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Projected hydrological changes and their consistency under future climate in the Chao Phraya River Basin using multi-model and multi-scenario of CMIP5 dataset

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Abstract:

It is important to examine what future hydrological changes could occur as a result of climate change. In this study, we projected hydrological changes and their consistency under near-future and end-of-21st-century climate in the Chao Phraya River Basin. Through hydrological simulations using output from six AOGCMs under the RCP 4.5 and 8.5 scenarios, we have reached the following conclusions. Our results demonstrate a projected increase in mid-rainy season precipitation under future climate, which is a necessary condition for a large volume of runoff to occur in the late rainy season. Under end-of-21st-century climate, all simulations using six AOGCMs showed a large increase (> 20%) in runoff in Nakhon Sawan catchment under both RCP scenarios. Compared to the capacities of the Bhumibol and Sirikit dams, projected increases in runoff at the end of the 21st century are high. New flood management and mitigation plans will likely be necessary. Ensemble mean increases in precipitation and runoff were higher under RCP 8.5 than under the RCP 4.5 scenario in both projected periods. Thus, higher global mean temperature would cause higher precipitation and runoff in the basin. This inference is also supported by the higher precipitation and runoff projected under the late future compared with under the near-future climate.

KEYWORDS climate change; Chao Phraya River Basin; runoff; CMIP5; RCP scenario

INTRODUCTION

Intermittent heavy rains starting in July 2011 caused large-scale flooding of the Chao Phraya River in Thailand. The World Bank (2012) reported that the 2011 flood caused economic damage of up to 1.425 trillion baht (USD 45.7 billion). Komori *et al.* (2012) and Kotsuki and Tanaka (2013b) reported that a 125% increase in annual runoff was caused by a 40% increase in annual rainfall in 2011. In response to the large 2011 flood, the government of Thailand conducted a review of the basin's water resource management plan and master plan, which were designed in 1999. An understanding of the hydrological characteristics of the basin is important for the revision of the master plan. The authors have investigated the hydrological characteristics of the basin through the Integrated Study on Hydro-Meteorological Prediction and Adaptation to Climate change in Thailand (IMPAC-T) project.

In recent years, climate change has created serious challenges for flood control. A warmer climate would increase the risk of flooding. Hirabayashi *et al.* (2013) investigated global flood risk under climate change using output from the 11 atmosphere-ocean general circulation models (AOGCMs), and revealed that global exposure to floods would increase depending on the degree of warming. Fekete and Vorosmarty (2004) and Kotsuki and Tanaka (2013d) pointed out that in wet regions, where precipitation always exceeds potential evaporation, any error in predictions of precipitation translates to approximately the same absolute error in runoff (which will result in higher relative error because runoff is always less than precipitation). This implies that small increases in precipitation caused by climate change can yield large increases in runoff. Indeed, Kotsuki and Tanaka (2013b) demonstrated that a 10% increase in annual precipitation caused a 50–75% increase in annual runoff in 1980, 1995, and 2006. It is also important to examine what future changes could occur in the Chao Phraya River Basin and its hydrological cycles as a result of climate change.

Several studies have been performed using hydrological models with climate projections to simulate the response of the Chao Phraya River Basin to climate change. Since flood management and operation rules are based on seasonal runoff in the basin, impact estimation studies have not been conducted on a finer resolution other than monthly temporal scale. To date, most of these studies have used outputs from atmospheric GCMs developed by the Japan Meteorological Research Institute (MRI-AGCMs; Kusunoki *et al.*, 2011). Hunukumbura and Tachikawa (2012) investigated projected future river discharge using version 3.1 of the 20 km mesh MRI-AGCM (MRI-AGCM3.1s), and projected that mean annual discharge would not change significantly in many major tributaries including at Nakhon Sawan station (hereafter, C.2). Kure and Tebakari (2012) evaluated future mean annual river discharge using the previous and latest version (3.2) of the 20 km mesh MRI-AGCM; they reported that mean annual river discharge is likely to increase at C.2 due to increased rainfall. Using different resolutions and ensemble experiments in the MRI-AGCM, Champathong *et al.* (2013) reported that precipitation was projected to

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increase significantly in the basin in future rainy seasons, excluding May; however, no significant changes in river discharge were projected at C.2. None of these climate-change studies of the Chao Phraya Basin included an uncertainty evaluation of emissions or Representative Concentration Pathway (RCP) scenarios. RCP scenarios provide data on the time-evolving emissions or concentrations of radiatively active constituents. Future climate projections were produced by climate model experiments under the time series of emissions and concentrations from four RCP scenarios (Moss *et al.*, 2010).

