Comparative study on climate change impact on precipitation and floods in Asian river basins

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Abstract:

As many water-related disasters occur frequently around the world, proper assessment of future climate change impact on floods and droughts is essential. In this study, we focused on basin-scale climate change impact assessment as necessary information for studying adaptation measures on the basis of integrated water resources management. We used Meteorological Research Institute-Atmospheric General Circulation Model (MRI-AGCM) 3.2S (20 km grid super high resolution model) and a series of simulation methods for climate change analysis. We conducted a comparative study on changes in precipitation, flood discharge and inundation in future climate change. We found that regional precipitation outputs from the high resolution model in this study were in good agreement in the point of tendency of their changes in wet and dry monsoon seasons with the regional precipitation analysis in the Fifth Assessment Report (AR5) of Working Group 1 (WG1) of the International Panel on Climate Change (IPCC, 2013). This study illustrated that the proposed methodology can make more detailed descriptions of climate change possible. As a result, this paper confirms the importance of basin-scale runoff and inundation analysis with downsampling especially for basins where floods occur for a short period, suggesting potential differences between flood change and precipitation change from General Circulation Model (GCM) outputs such as maximum 5-day precipitation index in a basin. As a result, this paper confirms the importance of basin-scale discharge and inundation analysis for climate change considering basin characteristics from the viewpoint of river management.

KEYWORDS climate change; MRI-AGCM 3.2S; cSPI; downsampling; flood inundation; basin-scale comparative study

INTRODUCTION

Recently, water related disasters have occurred frequently around the world (see Figure S1). The change of precipitation patterns due to climate change was also reported (Dore, 2005). To cope with disasters induced by precipitation change, it is necessary to assess future climate change impact on flood and drought properly in order to design effective adaptive countermeasures. According to the AR5 of IPCC WG1 (IPCC, 2013), global warming in the climate system is unequivocal and circulation will generally weaken in the monsoon area. It also reports a high possibility of precipitation increase during the summer monsoon season in Asia in the future and increase of extreme precipitation with very high confidence. Kitoh and Endo (2016) explained changes in precipitation extremes using MRI-AGCM 3.2S with four Sea Surface Temperature (SST) cases on a global and regional scale in wet and dry seasons. Water cycle alteration by climate change would give huge impacts on society and the economy. Thus, we need to analyze impacts caused by future precipitation and river discharge change on a basin scale to design adaptation measures in a scientific approach. Case studies on precipitation and discharge change have been conducted for specific basins (e.g., Kimaro et al., 2005; Rasmy et al., 2014), but only a few studies have been conducted on flood inundation change in the future climate (Kudo et al., 2015; Sayama et al., 2015). Furthermore, there are even fewer studies comparing different basins through a series of processes from precipitation analysis to flood discharge and inundation analysis. In general, climate change impact assessment has been performed by General Circulation Models (GCMs). The resolution of ordinary GCM outputs is often coarse, because of data processing limitations. On the other hand, coarse GCM outputs have an advantage to be able to produce more ensemble members for uncertainty analysis. However, they are too coarse to be used for climate change impact analysis for river basin management to investigate river runoff changes. Thus, we need to use a high resolution model or downsampling technology. It is also necessary to study on the proper temporal and spatial scale according to basin characteristics. In this paper, we aim to clarify key issues in applying the data and knowledge of the AR5 of IPCC WG1 (IPCC, 2013) to basin–level research. We will also compare and discuss the results from studies conducted in different river basins at proper temporal and spatial scales according to basin characteristics. To achieve these objectives, we first introduce a series of methodologies for climate change impact analysis using MRI-AGCM 3.2S (20 km grid) at the basin scale. Then we analyze
the difference in future precipitation changes during the wet monsoon season and the dry monsoon season, respectively, in five Asian monsoon basins by comparing the results of IPCC (IPCC, 2013) with those from the super high resolution model (MRI-AGCM3.2S) in terms of common precipitation indices. We also undertake in-depth analysis on the outputs of the super high resolution model using our proposed comparative Standardized Precipitation Index (cSPI). Furthermore, we perform a comparative analysis on changes in flood specific discharge and inundation area ratio for three of the five target basins. We finally discuss key issues regarding a proper methodology for basin-scale analysis of climate change impact on precipitation and floods, as well as differences in climate change impact in relation to basin characteristics.

