〈論文〉

Future Changes in Watershed-scale Rainfall Characteristics

―― Application of AGCM20 to the Johor River Watershed, Malaysia ――

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Abstract

This research introduced a super-high-resolution atmospheric model, AGCM20, to the Johor River Watershed in Malaysia to analyze future changes in rainfall characteristics, that is, annual, monthly, daily, and extreme rainfalls. The comparative analyses of the rainfall characteristics between the control (1979-2003) and future (2075-2099) periods clarified that more severe rainfall events would occur in the Northeast monsoon season. Moreover, there is a possibility that the onset of the Northeast monsoon season would become earlier and the intensity of rainfall events becomes quite higher among the decreased number of wet days. With regards to anticipated changes in extreme rainfall, the frequency of severe rainfall events would increase ; it was estimated that the return period for the current 100-year event corresponds to 2.4 years in the future. The findings obtained from the AGCM20 outputs will be beneficial to construct the proper watershed management systems that consider the impacts of climate change.

Keyword : AGCM20, rainfall characteristics, climate change, Johor River Watershed

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1. Introduction

In Malaysia, flooding is one of the major disasters occurring almost every year during two major monsoon seasons : the Southwest (SW), which runs from May to September, and the Northeast (NE), which runs from November to March. Most of the watersheds in Malaysia are affected by these monsoon climatic characteristics[1,2)], and the Johor River Watershed—the target area of this research—is one of the most vulnerable areas to floods caused by the NE monsoonal rainfall. To date, climate change has been a concern to people because of its unpredictable impacts on water resources. The situation of watershed hydrology has been changed, particularly with regard to rainfall characteristics such as amount, intensity, and pattern, in a time of climate change in Malaysia.

Recently, general circulation models (GCMs) have been used as the primary approach to simulate future projections of global climate and its changes by modeling global atmospheric and oceanic circulations. In Peninsular Malaysia, for example, it was predicted by GCMs that the monthly rainfall amount will increase in the NE monsoon season, even though the future average amount of annual rainfall will not be much different from now. In addition, the wet spell will become relatively short in the NE monsoon season[3,4)] ; thus, rainfall intensity will be higher when it rains in the NE monsoon season. These studies have demonstrated how GCMs can be used for assessing future changes in rainfall characteristics. However, the conventional GCMs' spatial operating scale is still coarse (e. g., grid size of 200-250 km) ; thus, some difficulties still remain for assessing the water resource problems such as a flood that usually occur on a regional scale (e. g., watersheds). In general, GCMs are downscaled by regional climate models (RCMs) or statistical methods to bridge the gaps of spatial resolution between GCMs and hydrologic usages. On the other hand, a cascade of uncertainty is one of the concerns for modelers and users when GCMs are downscaled by any methods[5)].

Since extreme events usually occur on a regional scale, it is necessary to analyze the impacts of climate change on regional climatology by GCMs. Therefore, this research introduced a super-high-resolution atmospheric model, AGCM20, to the Johor River Watershed in Malaysia in order to evaluate future changes in watershed-scale rainfall characteristics. Since AGCM20 has finer spatial resolution (20 km) than conventional GCMs, it does not require further regional downscaling. Moreover, AGCM20 can simulate local water cycles, such as the regional scale or watershed scale[6,7,8,9], and it enables us to assess extreme events occurring in shorter timescales, such as hourly or daily. As of now, there have been a few application studies of AGCM20 in Southeast Asia. For example, the future increases in mean and extreme precipitation were projected over Asia using the AGCM20 outputs for the future period[10]. However, the study did not apply the AGCM20 outputs for any watershedscale hydrologic analyses. Although watersheds in Southeast Asia are vulnerable to climate change, model validation of AGCM20 in this region is still one of the important challenges because of a lack of the observation data[11].

In this research, therefore, comparative analyses were conducted for annual, monthly, daily, and extreme rainfalls in the Johor River Watershed after the validation and bias correction of rainfall data. Although investigations using the AGCM20 outputs are preliminary examinations of the Johor River Watershed, they can confirm if AGCM20 is applicable to further hydrologic assessments to investigate the future changes in extreme events occurring in a watershed in Southeast Asia.

