Future projection of mean river discharge climatology for the Chao Phraya River basin

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Abstract:

We projected future river discharge in the Chao Phraya River basin and evaluated the uncertainty in future climate projections by using different resolutions and ensemble experiments of the Atmospheric General Circulation Model of the Meteorological Research Institute (MRI-AGCM). We also obtained estimates of precipitation, evaporation, runoff, and river discharge under climate conditions projected for the late 21st century. The results show that precipitation is projected to significantly increase in the future during April to August, excluding May. The projected river discharge at Nakhon Sawan located in the central region shows a peak in September, a delay of one month after the maximum monthly mean precipitation. The estimated reduction in river discharge for January and February was robust based on all members of the 60-km mesh MRI-AGCM ensembles changing in the same direction as that of the 20-km mesh MRI-AGCM. The uncertainty assessment conducted in this study could lead to increased robustness in projected changes in mean river discharge in the late 21st century for this basin.

KEYWORDS future climate projection; Chao Phraya River basin; Thailand; AGCM; Global River flow model using TRIP (GRiveT)

INTRODUCTION

Inundation of large areas of land in Thailand in 2011 caused immense domestic damage and problems worldwide because of its impact on industrial supply chains. The World Bank estimated the economic loss from this calamity as THB 1.4 trillion (USD 45.7 billion), placing it as one of the top five most costly natural disaster events in modern history (AON Corporation, 2012). The Emergency Operation Center for Flood, Storms, and Landslides (2012) also reported 815 lives lost and 3 missing nationwide. From a hydrological perspective, Komori et al. (2012) reported that the 2011 Thai flood was caused by the highest precipitation ever recorded in Thailand in the rainy season. The total amount of precipitation reached 1,439 mm, which was 143% of the average rainy season precipitation for the period 1982–2002, causing 2.4 times the runoff in the upper Chao Phraya River basin. In addition to the disastrous effects of inundation on the livelihood of the population in this basin, droughts are another hydrological problem, reducing the region’s water supply and agricultural productivity. In 2008, over 10 million people living in 55 provinces were affected by water shortages caused by severe drought (The Secretariat of the Cabinet of Thailand, 2008). During the past decade, weather patterns in Thailand have fluctuated from severe droughts to major floods (Kisner, 2008); however, the effects of climate change on such flood and drought cycles are unknown.

Most of the preliminary findings from previous research tended to predict an increase in temperature and the annual cumulative precipitation throughout most of Thailand including the Chao Phraya River basin (Southeast Asia START Regional Center, 2010; Suntisirisomboon and Krausawan, 2011). Meanwhile, Chaowiwat and Likitdecharote (2009) demonstrated a change in other projected hydrological variables such as an increase in potential evaporation caused by an increase in the minimum and maximum projected temperatures under lower relative humidity. Furthermore, Ogata et al. (2012) indicated that the mean highest peak discharge may increase within the next three decades.

Since a variety of general circulation models (GCMs) have been used for climate projection in this catchment, a comparison of downscaled GCM data was presented by Koontanakulvong and Chaowiwat (2011). Their study showed that the downscaled data from the Atmospheric General Circulation Model of the Meteorological Research Institute (MRI-AGCM) at a 20-km resolution demonstrated the highest correlation between the annual precipitation data and the observed data because the original GCM data were based on a finer spatial resolution. With the grid size of MRI-AGCM being several times finer than that previously used in climate model simulations (Kitoh et al., 2009), more published papers related to future climate projection for this basin using the downscaled data from MRI-AGCM have been produced recently. For example, Hunukumbura and Tachikawa (2012) determined the projection of future river discharge by using the current version (version 3.1) of the 20-km mesh MRI-AGCM output as the input of a distributed flow routing model, while Kure and Tebakari (2012) evaluated the future mean annual flow discharge and flood frequency using the current and new versions (version 3.1 and 3.2, respectively). However, neither Hunukumbura and Tachikawa (2012) nor Kure and Tebakari (2012) included an uncertainty evaluation.