**STUDY AREA**

Table I lists basic data of the target basins, showing that each target basin has different characteristics in climate (island or continent), location, size, topography and land cover. Not only climate pattern but also topography influences forms of precipitation. Runoff depends on topography variations and land use types. Therefore, we have to carefully select various kinds of river basins including different characteristics in the Asia monsoon region for a comparative study. Considering our resources, we selected five representative target basins with different characteristics such as Solo, Pampanga, Chao Phraya, Mekong, and Indus river basins. As the Solo river is located in the southern hemisphere, the months from November to March are the summer wet season.

<table>
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<tr>
<th>Table I. Basic data of the five river basins</th>
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<td>River basin</td>
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<td>Land cover</td>
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<td>Design rainfall period for flood analysis</td>
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METHODS

Bias correction and downscaling of MRI-AGCM3.2S

We used MRI-AGCM3.2S, a super high resolution 20 km grid model developed by Mizuta et al. (2012), with the Yoshimura cumulus convection scheme and four Sea Surface Temperature (SST) cases in the future climate experiment (three SST patterns, C1, C2 and C3, from the cluster analysis of Coupled Model Intercomparison Project Phase 5 (CMIP5) (Mizuta et al., 2014) and the multi-model ensemble (MME) (Mendlik and Gobiet 2015; Kitoh and Endo, 2016) as the 20 km model is too heavy to prepare many cases (Kitoh and Endo, 2016). The duration of the climate experiment of MRI-AGCM3.2S was 25 years for both present (1979–2003) and future (2075–2099 with Representative Concentration Pathways (RCP) 8.5 (Kitoh and Endo, 2016)) periods. Bias correction (Inomata et al., 2011) for GCM output was performed with grid-based daily precipitation observation data in Asia (The Asian Precipitation- Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) (APHRODITE Project, 2006–2011). The same bias correction factors used in this procedure were also applied to future climate analysis. We checked the MRI-AGCM 3.2S output without and with bias correction by comparing it with APHRODITE observation data for the target basins, and confirmed that the MRI-AGCM 3.2S output showed good agreement with the APHRODITE data on the monthly variation in basin average precipitation throughout the year (see Figure S2). In general, temporal and spatial downscaling is necessary for a small basin where the flood duration is short on an hourly basis and floods are influenced by micro-topography. We performed a dynamic downscaling for the Pampanga river basin using Weather Research and Forecasting (WRF) model with 5 km grid on an hourly basis to prepare input precipitation data for flood runoff and inundation calculation (Ushiyama et al., 2016). On the other hand, we did not conduct downscaling for the Solo river basin despite that it is a small basin, because the flood duration was about 4 days and we were able to reproduce a hydrograph on a daily basis.

Precipitation change analysis on basin scale

The target seasons for precipitation analysis were MJJAS (May to September, 25 samples/run), which is the wet summer season in the northern hemisphere, and NDJFM (November to March, 24 samples/run), which is the dry winter season in the northern hemisphere. We compared the five basins to analyze changes in precipitation between the present and future climate by season. The indices we used for comparison were: 1) R5d: maximum 5-day precipitation (mm/5-days); 2) CDD: consecutive dry days with precipitation less than 1mm (days); 3) Pav: seasonal average daily precipitation (mm day−1); and 4) SDII: simple daily precipitation intensity index, which is the total precipitation divided by the number of days with precipitation greater than or equal to 1 mm (refer to Kitoh et al., 2013). These indices were used on the global and regional scale in the previous studies. Before considering proper temporal and spatial resolution for the basin scale analysis, we compare the difference of the values of indices between the MRI-AGCM 3.2S 20 km grid model and the other GCMs in the AR5 of IPCC WG1 (IPCC, 2013). We calculated these indices by grid during the two target seasons. Then, we estimated the basin average of each grid-based index as an expectation value in the basin. We also calculated the ensemble mean of 25 MJJAS samples and 24 NDJFM samples for the present and future climate. Finally, we used the ensemble mean of four SST cases for the future climate.

Basin-scale seasonal precipitation change distribution in the future by cSPI

We calculated the comparative Standardized Precipitation Index (cSPI), (Hasegawa et al., 2015) of the five-month (MJJAS and NDJFM) accumulated precipitation change between present and future climate on the 20 km grid base and produced a distribution map. The cSPI of the future climate was calculated based on the present climate SPI function.