2. Research Area

The target watershed of this research is the Johor River Watershed in the state of Johor in southern Peninsular Malaysia (**Fig. 1**). The Johor River originates in Mt. Gemuruh, its main stream length is 122.7 km, and catchment area is 1,655 km^2. There are several main tributaries in the watershed, such as

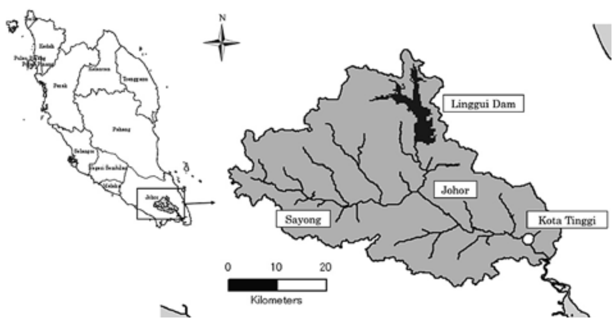

Fig. 1　Location of Johor River Watershed, Malaysia

Sayong, Linggui, Semangar, Tiram, Layang, and Lebam[12,13]. The Johor River Watershed plays a crucial role in water supply not only for the state of Johor, but also for Singapore. Thus, Linggui Dam is located in the upper stream of the Linggui tributary to provide the water supply. The upper area of the basin is mainly occupied by forest, while the lower area of the basin mainly by farmlands of palm oil and rubber plantations. The main city, Kota Tinggi, is located in the lower basin of the main stream.

In recent years, from December 2006 to January 2007, there were two large floods with heavy rain in the Johor River Watershed. These floods occurred during the NE monsoon season, and total rainfall amounts during these two events were greater than 400 mm, which exceeds the monthly average value of 200 mm[14,15]. Given that the Johor River Watershed is prone to flooding because of the monsoon climate, analyzing the impacts of climate change on the watershed's rainfall characteristics is important to design and construct a concrete flood prevention system.

3. Materials and Methods

3.1　Rainfall Data Collection

(1) APHRODITE

As observed rainfall data over the Johor River Watershed, this research used daily gridded rainfall data from 1979 to 2003 (25 years) based on Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE; http://www.chikyu.ac.jp/precip/) with a 0.25° resolution. The APHRODITE project has created high-precision daily precipitation data based on the rain gauge station network over Asia[16]. Observed precipitation data were collected and improved by developing methodologies for considering orographic rainfall, using both satellite and ground radar data, and evaluating extreme events. Thus, the dataset of APHRODITE has been providing high-precision precipitation data for many years, and its high accuracy has already been confirmed[17,18].

(2) AGCM20

This research used a super-high-resolution atmospheric model called MRI-AGCM3.2 (hereafter, AGCM20) with 20-km spatial resolution and 1-hour time resolution to obtain simulated future rainfall data of the Johor River Watershed. AGCM20 has been developed by the Japan Meteorological Agency and the Meteorological Research Institute in Japan. A specification of AGCM20 was summarized by Mizuta et al. (2012)[19]. AGCM20 provides a variety of hydrologic data, such as rainfall, snowfall, and evapotranspiration, for two periods (i. e., the control from 1979 to 2003, and the future from 2075 to 2099). The outputs of AGCM20 in the future period were simulated under RCP8.5, one of the Representative Concentration Pathways (RCPs) scenarios, of the Intergovernmental Panel on Climate Change. The RCP8.5 corresponds to the pathway with the highest greenhouse gas emissions, and the details of the scenario were summarized by Riahi et al. (2011)[20]. In this research, the rainfall data in both the control and future periods were obtained from AGCM20 over the Johor River Watershed.

3. 2 Analysis of Changes in Rainfall Characteristics

The performance of AGCM20 was first validated by comparing the raw AGCM20 outputs with the observed rainfall data in the control period. A bias correction was then conducted to adjust AGCM20's outputs. After that, comparative analyses were conducted for annual, monthly, and daily rainfalls to investigate the changes in rainfall characteristics in the future period. Seven rainfall indices were also investigated based on daily rainfall data to analyze the differences in representative daily rainfall intensity between the control and future periods. Finally, the probable rainfall values in both the control and future periods were obtained by hydrological frequency analysis to check the future changes in extreme rainfall. All the analyses conducted and results shown in this research are based on the watershed's average rainfall, calculated by the arithmetical average method.

3. 3 Bias-correction Method

A combination of two bias-correction methods, the multiplicative-shift method and Cumulative Distribution Function (CDF) mapping method, was applied to the AGCM20 outputs in this research. A bias-correction procedure is as follows:

① Ranking the daily rainfall data in descending order of rainfall amount in each month of each year for both the control and future periods.

② Calculating the mean rainfall amount at each rank for both the control and future periods.

③ Applying ① and ② above to both the observed and simulated rainfall data, and comparing them in the control period.