Many researchers have projected river discharge under future climate using hydrological models applying statistical downscaling or bias correction methods to output from GCMs (e.g. Maurer *et al.*, 2010; Leander and Buishand, 2007). Additionally, those statistical downscaling and bias correction methods have been compared to reduce the bias of future climate projection and to investigate their impacts on river discharge projections (e.g. Freddie *et al.*, 2009; Lafon *et al.*, 2013).

Here, we used output from the latest six AOGCMs participating in the fifth phase of the Coupled Model Intercomparison Project (CMIP5; Taylor *et al.*, 2012). We conducted simulations for historical, near-future, and end-of-21st-century scenarios. For future simulations, we used bias-corrected climate scenarios under two RCP scenarios: RCP 4.5 and RCP 8.5 (Vuuren *et al.*, 2011). Through hydrological simulations using output from the AOGCMs under the two RCP scenarios, we computed projections of hydrological changes and evaluated their consistency in the Chao Phraya River Basin.

METHODOLOGY

Overview of the Chao Phraya Basin

The Chao Phraya River has a catchment area of approximately 160,000 km^2 and is divided into the upper and lower basins at the Nakhon Sawan station (C.2; 15°67'N, 100°1'E), which is a narrow area in the middle of the basin (Supplement Figure S1a). The catchment area of the upper basin is 110,000 km^2, which represents 68% of the entire basin area. Four branch rivers (the Ping, Wang, Yom, and Nan rivers) flow from the northern mountainous area and merge at C.2. The Bhumibol and Sirikit dams (storage capacity 13.5 and 9.5 × 10^9 m^3, respectively) were constructed on the Ping and Nan rivers for irrigation, flood control, and electricity generation, and have a great impact on the duration of downstream discharge. Dissimilar to northern mountain regions, topography and river channel slope of the southern basin becomes low (Supplement Figure S1b).

The Chao Phraya River basin is located in the Southeast Asia monsoon region, which has a clear distinction between the rainy season (May to October) and the dry season (November to April). Ninety percent of the basin's total precipitation falls during the rainy season (Kure and Tebakari, 2012), and precipitation in general is higher in the mountainous northern area (Supplement Figure S1c). Although the northern mountain basin has higher rainfall than the southern basin, the density of rainfall-gauging stations is lower than the southern basin (Supplement Figure S3). One major institute to gauge rainfall is the Royal Irrigation Department (RID), whose gauging stations are distributed mainly in irrigated fields.

Climate data

To detect hydrological impacts of climate change on the Chao Phraya Basin, we conducted simulations using a land surface model for three periods: historical (1980–1999), near-future (2040–2059), and end-of-21st-century (2080–2099) periods. To perform the historical simulation, we developed a historical climate dataset called IMPAC-T Forcing Data (IFD). A detailed description of the IFD is presented in Supplement Information S1. Future simulations were conducted with IMPAC-T Driving Data (IDD) developed by Watanabe *et al.* (2014). The IDD is the future atmospheric forcing dataset which was created by correcting the bias in AOGCMs participating in the CMIP5 using the IFD. The IDD was developed with a newly developed bias correction method which scales the change in monthly and daily variations of AOGCMs between historical and future periods on the IFD. Here, the changes in atmospheric forcing from AOGCMs are linearly interpolated into the resolution of the IFD. With this bias correction method, the time series of the IDD become the analogue of that of IFD. Both the IFD and IDD comprise seven meteorological forcings: temperature, specific humidity, short-wave radiation, long-wave radiation, atmospheric pressure, wind speed, and precipitation.