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To elucidate future hydrological changes, this study projected future river discharge in the Chao Phraya River basin and evaluated the uncertainty in the climate projection schemes by using different resolutions and ensemble experiments of the MRI-AGCM. Furthermore, by using the evaluated projection for future climate, we assessed future hydrological conditions in this basin. In particular, we estimated the future annual and monthly mean river discharges using a river routing model with output from the current versions of 20-km and 60-km mesh MRI-AGCM.

**METHODOLOGY**

**Overview of Chao Phraya River basin**

The Chao Phraya River basin, covering approximately 160,000 km², is the largest catchment in Thailand. It is divided into upper and lower catchments at Nakhon Sawan located in the central region (Figure 1). Originating within the mountainous headwaters in the northern region, the Ping, Wang, Yom, and Nan Rivers flow through the valleys and merge to form the Chao Phraya River at Nakhon Sawan. Situated in the Upper Chao Phraya River basin, two large dams, Bhumibol and Sirikit, are a significant tool for water management. Moreover, numerous irrigation projects facilitating water delivery to irrigated agricultural land, dams, head regulators, and other auxiliary structures have been constructed along the river basin. A large amount of upstream flow eventually drains into the Gulf of Thailand.

**Climate model**

The climate model used in this study is the MRI-AGCM with two versions of 20-km and 60-km horizontal resolution. Both were developed by the Meteorological Research Institute (MRI) and the Japan Meteorological Agency (JMA) (Mizuta et al., 2006). The land-surface scheme in this model is the Simplified Biosphere (SiB) model, originally developed by Sellers (1986). SiB was later revised by MRI for predicting soil water storage and canopy retention water, as well as their temperatures (Hirai et al., 2007). It diagnostically computes the total runoff, which is a summation of the surface and subsurface runoff, into a river channel.

The 20-km mesh MRI-AGCM was employed in 25-year time-slice experiments for the present-day and late 21st century climates with the A1B SRES scenario. For the present-day climate, the observed monthly SST and the sea-ice concentration during 1979–2003 derived from Rayner et al. (2003) were used in the simulation. For future climate projections, the lower boundary SST data were arranged by superimposing three components comprising (a) future change in the multiple-model ensemble (MME) of SST projected under the A1B SRES scenario in the 3rd Couple Model Intercomparison Project (CMIP3), (b) the trend in the MME of SST, and (c) the detrended observed SST anomalies during 1979–2003 (Mizuta et al., 2008). The future sea-ice distribution was similarly obtained by this process. Although the 20-km mesh MRI-AGCM was chosen for this study due to its finer resolution, computer power is incapable of generating ensemble simulations under such a fine-resolution model. Hence, Kitoh et al. (2009) suggested that ensemble simulations under the 60-km mesh version should also be performed in order to cover this limitation.

Therefore, to assess the uncertainty of the climate projections using the 20-km mesh MRI-AGCM, ensemble simulations under the 60-km mesh MRI-AGCM were also performed. The 60-km mesh experiments, using the twelve-ensemble members for the future climate (3 initial conditions × 4 future SSTs) together with three-ensemble members for the present-day climate (3 initial conditions × 1 observed SST), were conducted in this study. The four different lower boundary conditions used in this study were derived from (i) MME’s mean of CMIP3, as in the 20-km mesh MRI-AGCM experiment, (ii) CSIRO Mark3.0 (CSIRO-Mk3.0), (iii) the MRI Coupled General Circulation Model version 2.3.2 (MRI-CGCM2.3.2), and (iv) the Model for Interdisciplinary Research on Climate version 3.2 (hi-resolution) (MIROC3.2 (hires)). The 60-km mesh MRI-AGCM was also employed for the present-day climate simulation using the same boundary conditions as the 20-km mesh MRI-AGCM. In each lower boundary condition, three members were run with different atmospheric initial conditions, as in Kitoh et al. (2009) and Nakaegawa et al. (2012).