④ Obtaining the bias-correction factor (i. e., a ratio between observed and simulated values) at each rank of the control period. The bias-correction factor (α_i) can be obtained using the following equation[21]:

$$\alpha_i = \frac{R_{ave,i,obs}}{R_{ave,\,i,\,sim}} \tag{1}$$

In Equation (1), α_i is the bias-correction factor at rank ith, $R_{ave,i,obs}$ is the mean daily rainfall amount (mm) of the observed data at rank ith, and $R_{ave,i,sim}$ is the mean daily rainfall amount (mm) of the simulated data at rank ith.

⑤ Multiplying the simulated values in the control period by the obtained bias-correction factor at each rank so that the simulated values become the same as the observed values.

⑥ Multiplying the simulated values in the future period by the same bias-correction factor at each rank. Finally, the biases of the raw AGCM20 outputs in the future period are corrected using the same correction factors.

⑦ Rearranging the daily rainfall data in an original order in each month.

3. 4 Hydrological frequency analysis

The changes in future extreme rainfall were investigated by comparing the changes in return periods between the control and future periods. In so doing, the hydrological frequency analysis was conducted using the rainfall data in both the control and future periods in the Johor River Watershed. One-day probable rainfall values corresponding to the representative design values (e. g., 100-year return period) were first estimated by applying the Generalized Pareto (GP) distribution to the annual maximum rainfall. The GP distribution is known as an extreme-value distribution and has been mainly employed for extreme values. The suitability of the GP distribution in the Johor River Watershed for two rainfall datasets, i. e., APHRODITE and AGCM20, has already been confirmed[22]. The GP distribution is described using the following equations:

・Probability Density Function

$$f(x)=\frac{1}{a}\left(1-k\frac{x-\xi}{a}\right)^{\frac{1}{k}-1} \quad (2)$$

・Cumulative Distribution Function

$$F(x)=1-\left(1-k\frac{x-\xi}{a}\right)^{1/k} \quad (3)$$

・Probable hydrologic value that corresponds to the non-exceedance probability (p)

$$x=-\frac{a\{(1-p)^{k}-1\}}{k}+\xi \quad (4)$$

where a, k, and ξ denote the scale parameter, the shape parameter, and the location parameter, respectively.

The return periods were estimated and compared between the control and future periods based on the obtained Probability Density Function (PDF) of the GP distribution and the estimated probable rainfall values in the Johor River Watershed. The concept of this method was summarized by Fujiwara et al (2006) [23] as the PDF mapping method.

3.5 Rainfall Indices

The differences in rainfall trends between the control and future periods were analyzed by seven rainfall indices, which particularly represent the extreme events, according to daily rainfall data. The seven indices, the simple precipitation daily intensity index (SDII) [24], average rainfall intensities of wet days exceeding 95th and 99th percentiles (I95 and I99) [25], proportion of wet days to the total wet day exceeding 95th and 99th percentiles (R95 and R99) [25], and numbers of wet days exceeding 95th and 99th percentiles (N95 and N99) [25], were examined. **Table 1** shows the definitions and units of these rainfall indices. The 95th and 99th percentiles are determined as the thresholds of extreme events that represent very wet days and extremely wet days, respectively[25]. Since 1.0 mm/day was determined as the threshold of a rainy day in the Johor River Watershed[26], the analyses in this research used the 1.0 mm/day benchmark.

4. Results and Discussion

4.1 Validation of Rainfall Data

The goodness-of-fit of the mean monthly rainfall in the control period between the observed data and raw AGCM20 outputs is shown in **Fig. 2**. The coefficient of determination is 0.71 ; thus, the raw AGCM20 outputs already showed satisfactory reproducibility of rainfall in the control period. However, AGCM20 tends to overestimate the mean monthly rainfall and slightly underestimate the monthly rainfall in the months of December and January, which are in the NE monsoon season historical major flood events have occurred frequently. Since the bias-correction method used in this research is used to adjust the biases of the mean monthly rainfall, the mean monthly rainfall was duly corrected by the bias-correction procedure mentioned above, as shown in **Fig. 3**.

