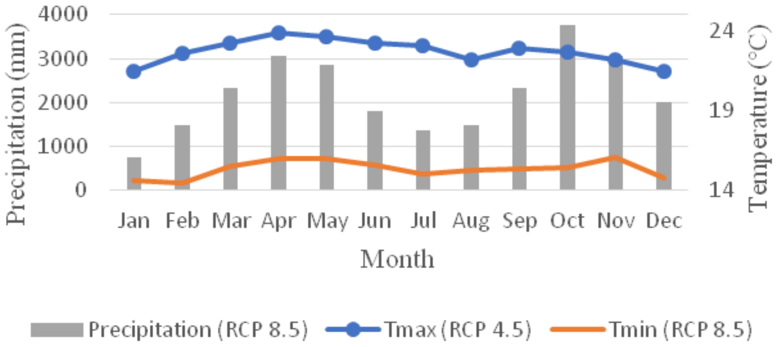

Figure 9: Comparison of monthly temperature and rainfall from 2006 to 2015 based on RCP 8.5 Models

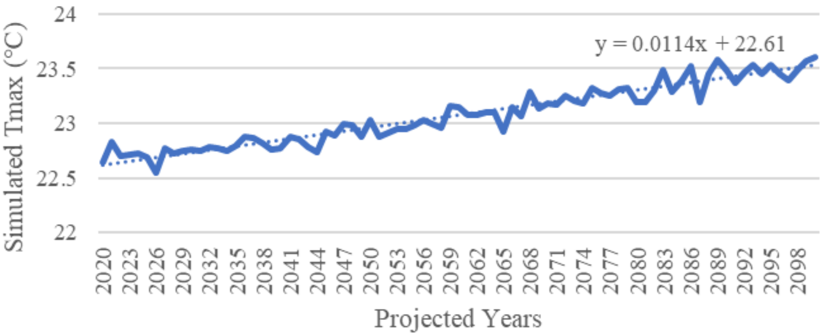

Figure 10: Projected future maximum temperature from 2020 to 2100

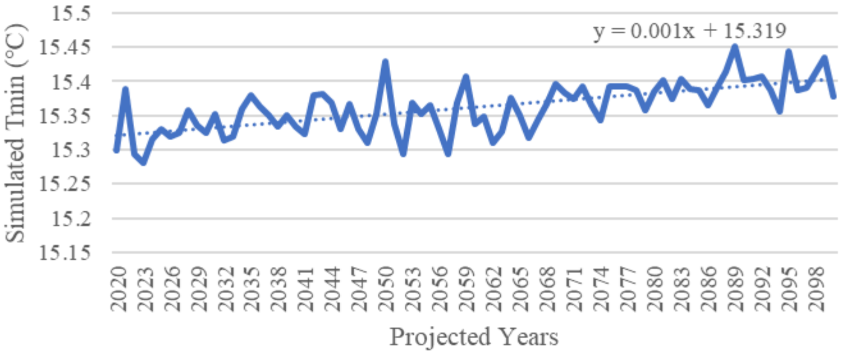

Figure 11: Projected future minimum temperature from 2020 to 2100

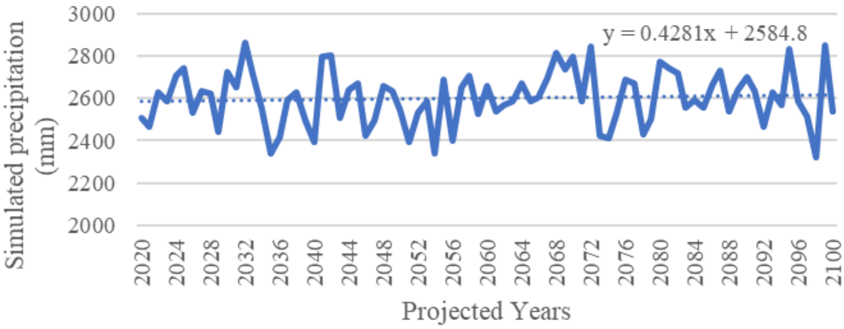

Figure 12: Projected future precipitation from 2020 to 2100

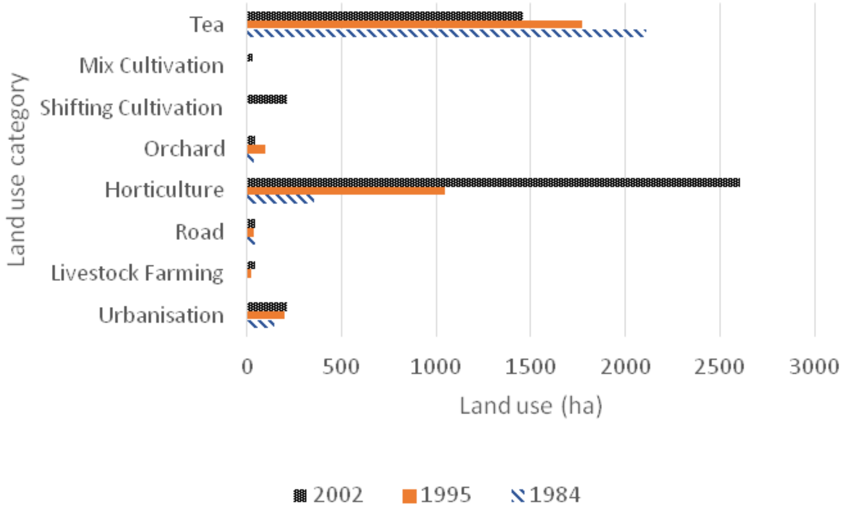

Figure 13: Land Use Change of Different Categories from 1984 to 2002 in Cameron Highlands (Modified from Gasim et al 2010)

Local climate change in Cameron Highlands is mostly due to land use change, as shown in Fig. 13. Total land use has increased from 180 hectares (ha) in 1984 to more than 300 ha in 2002 for development, whereas land use for agriculture activities increased from approximately 2,500 ha to more than 4,000 ha. Urbanization and agricultural activities, especially horticulture and tea plantation, significantly contribute to local carbon dioxide emissions. As presented in Fig. 13. Land clearing and deforestation also progressed intensively for agricultural activities in early years and eventually turned to neglected areas (approximately 5,000 ha) after harvesting the products (Gasim et al. 2010). Intensified deforestation has had negative impacts and altered the ecological function of forests, such as carbon and hydrological cycles. Deforestation lowers the input of water to the atmosphere through evapotranspiration and eventually reduces the precipitation recycling process (Empidi and Emang 2021). Therefore, increased temperature does not necessarily cause more precipitation, but it is possible for drought to occur in some cases.

Flood threshold estimation