**River model**

The Global River flow model using TRIP (GRiveT), developed by MRI, was used for the river flow model in this study. This model employed the Total Runoff Integrating Pathway (TRIP) which is a global river channel dataset at 0.5° spatial resolution (Oki and Sud, 1998). GRiveT assumes that the river discharge is proportional to the river water storage and sets the default of effective velocity as 0.4 m s⁻¹ (Nakaegawa et al., 2013). In addition, this model focuses on natural river flows, excluding lake and human controls, e.g., reservoir operations and water withdrawal. Nevertheless, Nakaegawa and Hosaka (2008) demonstrated that river discharges in the world’s major rivers were well simulated by this model.

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Figure 1. The Chao Phraya River basin (yellow area) and Total Runoff Integrating Pathway (TRIP) showing locations of hydrological stations at Nakhon Sawan, Bhumibol Dam, and Sirikit Dam.
Validating data

To validate the climatological mean precipitation and river discharge in the present-day climate simulation, three observed datasets consisting of the Climate Research Unit TS2.1 (CRU TS2.1), the Royal Irrigation Department (RID), and the Electricity Generating Authority of Thailand (EGAT) were utilized. The CRU TS2.1 dataset contains data of monthly mean precipitation over land areas at a horizontal resolution of 0.5° during 1979–2003. The climatological monthly mean river discharges were provided by the RID river gauge stations, and the flow released from the main dams was derived from EGAT. The river discharge on the present-day climate simulations are compared with the “naturalized observed discharge” which was computed by removing the effect of the Bhumibol and Sirikit reservoirs.

RESULTS

Validation

Table I shows the comparisons between the model simulations and observations for the upper basin average precipitation and river discharge at Nakhon Sawan during the present-day climate simulation (1979–2003). This experiment was conducted with the 20-km and 60-km mesh MRI-AGCMs in comparison with the observation data at a horizontal resolution of 0.5°. The annual mean ratio was defined as the ratio of the simulated output and observed data. The 20-km mesh showed larger annual mean ratio of precipitation than that of 60-km mesh; however, the seasonal cycle in precipitation derived from the 20-km mesh shows higher temporal correlation (0.94 > 0.89). In the seasonal cycle, the 20-km mesh showed a lower standard deviation ratio (1.105 < 1.123). Furthermore, the Relative Root Mean Square Error (RRMSE) of the 20-km mesh was lower than that of the 60-km mesh (0.38 < 0.43).

On the other hand, although the river discharges were simulated by the same river model, GRíveT, using input data derived from the 20-km and 60-km mesh MRI-AGCMs, resulted in obvious deviations in the outputs (Table I). While the 125% annual mean precipitation of the 20-km mesh MRI-AGCM could produce 121% of the observed river discharge, the 116% annual mean precipitation of the 60-km mesh MRI-AGCM could generate only 77% of the observed river discharge. One possible reason is that the 60-km mesh model covers a larger area outside the boundary of the upper Chao Phraya River basin, and thus might model river discharge originating outside the basin boundary. The seasonal cycles in river discharges from both horizontal resolutions showed similar temporal correlation. In addition, the standard deviation ratio and RRMSE of the 20-km mesh were higher than those of 60-km mesh.

As illustrated in Figure 2, the simulated peak discharge period under the 20-km mesh MRI-AGCM corresponded to the peak monsoon season (August–October) and showed a similar pattern to the observations. The estimate of the reduction in river discharge for January and February can be considered robust since all members of the 60-km mesh MRI-AGCM ensembles changed in the same direction as that of the 20-km mesh MRI-AGCM, which is evidenced by a complete consistency in sign change (4 out of 4) in the lower figure of Figure 2. In contrast, during August and September, the increase in the projected river discharge was not a robust estimate because only one member of the 60-km mesh MRI-AGCM ensembles changed in the same direction as that of the 20-km mesh AGCM (1 out of 4 as indicated).