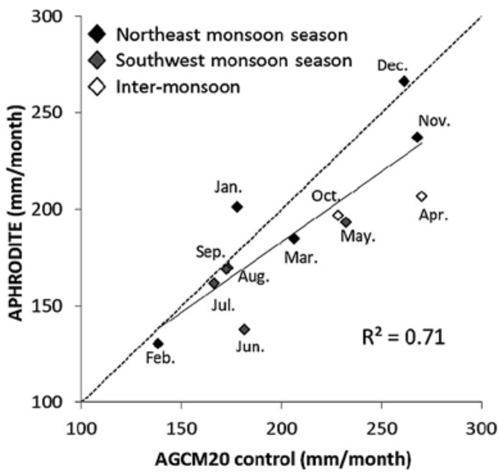

Fig. 2 The goodness-of-fit of mean monthly rainfall between the observed data (APHRODITE) and raw AGCM 20 outputs in the control period in the Johor River Watershed

Table 1 Definitions and units of the seven rainfall indices[24,25]

Indicator	Definitions (units)
Simple precipitation daily intensity index (SD II)	The total precipitation divided by the numer of rainy days (mm)
Very wet day intensity (I95)	Average intensity of events greater than or equal to the 95 th percentile, i. e., average 18 wettest rainy days (mm)
Extremely wet day intensity (I99)	Average intensity of events greater than or equal to the 99 th percentile, i. e., average four wettest rainy days (mm)
Very wet day proportion (R95)	ercentage of annual total rainfall from events greater than or equal to the 95 th percentile (%)
Extremely wet day proportion (R99)	Percentage of annual total rainfall from events greater than or equal to the 99 th percentile (%)
Very wet days (N95)	Number of rainy days exceeding the 95 th percentile (days)
Extremely wet days (N99)	Number of rainy days exceeding the 99 th percentile (days)

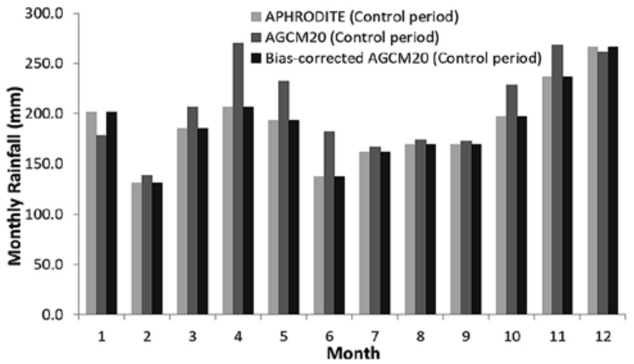

Fig. 3 Mean monthly rainfall in the control period in the Johor River Watershed

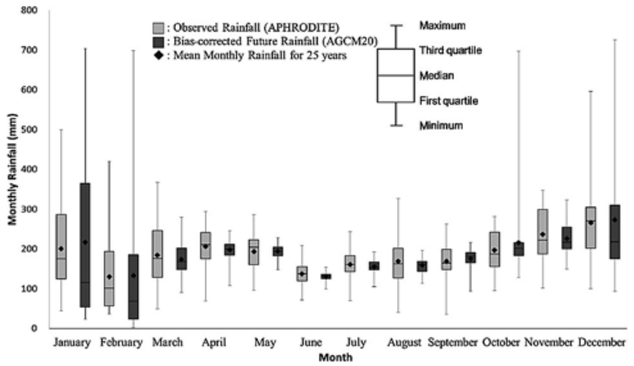

Fig. 5 Comparison of monthly rainfall for 25 years between the control and future periods in the Johor River Watershed

4. 2 Future Changes in Annual Rainfall

Fig. 4 compares the annual rainfall for 25 years between the control and future periods in the Johor River Watershed. First of all, the mean annual rainfall of 25 years shows almost the same values in both the control (2,252.4 mm) and future (2,244.7 mm) periods. This result matches the previous studies[3,4]. However, the difference between the maximum and minimum values is large in the future period. Even though the mean annual rainfall is almost the same in both periods, the maximum annual rainfall in the future period becomes particularly higher than the maximum annual rainfall in the control period. These results indicate that the watershed would receive more rainfall when it is a pluvial year in the future. The future monthly rainfall tendency is checked in the following analyses for a better understanding of seasonal rainfall situations in the future.