From eight AOGCM datasets of the IDD providing both RCP 4.5 and 8.5 scenarios, six AOGCMs (CSIRO-Mk3.6, INM-CM4, MIROC5, CNRM-CM5, GFDL-ESM2M, and IPSL-CM5A-LR) were selected for use in this study (Supplement Table SI). Watanabe *et al.* (2014) indicated that those six AOGCMs showed relatively higher spatial correlation with APHRODITE precipitation data (Yatagai *et al.*, 2012). MRI-CGCM3 and BCC-CSM1.1 were excluded because of their low spatial correlation with APHRODITE data. Note that the excluded MRI-CGCM3 is a different dataset from the MRI-AGCMs used by Hunukumbura and Tachikawa (2012), Kure and Tebakari (2012), and Champathong *et al.* (2013).

Hydrological model

Hydrological simulations were conducted using a land surface model: the Simple Biosphere model including Urban Canopy (SiBUC; Tanaka, 2004). This model calculates energy, radiation, and water budgets on the land surface with seven meteorological forcings. Similar impact estimation on hydrological change was performed with SiBUC in entire Japanese basins (Kotsuki and Tanaka, 2013a).

In addition to the meteorological forcings, the model requires land surface parameters (e.g. land cover; leaf area index; vegetation cover fraction), soil physical parameters (e.g. soil and root depths; porosity; soil types), and geographical data (elevation and slope). Ground-surface physical parameters were created using Ecoclimap (Faroux *et al.*, 2013) provided by Meteo-France, and ground surface-cover data were created using MIRCA2000 (Portmann *et al.*, 2008) and GLCC version 2.0 provided by the United States Geological Survey (USGS). The Shuttle Radar Topography Mission (SRTM) 90 m digital elevation data was used to determine elevation and slope. Simulations have been

performed at a spatial resolution of five minutes and a temporal resolution of one hour.

It should be noted that both historical and future simulations are conducted without gate operations of Bhumibol and Sirikit Dams. Thus, this study projects runoff change under no reservoir condition. Kotsuki and Tanaka (2013c) conducted an analysis of 24 years' worth of data (1981–2004) under the same land-surface parameters and IFD and reported that annual runoff at C.2 was well reproduced. Simulated monthly runoff also agreed well with naturalized monthly runoff at C.2 (Nash-Sutcliffe model efficiency coefficient is 0.70). Naturalized runoff was obtained by excluding the two dams' effect from recorded runoff data at C.2.

RESULTS

The IDD (seven bias-corrected meteorological forcings from six AOGCMs) was used as input for the land surface analysis. The results of this analysis are presented in Figures 1 and 2 and Table I. Figure 1 shows changes in annual mean hydrological variables in the future climate relative to the present climate. Figure 2 compares monthly precipitation, evapotranspiration, and runoff in the Nakhon Sawan catchment for the three time-period simulations. Table I shows mean annual precipitation and runoff in the Nakhon Sawan catchment.

Near future (2040–2059) under RCP 4.5 scenario

As shown in Figure 1, this simulation indicated a 5–10% increase in precipitation in the southern basin. In contrast, a significant increase (> 5%) in precipitation was not detected in the northern basin. Significant increases in evapotranspiration were not detected in the basin except for the lower areas including irrigated fields and the Bhumibol and Sirikit dams. Most increases in precipitation translated to increases in runoff. Thus, runoff was projected to increase significantly (by >5%) in the entire basin under future projected climate conditions. As shown in Table I, the six AOGCMs agreed on increased precipitation in the C.2 catchment. The ensemble mean increase in precipitation was 46.7 mm (4% larger than the present climate). The six AOGCMs also agreed on a significant (> 10%) increase in runoff. The ensemble mean increase in runoff was 45.8 mm (22% larger than that of the present climate). As shown in Figure 2, projected future seasonal precipitation was almost the same as that under the present climate. Slight increases in precipitation were detected in June and August. Future seasonal evapotranspiration was also similar to that of the present climate; minor increases in evapotranspiration were detected in October and November. In contrast, future runoff was shown to increase from May to September.