Rainfall intensity and rainfall duration are used to plot the IDF curve, and both scales are set to a logarithmic scale to obtain a linear relationship. Fig. 14 shows the rainfall IDF curve of the Cameron Highlands. To estimate the rainfall threshold for the occurrence of flood events, a two-year return period and a four-hour rainfall duration are chosen for the estimation. The result obtained is 11.3 mm/hr. There are a total of 12 flash floods reported in the past, and the sensitivity of flash floods occurring above the estimated threshold is 83.3%. The remaining two flood events, which occurred with rainfall intensities lower than 11.3 mm/hr, could be due to saturated soil moisture. The occurrence of antecedent floods and consecutive rain could increase the soil moisture. An increase in soil moisture eventually leads to higher direct runoff, and floods are triggered with lower rainfall intensity. According to the DID flood reports, these flood events below the threshold are probably due to the occurrence of antecedent floods in the same month. A flood event in April with a rainfall intensity of 10 mm/hr had an antecedent flood three days before. Furthermore, another flood occurred with a rainfall intensity of 6.4 mm/hr during the Northeast monsoon season (November). Hence, there is also a possibility that rainfall for a few consecutive days causes floods to occur at such low intensities.

To determine the monthly rainfall threshold for floods, the number of rainfall days in the Cameron Highlands was calculated from the observed rainfall data. From the entire length of MMD rainfall record, the average monthly rainfall days from 1984 to 2015 is 21 days. Hence, the daily rainfall threshold is then multiplied by 21 days to estimate the monthly rainfall threshold in the simulated RCP8.5 model, as shown in Fig. 15. The estimated monthly rainfall above 237.3 mm has a possibility of flood occurrence. Then, the average number of rainfall days in the driest month (January) was also calculated as 16 days. The daily threshold is then multiplied by 16 days, and the result is 180.8 mm/month. This value acts as the warning level of flood occurrence.