4. 3 Future Changes in Monthly Rainfall

Fig. 5 shows a comparison of monthly rainfall for 25 years in the control and future periods. The monthly

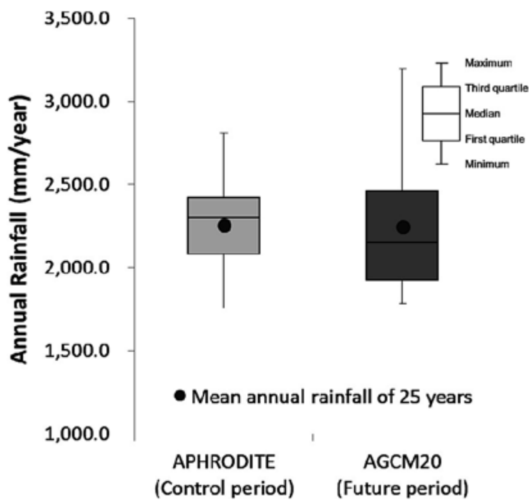

Fig. 4 Box plots of basin-average annual rainfall for 25 years in the Johor River Watershed

rainfall amounts do not change in the future in the dry season (i. e., from April to September) in the Johor River Watershed. However, high rainfall amounts are simulated in the NE monsoon season (i. e., December and January). In addition, high monthly rainfall amount is confirmed in October in the future period even though the NE monsoon season generally starts in November and ends in March. This means that there is a possibility that the onset of the NE monsoon season would be earlier (starting in October) in the future. Several types of research have also reported the possibilities of the earlier onset, later retreat, and thus longer duration of the monsoon season in Southeast Asia in the future due to a change of hydrologic cycle, caused by rises in the sea surface and air temperatures that induce an increase in water vapor in the atmosphere[24,27].

There are also some cases in which future monthly rainfall amounts are quite high in the NE monsoon season (e. g., January and February). This means that more severe rainfall and flood events would occur in the NE monsoon season in the future. Given that a flood usually occurs in the NE monsoon season in the Johor River Watershed, these seasonal rainfall situations—the longer duration of the NE monsoon season and higher rainfall amounts during the NE monsoon season—should be taken into account in future design flood criteria.

4. 4 Future Changes in Daily Rainfall

Daily rainfall data in both the control and future periods were arranged in descending order for each year, and the mean daily rainfall for 25 years at each rank was obtained to investigate future changes in daily rainfall intensity. **Fig. 6** shows a rank comparison of daily rainfall data between the control and future periods. It is obvious that the future daily

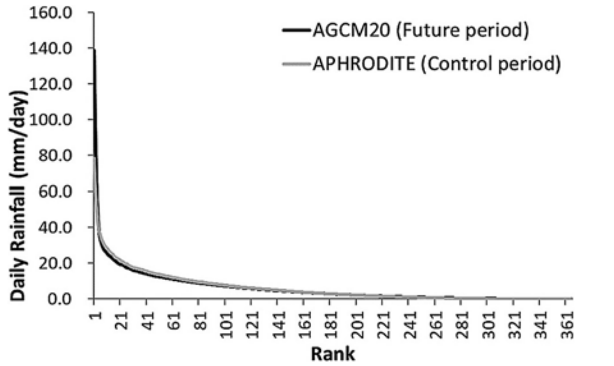

Fig. 6 Daily rank comparison of the bias-corrected rainfall in the Johor River Watershed

rainfall shows significantly high values at the higher ranks (ranks 1 to 3, as shown in **Table 2**). Except for the higher ranks (ranks 1 to 3), the mean daily rainfall at each rank shows almost the same value with the observed data. It means that, based on the AGCM20 outputs, more severe torrential rain is likely to occur in the future. This finding simply implies that when it rains, it will pour.

Table 2 Mean daily rainfall for 25 years at ranks 1 to 5 extracted from Fig. 6

Rank	Observed Rainfall (APHRODITE)	Bias-corrected Future Rainfall (AGCM 20)
1	78.5	138.8
2	61.0	95.5
3	49.7	64.9
4	41.7	44.6
5	37.6	37.1

(mm/day)

4.5 Rainfall Indices

Table 3 shows the results of the seven rainfall indices examined for the rainfall data in the control and future periods. In the future period, although the mean annual rainfall slightly decreases (−11.0 mm), the mean number of rainy days slightly increases (+6 days) in the Johor River Watershed. In addition, even though the numbers of wet days exceeding the 95th and 99th percentiles (i. e., N95 and N99) decrease, average rainfall intensities exceeding the 95th and 99th percentiles (i. e., I95 and I99) significantly increase in the future period. These results indicate that the intensity of rainfall events becomes quite higher among the decreased number of very wet days in the future. In other words, extremely heavy rainfall would occur in the future when it rains in the Johor River Watershed.