Near future (2040–2059) under RCP 8.5 scenario

This simulation indicated an increase in precipitation of more than 5% across the entire basin (Figure 1), a larger increase than that projected under RCP 4.5 scenario. In addition, more than five of the six AOGCMs agreed on a significant increase in the southern and northwest basin. However, as for RCP 4.5 scenario, a significant increase in evapotranspiration was not detected under RCP 8.5 scenario. Thus, runoff was projected to increase dramatically (> 25%) throughout the entire basin. The six AOGCMs agreed on increased precipitation in the C.2 catchment (Table I). The ensemble mean increase in precipitation was 105.4 mm, 9%

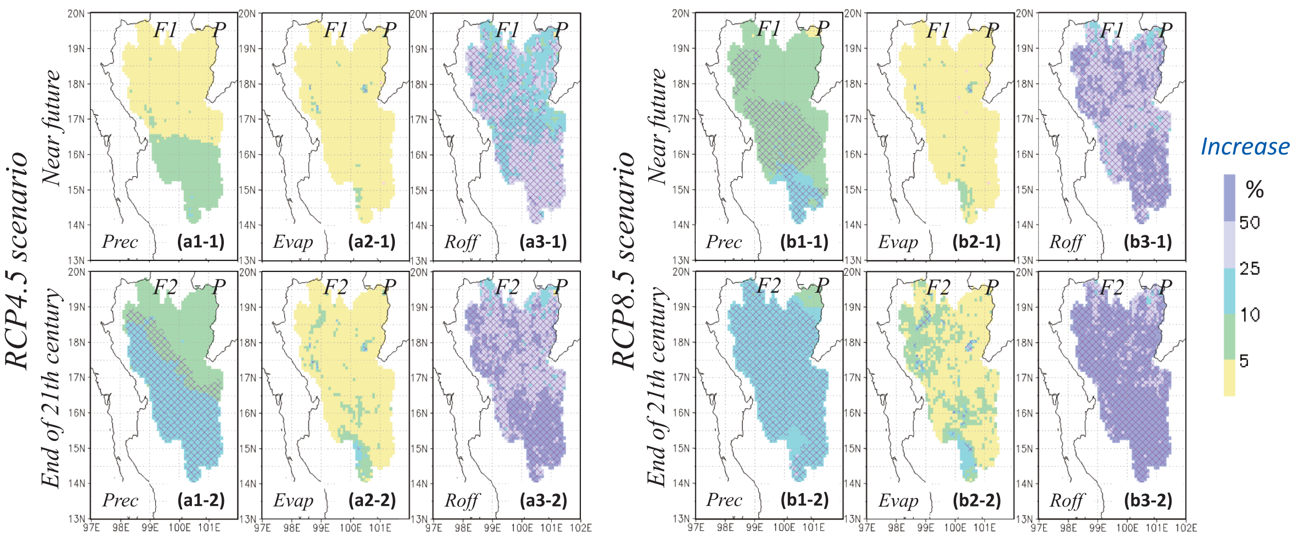

Figure 1. Changes (%) in annual mean hydrological variables under future climate scenarios relative to the present climate (P: 1980–1999). Top-left figures (a1-1, a2-1, and a3-1) show projected near-future (F1: 2040–2059) change under the RCP 4.5 scenario. Bottom-left figures (a1-2, a2-2, and a3-2) show projected end-of-21st-century (F2: 2080–2099) changes under the RCP 4.5 scenario. Top-right figures (b1-1, b2-1, and b3-1) show projected near future (F1: 2040–2059) changes under RCP 8.5. Bottom-right figures (b1-2, b2-2, and b3-2) show projected end-of-21st-century (F2: 2080–2099) changes under RCP 8.5. Future projections were calculated with six bias-corrected general circulation models (GCMs). Hatch areas in the figures indicate that a significant increase (> 5%) was detected from the results using at least five of the six GCMs. (a1-1, a1-2, b1-1, and b1-2): precipitation; (a2-1, a2-2, b2-1, and b2-2): evapotranspiration; (a3-1, a3-2, b3-1, and b3-2): runoff. Prec, Evap, and Roff in the figure are the abbreviations of precipitation, evapotranspiration, and runoff, respectively