Analysis on river-specific discharge and inundation area ratio in an extreme flood event

We calculated river discharge and inundation area for Solo, Pampanga, and Chao Phraya rivers by inputting the bias-corrected daily precipitation data of the present and future climate experiments (RCP8.5, MME case) into the Rainfall Runoff Inundation (RRI) model (Sayama et al., 2012) which can describe inundation phenomena on the physical base. For the Pampanga river basin, we used hourly precipitation data with 5 km grid after dynamic downscaling of MRI-AGCM 3.2S (20 km grid output). The design rainfall period, which is an effective precipitation continuation period having the highest correlation with the annual maximum flood inundation volume, was four days, 48 hours, and 6 months for Solo, Pampanga, and Chao Phraya rivers, respectively.

The input precipitation data were prepared in the following steps: 1) The temporal and spatial precipitation distribution pattern (hereafter the designed rainfall pattern), which causes the maximum flood inundation in the design rainfall period, was selected for each of the 25 and 24 samples of the present and future climate experiments; 2) The accumulated rainfall in the design rainfall period with 100-year return period probability was estimated as the design accumulated rainfall by statistical probability analysis based on annual maximum accumulated precipitation in the design rainfall period in the present and future climate; and 3) The temporal and spatial distribution of the design rainfall with 100-year return period probability was produced as input data for RRI model simulation after adjusting the designed rainfall patterns estimated in step 1 to the design 100-year accumulated rainfall estimated in step 2. Climate change experiment precipitation output data were used as sequential rainfall input data before and after the design rainfall period. The designed rainfall patterns in the present climate and future climate were different in consideration of changes in extreme flood patterns according to the climate change experiment outputs.

We compared each inundation area ratio (inundation area divided by basin area) among the three basins because each basin size was different. Also, we compared each specific discharge (discharge divided by upper catchment area) at each representative river station located upstream from the
main inundation area (see each location of the station (calculation point) in Figure 4).

RESULTS AND DISCUSSION

Analysis on precipitation change on a basin scale

Figure 1 shows the differences in R5d and CDD between the future climate (EM: ensemble mean of four SST cases) and the present climate. Figures 1a and 1c compare grid-based spatial distribution of changes in R5d between MJJAS and NDJFM. The boundaries of the five target river basins are also shown in the maps. Figures 1b and 1d show basin averages of R5d for the five basins in MJJAS and NDJFM. The plus/minus signs (+/−) mean that more than three SST cases indicate the same increase/decrease direction as that of the EM of the four SST cases in the future compared with the present climate case. The other cases are marked using a triangle (△), indicating that they contain high uncertainty.

There is a clear increasing tendency in basin-average R5d expectation value for Chao Phraya, Mekong, and Indus river basins in both seasons of MJJAS and NDJFM, as shown in many regions in Asia. The Solo river basin shows an increase in R5d during the wet season of NDJFM. On the other hand, the basin average of R5d in Pampanga decreases in MJJAS and increases in NDJFM. It seems that the AR5 (Chapter 14, Figure 14.24) of IPCC WG1 (IPCC, 2013) shows some variance in future precipitation change over the Pampanga basin in the Philippines due to limited resolution of the models used for the assessment report. Further study is necessary on proper downscaling for small basins for more accurate understanding of precipitation change impact on extreme flood events based on hourly-based analysis (described later) instead of daily-based seasonal average analysis such as this one.

Changes in seasonal average precipitation of Pav and SDII between the present and future climate show the same tendency of R5d, as shown in Figures S3 and S4 attached for reference.

Figure 1 (e), (f), (g), and (h) show changes in CDD. It clearly illustrates that CDD in NDJFM increases in southern Asia but decreases in the northern part of Tibet. CDDs in the Pampanga, Chao Phraya, and Mekong river basins during the dry season of NDJFM are relatively high compared with those of MJJAS. CDD in the Solo river basin is relatively high in MJJAS and increases in MJJAS in the future climate because of its location in the southern hemisphere. CDD in the Mekong river basin slightly decreases in the future dry season. In the Indus river basin located in a semi-arid region, CDD in the summer monsoon season is relatively higher than other areas in southeastern Asia. The drought tendency in the Indus basin is strengthened throughout the year in the future, but CDD decreases in its highland area contrarily. This suggests that the future tendency may be different even within a single basin. In addition, as the Indus river basin is located at the western edge of the Asia monsoon area, the basin may be more sensitive to the projected climate change impact than other basins, which may have resulted in its characteristic tendency. CDD in the Pampanga river basin slightly increases throughout the year. This indicates that both floods and droughts can be more frequent because in the future, precipitation may concentrate during the winter season while dry weather may also last for a longer period of time.