Table 3 Results of examination of the rainfall indices in the Johor River Watershed

	Observed Rainfall (APHRODITE)	Bias-corrected Future Rainfall (AGCM20)
Mean annual rainfall	2,223.1	2,212.1
Mean number of rainy days	241.5	247.0
SD II	9.2	9.0
I95	34.9	39.4
99	57.7	85.9
R95	1.5	0.9
R99	0.4	0.4
N95	5.6	3.2
N99	1.6	1.3

4.6 Future Changes in Extreme Rainfall

The future return periods that correspond to the non-exceedance probability from 0.01 (i. e., 1.0-year return period) to 0.99 (i. e., 100-year return period) of the control period are estimated using the PDF mapping method. **Fig. 7** shows a comparison of rainfall return periods between the control and future periods. In all cases, the future return periods dramatically decreases, particularly when the longer return period is considered. In Malaysia, the 100-year return period is a commonly used planning scale for design flood estimation and river planning[28]. According to **Fig. 7**, the rainfall event for the 100-year return period in the control period occurs more frequently in the future, with a corresponding return period of 2.4 years. In this case, the estimated probable rainfall for the 100-year return period increases from 133.9 mm/day in the control period to 557.5 mm/day in the future period.

Since the future scenario was simulated under the RCP8.5 with the highest greenhouse gas emission, these results might represent the worst-case scenario. Thus, more investigations with several scenarios are needed to generalize the methodology and integrate it into further hydrologic assessments. However, the

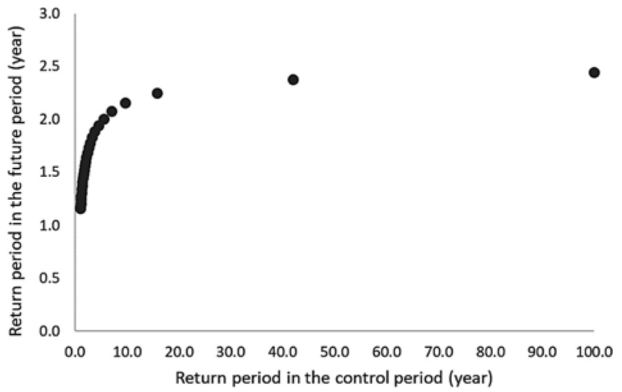

Fig. 7 Comparison of rainfall return periods between the control and future periods in the Johor River Watershed

results imply that the current planning scale, the 100-year return period, might not be adequate to prevent and/or mitigate the flooding caused by climate change.

5. Conclusions

In this research, a super-high-resolution atmospheric general circulation model (AGCM20) was introduced to the Johor River Watershed in Malaysia. The performance of AGCM20 was first validated, and future changes in watershed-scale rainfall characteristics were investigated using the AGCM20 outputs.

Annual rainfall analysis indicated that the watershed would receive more rainfall when it is a pluvial year in the future, though the mean annual rainfall of 25 years showed almost the same values in both the control and future periods. Monthly rainfall analysis showed that more severe rainfall events would occur in the NE monsoon season, and there is a possibility of the earlier onset of the NE monsoon season. The daily rainfall analysis clarified that more severe torrential rain would occur in the future. The seven rainfall indices were able to elaborate on the results of the daily rainfall analysis. In terms of the changes in extreme rainfall, the future return periods dramatically decreased when the longer return period was considered. This implied that the current planning scale, the 100-year return period, might not be suitable for design flood estimation and river planning under climate change in the future.

The analyses conducted in this research using AGCM20 were preliminary investigations in the Johor River Watershed. The future changes in rainfall characteristics simulated by AGCM20 showed the same tendencies as the previous studies using different types of GCMs[3,4]. Accordingly, AGCM20 can also be a powerful tool to simulate the watershed-scale climatic conditions of the future. For further research, the application of the AGCM20 outputs to further hydrologic assessments such as runoff simulation is needed to make good use of AGCM20 and construct an effective watershed management system that considers the impacts of climate change.

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AGCM20を用いたマレーシア・ジョホール川流域降水量の将来変化の分析

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概　要

本研究は，気候変動の影響を考慮した流域管理実現へ向けてマレーシアのジョホール川流域へ高分解能大気気候モデル（AGCM20）を導入した。そしてIPCCのRCP8.5シナリオの下で計算された降雨データをもとに，年・月・日降水量と確率降水量の将来期間（2075-2099年）における変化を分析した。その結果，将来期間では1年の中でも北東モンスーン期に降水量が集中し，その北東モンスーン期の時期も変化することが予測された。また，雨の日はより高強度の雨が降る傾向がみられ，現在の100年確率レベルの降雨イベントが将来2.4年の再現期間で起こることが推定された。

キーワード：高分解能大気気候モデル，流域降水量，気候変動，ジョホール川流域