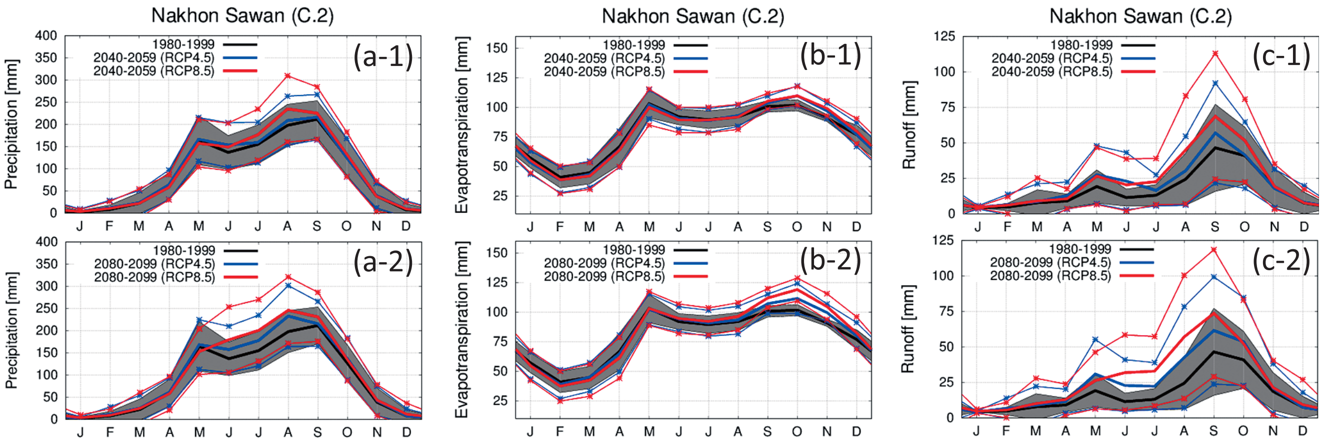

Figure 2. Comparisons of monthly precipitation (a-1, a-2), evapotranspiration (b-1, b-2), and runoff (c-2, c-2) in Nakhon Sawan catchment. Panels a-1, b-1, and c-1 show comparisons between present climate (1980–1999) and near-future climate (2040–2059). Panels a-2, b-2, and c-2 show comparisons between present climate and end-of-21st-century climate (2080–2099). Solid black lines and gray shaded areas show averages and standard deviations for the present climate. Solid blue lines and blue lines with x-marks show averages and standard deviations under the RCP 4.5 scenario. Solid red lines and red lines with x-marks show averages and standard deviations under the RCP 8.5 scenario

Table I. Mean annual precipitation and runoff in Nakhon Sawan catchment. Results of six general circulation models (GCMs) under the RCP 4.5 and 8.5 scenarios, and their ensemble means are shown for near future (F1: 2040–2059) and end-of-21st-century (F2: 2080–2099) periods. Green, blue, and red labels in the table represent a significant increase (> 10%), a large increase (> 20%), and a drastic increase (> 40%), respectively, relative to the present

			Bias-corrected CMIP5 (IDD)						Ensemble	Present	Change
			CSIRO	INM	MIROC	CNRM	GFDL	IPSL	(IDD)	(IFD)	(F / P)
Precipi-tation (mm/yr)	RCP 4.5	F1	1180.5	1148.4	1228.3	1214.0	1138.0	1160.8	1178.4	1131.7	1.04
		F2	1246.4	1236.7	1347.6	1210.0	1202.1	1179.9	1237.1		1.09
	RCP 8.5	F1	1226.9	1249.2	1247.4	1231.0	1175.6	1175.7	1217.6		1.07
		F2	1423.6	1376.7	1346.2	1277.1	1231.1	1114.5	1294.9		1.14
Runoff (mm/yr)	RCP 4.5	F1	239.2	244.0	275.7	273.8	246.7	244.0	253.9	208.1	1.22
		F2	269.2	292.6	360.1	257.3	310.1	271.7	293.5		1.41
	RCP 8.5	F1	282.1	302.2	303.3	296.6	278.2	289.7	292.0		1.40
		F2	400.1	377.3	354.2	305.0	331.5	257.3	337.6		1.62

larger than that of the present climate. The six AOGCMs agreed on a large (> 20%) increase in runoff. The ensemble mean increase in runoff was 85.4 mm (41% larger than that of the present climate). In addition, increased precipitation was detected from June to August, while increased evapotranspiration was detected only in October and November and these increases were minor (Figure 2). On the other hand, future runoff showed a large increase from May to October. Precipitation and runoff under RCP 8.5 scenario were larger than those under RCP 4.5 scenario in the rainy season; these variables did not show a significant increase under either RCP scenario during the dry season.