Table I. Validation of upper basin-mean precipitation and river discharge at Nakhon Sawan in the model simulations

| Model horizontal resolution | Annual mean ratio | Seasonal cycle |
|-----------------------------|-------------------|----------------|
|                             |                   | Temporal correlation | Standard deviation ratio | RRMSE |
| (a) Precipitation           |                   |                |           |          |
| 20 km                       | 1.25              | 0.94           | 1.105     | 0.38     |
| 60 km                       | 1.16              | 0.89           | 1.123     | 0.43     |
| (b) River discharge         |                   |                |           |          |
| 20 km                       | 1.21              | 0.96           | 1.50      | 0.78     |
| 60 km                       | 0.77              | 0.95           | 1.05      | 0.57     |

Figure 2. Upper panel: Naturalized river discharge (black dash line) with one standard deviation range (light blue shaded area) at the C.2 Nakhon Sawan in the Chao Phraya River, and simulated river discharge for the present-day climate (black solid line) and future climate (red solid line) under the 20-km mesh MRI-AGCM. Lower panel: Percentage change (blue solid line) in river discharge between the present-day and future climates under the 20-km mesh MRI-AGCM. These are statistically non-significant changes at the 95% level. The numbers above the horizontal axis indicate the number of members of the 60-km mesh MRI-AGCM ensemble that changed in the same direction as the 20-km mesh MRI-AGCM.
The climatological annual mean precipitation showed a 5–10% increase at the headwaters of the Ping, Yom, and Nan River basins in the future (Figure 3a); however, these increases were not always robust because of the low consistency arising from one to two consistent changes in signs (Figure 3e). The 5–10% increase in projected precipitation at the confluence of the Yom and Nan Rivers, Nakhon Sawan, and the downstream area of the lower Nakhon Sawan are robust because most of these estimates had a full number (4) of consistent changes in signs (Figure 3a, 3e). The 5–10% increase in evaporation was also found almost throughout the basin (Figure 3b); particularly, the 5–10% increase in projected evaporation was robust along most of the Yom and Nan Rivers, Nakhon Sawan, and the downstream area of Nakhon Sawan (Figure 3f). In addition, the 20–30% decreases in projected runoff near the headwater of the Ping River—as well as the middle of the Ping and Nan Rivers—were robust (Figure 3c, 3g). Last, robust 10–20% decreases in projected river discharges were found near the middle of the Ping and Nan Rivers (Figure 3d, 3h). An overview of the water budget in the river basin can be described as follows: a 20–30% decrease in projected runoff at the middle of the Ping River was caused by a 5% increase in projected evaporation with little change in future precipitation. Furthermore, the decreasing tendency of the projected river discharge near the middle of the Ping River may be due to an increase in projected evaporation with no change in the projected precipitation. Almost half of all the grids in Figure 3e indicate low consistency, suggesting that the precipitation distributions simulated by the 20-km and 60-km mesh MRI-AGCMs were different. Furthermore, these differences were also reflected in the simulated river discharge, as indicated in Table I.

**Projection of monthly mean climatology**

Figure 4 presents the projected climatological monthly means of hydrological variables (precipitation, evaporation, total runoff, and river discharge) at Nakhon Sawan in the future climate. The changes in this figure are basin mean values of all the grid values in the upper Chao Phraya River basin. The precipitation from April to August excluding May is projected to significantly increase, and the climatological monthly mean evaporation is projected to increase from May to December in the future. Although the significant changes are not reflected in future climatological monthly mean total runoff and river discharge, they increased in August and decreased in July and October. The peak of the projected river discharge appeared in September, a delay of one month after the maximum precipitation, and decreased in July and October.

**DISCUSSION**

One of our findings was that the annual mean river discharges derived from the 20-km mesh was overestimated during

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**Figure 3.** (Top; a–d): Climatological annual mean hydrological variable changes (%) in the future climate relative to the present using the 20-km mesh MRI-AGCM. Only statistically significant areas at 95% level are colored. (Bottom; e–h): The number of consistent changes in sign between the 4 multi-SST 60-km mesh MRI-AGCM ensemble simulations and the 20-km mesh MRI-AGCM. Four represent completely consistent changes in the 20-km mesh model and the 4 multi-SST 60-km mesh MRI-AGCM (dark blue shaded), while unity represents inconsistent changes between the 20-km and the 4 multi-SST 60-km mesh MRI-AGCM simulations. (a) and (e): precipitation; (b) and (f): evaporation; (c) and (g): runoff; (d) and (h): river discharge.