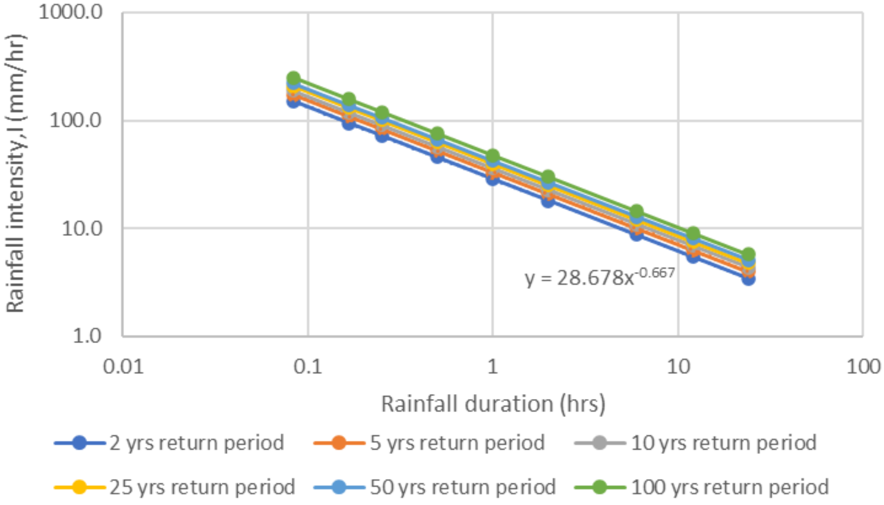

Figure 14: Rainfall IDF relationship in Cameron Highlands

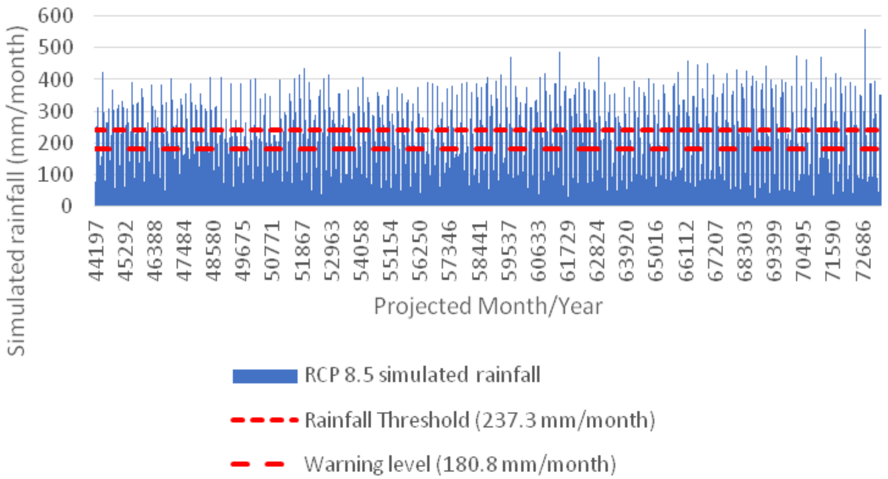

Figure 15: Projected months with flood reoccurrence

CONCLUSION

In conclusion, a regional climate model (RCM) based on RCP 4.5 and 8.5 was developed in this study. The T_{max}, T_{min}, and rainfall future trends are likely to follow the RCP 8.5 scenario. The projected monthly average rainfall in Cameron Highlands decreases as the maximum temperature increases. This could be due to the rapid development in Cameron Highlands. Land use for different purposes increases the local GHG concentration and eventually leads to warming effects. In addition, there is no drought recorded previously; however, a decrease in monthly average rainfall gives a signal that there is a possibility of drought occurrence in the future. Therefore, the community should be alert and prepare for floods and droughts.

SDSM is recommended for downscaling work because its performance in simulating climate models is satisfactory. Different scenarios, such as RCP 2.6 and RCP 6.0, should be applied in the Cameron Highlands to study the future climate, as the safety of the local community and agricultural activities are highly dependent on precipitation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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