End of the 21st century (2080–2099) under RCP 4.5 scenario

This simulation indicated a projected increase in precipitation of >5% in the entire basin (Figure 1). In addition, more than five of the six AOGCMs agreed on a significant increase in the southern and northwestern parts of the basin. However, a significant increase in evapotranspiration was not detected except in lower areas including irrigated fields and the Bhumibol and Sirikit dams. Thus, runoff was projected to increase drastically (by >25%) across the basin. The six AOGCMs agreed on increased precipitation in the C.2 catchment (Table I). The ensemble mean increase in precipitation was 85.9 mm, which is 7% larger than precipitation under the present climate. The six AOGCMs agreed on a large (> 20%) increase in runoff; the ensemble mean increase in runoff was 83.9 mm, a value that is 40% larger than that of the present climate. Precipitation was projected to increase from June to August (Figure 2) while a slight increase in evapotranspiration was projected from September to November. Future runoff showed a large increase from May to October.

End of the 21st century (2080–2099) under RCP 8.5 scenario

Precipitation was projected to increase by more than 5% across the basin under this scenario (Figure 1), a greater increase than expected under RCP 4.5 scenario. Five of the six AOGCMs agreed on a significant increase across most of the basin. A significant increase in evapotranspiration

was detected in many grids. Runoff was projected to increase dramatically (by >25%) across the entire basin. Four of the AOGCMs agreed on a large increase (more than 10%) in precipitation in the C.2 catchment (Table I). In contrast, IPSL-CM5A-LR showed a slight decrease in precipitation. The ensemble mean increase in precipitation was 163.2 mm, which is 14% larger than precipitation under the present climate. The six AOGCMs agreed on a large (> 20%) increase in runoff; the ensemble mean increase in runoff was 129.5 mm (62% larger than current runoff). The increases in precipitation were detected from June to September and increases in evapotranspiration were projected from September to November (Figure 2). Future runoff showed a large increase from May to October. Projected precipitation and runoff under the RCP 8.5 scenario were larger than those under RCP 4.5 scenario during the rainy season, while neither variable was expected to increase significantly during the dry season under either scenario.

DISCUSSION

Our results demonstrate a projected increase in mid-rainy season precipitation under future climate projections. Kotsuki and Tanaka (2013b) pointed out that higher precipitation in the mid-rainy season brings soil moisture close to saturation, a necessary condition for a large volume of runoff to occur in the late rainy season. Increases in annual runoff in the C.2 catchment were 45.8 mm (5.0×10^9 m^3) and 85.4 mm (9.4×10^9 m^3) under the near-future climate scenario, and 83.9 mm (9.2×10^9 m^3) and 129.5 mm (14.2×10^9 m^3) under end-of-the-21st-century climate scenario, for RCP 4.5 and RCP 8.5, respectively. Compared to the capacities of the Bhumibol and Sirikit dams (13.5 and 9.5×10^9 m^3), projected increases in runoff at the end of the 21st century are high. Kure and Tebakari (2012) also projected a large increase in discharge at C.2 in the late future using MRI-AGCM3.2s. As Kure and Tebakari (2012) suggested, new flood management and mitigation plans, including the construction of new dam reservoirs and changes in the rules for operation of dam gates, will likely be necessary.

Some of our results do not agree with those of previous studies. Hunukumbura and Tachikawa (2012) used MRI-AGCM3.1s and projected a significant decrease in discharge in the Pasak River Basin. However, our results showed that five of the six AOGCMs agreed on a trend towards increased runoff throughout the basin. Kure and Tebakari (2012) also projected an increase in river flow using MRI-AGCM3.2s. Thus, differences among results may be a result of the use of different GCMs. Supplement Figure S4 shows climatological annual mean runoff change with each of the six AOGCMs. In Figure 1, the ensemble mean runoff changes showed increases across the entire basin (Figure 1 a3-1, a3-2, b3-1, and b3-2). However, several results projected a decrease trend with CSIRO and IPSL (Supplement Figure S4 a-1, a-3, f-1, and f-4). Additionally, decrease trends in runoff were projected round the northeast basin. Those decrease trends in runoff were caused by decrease trends in precipitation. On the other hand, simulations with the six AOGCMs agreed an increase trend in runoff in the southern basin. Our results indicated that uncertainties in the future precipitation and runoff are large around the northeast basin.