**Figure 4.** Climatological monthly mean hydrological variables at Nakhon Sawan in the late 21st century using the 20-km mesh MRI-AGCM. Black solid, red dashed, green centered and blue cutting-planed lines denote precipitation, evaporation, total runoff, and river discharge, respectively. Circles denote statistically significant change (P < 5%) compared to the present-day values. (a): The amount of the projected future climate, (b): The changing amount of the projected future climate.
by 21%; whereas, that of the 60 km-mesh was underestimated by 23%, as presented in Table I. Because the 20-km mesh MRI-AGCM can resolve the topographical conditions in the upper Chao Phraya River basin more precisely than the 60-km mesh MRI-AGCM, mountain ranges could only be reproduced under the finer resolution model. In most regions of the world, orographic effects induce long-term mean precipitation increases with elevation. Particularly in tropical regions, the rates of precipitation due to elevation vary widely from region to region and may even reverse at the highest elevations (Dingman, 2002; World Meteorological Organization, 2009). Additionally, Kuraji et al. (2009) reported an altitudinal increase in precipitation over Mount Inthanon and the Mae Chaem Watershed, parts of the upstream watershed of this basin.

Since a large volume of water from the whole tributaries of Ping, Wang, Yom, and Nan Watersheds, gathers at the C.2 hydrological station in Nakhon Sawan, the river discharge has an increasing tendency at this station when an increase in precipitation occurs in these sub-drainage basins. It is obvious in Table I that the annual mean ratio of the river discharge obtained from the 60-km mesh model (0.77) should be simulated at a higher annual mean ratio due to the overestimation of the precipitation (1.16). In contrast, the 20-km mesh model produced the annual mean ratio showing overestimation of the river discharge (1.21) when that of the overestimated precipitation was 1.25. As a result, from the perspective of river discharge simulation, the precipitation derived from the 20-km mesh MRI-AGCM tends to be more acceptable than that derived from the 60-km mesh MRI-AGCM. This study can serve as a guide for Southeast Asia START Regional Center (2010) and Suntisirisomboon and Kuwasawan (2011) in developing climate projection using finer resolutions. In addition, this study result has been confirmed by the study of Koontanakulvong and Chaowiwat (2011), who showed well-correlated annual precipitation projection using the 20-km mesh MRI-AGCM.

No significant change in the projected river discharge at the C.2 Nakhon Sawan was detected (Figure 3d, 3h) due to two major causes: a 5–10% increase in projected precipitation (Figure 3a, 3e) and a 5–10% increase in projected evaporation (Figure 3b, 3f). However, Kure and Tebakari (2012) found significant increases of 5% in the projected evaporation (Figure 3b, 3f). Nevertheless, the uncertainty assessment conducted in our study could lead to an increase in the robustness of projected changes in mean river discharge in the late 21st century for this basin.

CONCLUDING SUMMARY

This study evaluated the uncertainty in climate projection by using different resolutions and ensemble experiments of the MRI-AGCM. Then, estimates of precipitation, evaporation, runoff, and river discharges for the Chao Phraya River basin were presented under changing future climate conditions in the late 21st century.

In terms of the monthly mean climatology, there was a clear indication that the projected river discharge will decrease, particularly in January, with a dramatic 60% drop. This was supported by an identical change in direction for all four members of the 60-km mesh MRI-AGCM and 20-km mesh MRI-AGCM; however, the peak river discharge in September was not robust because only one SST 60-km mesh MRI-AGCM ensemble simulation changed in the same direction as that of the 20-km mesh MRI-AGCM. Nonetheless, since the current version of the 20-km mesh MRI-AGCM experiment was conducted with a single member, an uncertainty remains in this MRI-AGCM. Further studies using the new version of MRI-AGCM with MMEs should be conducted to investigate the changing hydrological conditions under future climate predictions.

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