Champathong *et al.* (2013) used MRI-AGCM3.2s and physically downscaled CMIP3 GCMs and projected no significant change in C.2. However, Kure and Tebakari (2012) and this study projected large increases in runoff under the late future climate. Champathong *et al.* (2013) projected a significant increase in evapotranspiration in the entire basin, which differs from our results. Champathong *et al.* (2013) indicated that a projected increase in precipitation was not significant in the Ping and Wang River basins, suggesting that fewer cloudy days were projected by their GCMs than by the CMIP5 AOGCMs. That could also explain the increase in evapotranspiration projected by Champathog *et al.* (2013). Two possible explanations for such differences include different GCMs (CMIP3 GCMs vs. CMIP5 AOGCMs) and different methods (physical downscaling vs. bias correction). It is difficult to identify the reasons for different projected scenarios from the present results. One potential method for clarifying the differences would be to conduct a simulation using physically downscaled CMIP5 AOGCMs. Differences among projections demonstrate uncertainty in the projected future climate in the Chao Phraya River Basin.

One of our new findings was that ensemble mean increases in precipitation and runoff were higher under RCP 8.5 than under the RCP 4.5 scenario in both projected periods. Thus, higher global mean temperature would cause higher precipitation and runoff in the basin. This inference is also supported by the higher precipitation and runoff projected under the late future than under the near future.

CONCLUSIONS

In this study, the authors projected hydrological changes and their consistency under near future and end-of-21st-century climate in the Chao Phraya River Basin. Through hydrological simulations using output from the six AOGCMs under the two RCP scenarios, the authors have reached the following main conclusions:

1) Our results demonstrate a projected increase in mid-rainy season precipitation under future climate, which is a necessary condition for a large volume of runoff to occur in the late rainy season.
2) Under end-of-21st-century climate, all simulations using six AOGCMs showed a large increase (> 20%) in runoff in the Nakhon Sawan catchment under both RCP scenarios. Compared to the capacities of the Bhumibol and Sirikit dams, projected increases in runoff at the end of the 21st century are high. New flood management and mitigation plans will likely be necessary.
3) Ensemble mean increases in precipitation and runoff were higher under RCP 8.5 than under the RCP 4.5 scenario in both projected periods. Thus, higher global mean temperature would cause higher precipitation and runoff in the basin. This inference is also supported by the higher precipitation and runoff projected under the late future than under the near future.

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SUPPLEMENTS

Supplement Information S1. Description of IMPAC-T Forcing Data (IFD)

Supplement Table SI. The six AOGCMs, their modeling center and abbreviations

Supplement Table SII. The meteorological datasets obtained from Hirabayashi *et al.* (2008) and Onogi *et al.* (2007)

Supplement Figure S1. Characteristics of Chao Phraya River basin

Supplement Figure S2. Procedures to generate IFD precipitation dataset

Supplement Figure S3. Locations of gauging stations obtained through GAME-T (a) and IMPAC-T (b) projects

Supplement Figure S4. Climatological annual mean runoff change (%) in the future climate relative to the present climate

REFERENCES

Champathong A, Komori D, Kiguchi M, Sukhapunnaphan T, Oki T, Nakaegawa T. 2013. Future projection of mean river discharge climatology for the Chao Phraya River basin. *Hydrological Research Letters* **7**: 36–41. doi: 10.3178/HRL.7.36.

Faroux S, Tchuenté K, Roujean L, Masson V, Martin E, Moigue L. 2013. ECOCLIMAP-2/Europe: a twofold database of ecosystems and surface parameters at 1-km resolution based on satellite information for use in land surface, meteorological and climate models. *Geoscientific Model Development* **6**: 563–582. doi: 10.5194/gmd-6-563-2013.

Fekete BM, Vorosmarty CJ. 2004. Uncertainties in precipitation and their impacts on runoff estimates. *Journal of Climate* **17**: 294–304. doi: 10.1175/1520-0442(2004)017<0294:UIPATI>2.0.CO;2.

Freddie SM, Francis HSC. 2009. Influence of rainfall scenario construction methods on runoff projections. *Journal of Hydrometeorology* **10**: 1168–1183. doi: 10.1175/2009JHM1045.1.

Hirabayashi Y, Mahendran R, Koirala S, Konoshima L, Yamazaki D, Watanabe S, Kim H, Kanae S. 2013. Global flood risk under climate change. *Nature Climate Change* **3**: 816–821. doi: 10.1038/nclimate1911.

Hunukumbura PB, Tachikawa Y. 2012. River discharge projection under climate change in the Chao Phraya River Basin. *Journal of the Meteorological Society of Japan* **90A**: 137–150. doi: 10.2151/jmsj.2012-A07.

Komori D, Nakamura S, Kiguchi M, Nishijima A, Yamazaki D, Suzuki S, Kawasaki A, Oki K, Oki T. 2012. Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrological Research Letters* **6**: 41–46. doi: 10.3178/HRL.6.41.

Kotsuki S, Tanaka K. 2013a. Estimation of Climate Change Impact on Japanese Rice Yield and Water Resources. *Proceedings of 2013 IAHR World Congress September 8–13, 2013 Chengdu, China*; A10344.

Kotsuki S, Tanaka K. 2013b. Impacts of Mid-Rainy Season Rainfall on Runoff into the Chao Phraya River, Thailand. *Journal of Disaster Research* **8**: 397–405.

Kotsuki S, Tanaka K. 2013c. Long-term Water Balance Analysis Using Different Precipitation Products in Upper Chao Phraya River, Thailand. *Proceedings of 6th APHW conference August 19–21, 2013 Seoul, Korea*.

Kotsuki S, Tanaka K. 2013d. Uncertainties of precipitation products and their impacts on runoff estimates through hydrological land surface simulation in Southeast Asia. *Hydrological Research Letters* **7**: 79–84. doi: 10.3178/HRL.7.79.

Kure S, Tebakari T. 2012. Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. *Hydrological Research Letters* **6**: 53–58. doi: 10.3178/hrl.6.53.

Kusunoki S, Mizuta R, Matsueda M. 2011. Future changes in the East Asian rain band projected by global atmospheric models with 20-km and 60-km grid size. *Climate Dynamics* **37**: 2481–2493. doi: 10.1007/s00382-011-1000-x.

Lafon T, Dadson S, Buys G, Prudhomme C. 2013. Bias correction of daily precipitation simulated by a regional climate model: a comparison of methods. *International Journal of Climatology* **33**: 1367–1381. doi: 10.1002/joc.3518.

Leander R, Buishand TA. 2007. Resampling of regional climate model output for the simulation of extreme river flows. *Journal of Hydrology* **332**: 487–496. doi: 10.1016/j.jhydrol.2006.08.006.

Maurer EP, Hidalgo HG, Das T, Dettinger MD, Cayan DR. 2010. The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrology and Earth System Sciences* **14**: 1125–1138. doi: 10.5194/hess-14-1125-2010.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ. 2010. The next generation of scenarios for climate change research and assessment. *Nature* **463**: 747–756. doi: 10.1038/nature08823.

Portmann FT, Siebert S, Doll P. 2008. MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles* **24-GB1011**: 1–24. doi: 10.1029/2008GB003435.

Tanaka K. 2004. Development of the New Land Surface Scheme SiBUC Commonly Applicable to Basin Water Management and Numerical Weather Prediction Model. Doctoral Dissertation, Graduate School of Engineering, Kyoto University, Kyoto; 289.

Taylor K, Stouffer R, Meehl G. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* **93**: 485–498. doi: 10.1175/BAMS-D-11-00094.1.

The World Bank. 2012. Thai Flood 2011: Rapid Assessment for resilient recovery and reconstruction planning. https://www.gfdrr.org/thaifloods2012. Last access April 10, 2013.

Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque JF. 2011. The representative concentration pathways: an overview. *Climate Change* **109**: 5–31. doi: 10.1007/s10584-011-0148-z.

Watanabe S, Hirabayashi Y, Kotsuki S, Hanasaki N, Tanaka K, Mateo CM, Kiguchi M, Ikoma E, Kanae S, Oki T. 2014. Application of performance metrics for climate models to project future river discharge in Chao Phraya River Basin. *Hydrological Research Letters*. (in press)

Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A. 2012. APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges. *Bulletin of American Meteorological Society* **93**: 1401–1415. doi: 10.1175/BAMS-D-11-00122.1.