Analysis of future seasonal average precipitation change by cSPI

Figure 2 shows the distribution of cSPI median value in the future climate (ensemble mean of the four SST cases)
based on the present climate during MJJAS and NDJFM. The masking area (gray colored grids) consists of grids whose absolute value of SPI median of the present climate (MJJAS 25 samples/NDJFM 24 samples) exceeds one (1). Originally the SPI median of present climate precipitation should be zero because SPI assumes that its distribution follows gamma distribution. In some cases, however, five-month accumulated precipitation does not seem to follow gamma distribution. As a result, the Pampanga river basin in NDJFM is included in the gray area. When a cSPI value exceeds +1 or –1, it means meteorologically wet (flood) or dry (drought). According to Figure 2, the Chao Phraya, Mekong, and Indus river basins in MJJAS are found to be wet in the future. However, the Pampanga river basin is likely to be dry in the summer monsoon. In NDJFM, the Solo river basin is likely to be wet and Chao Phraya river basin is partially likely to be dry. The highland in the Indus basin and the northern part of China will also be wet in winter.

Analysis on river inundation area ratio and specific discharge change in an extreme flood event

Figure 3 shows the results from calculation using the RRI model of changes in river inundation area ratio and specific discharge with design 100-year rainfall in the present and future climate (MME SST case only). In the Pampanga river basin, we ran RRI using downscaled hourly precipitation data by the WRF model.

We found an 8% increase in inundation area ratio in the Pampanga river basin in the future. Figure 1 suggests that R5d will decrease in the summer monsoon season in the Pampanga river basin. However, hourly-scale analysis using the design 48-hour rainfall pattern clearly shows that inundation will increase due to concentrated precipitation events. This kind of phenomena can be revealed only through downscaling GCM climate data and conducting runoff inundation analysis. In addition, inundation area ratio often varies because it is greatly affected by the characteristics of a basin, and thus it is not always consistent with results from precipitation change analysis.

Besides the fact that specific discharge is considered to be strongly affected by river slope gradient, careful consideration is needed to understand the specific discharge of the Pampanga river because it tends to show a sharp peak due to hourly-based analysis, compared with those of the Solo and Chao Phraya rivers resulting from daily-based analysis. The specific discharge in the Chao Phraya river is small since its flood continuation period is long and the river flow is slow. However, the inundation ratio of Chao Phraya is larger than that of the Solo river basin.

This is a good example to show that precipitation change analysis alone is not enough to discuss the phenomena of runoff and inundation, and that it becomes possible to understand the actual behavior of river water when discharge and inundation simulation is also conducted. Figure 4 shows changes of inundation area in the three basins. The inundation...
tion area in each river basin is completely different due to topographical characteristics. The inundation area ratio in Pampanga river is the largest in the three basins but the flood time is not so long compared with that of the Chao Phraya case which lasts for a couple of months. This study has revealed the importance of analyzing flood runoff and inundation on a basin scale together with GCM precipitation output for studying necessary adaptive countermeasures in the future.

SUMMARY AND CONCLUSIONS

Table II shows a summary of the results on changes in precipitation (R5d, CDD, cSPI), specific discharge and inundation area ratio during MJJAS and NDJFM. The blue color indicates being wet and yellow being dry. According to this table, the Mekong river basin will be wet in both summer monsoon season and winter dry season though CDD will increase partially in winter. In the Indus river basin, CDD will increase in the future both in summer and winter but its highland area will be wet in winter. This is also the case in cSPI during the dry season. The Solo river basin will be wet as a whole except the CDD will increase partially in the wet season (NDJFM). In the Chao Phraya river basin, precipitation tends to increase though the cSPI analysis found that the basin will be partially dry in the dry season. In the Pampanga river basin, precipitation will decrease in the wet season and the drought tendency will increase according to MRI-AGCM 20 km analysis (R5d, CDD and cSPI). This indicates that regional precipitation outputs from the high resolution model were in good agreement with those in the fifth Assessment Report (AR5) of IPCC WG1 (IPCC, 2013) in terms of tendency of changes in wet and dry monsoon seasons. However, dynamic downscaling for extreme flood event analysis found that the magnitude of extreme floods will increase in the summer monsoon season in Pampanga river basin.

In this study, we conducted a series of basin-scale simulation from precipitation to runoff to inundation. This type of comprehensive approach should be employed to achieve better understanding of climate change phenomena as a whole. Though we did not consider the effects of land use change (urbanization etc.) in this study, we understand the importance of considering the effect of changes of social development which influences runoff (Kimaro et al., 2005).

In addition, we should consider snow and glacier melt effects (Wakazuki et al., 2015) in the future climate when we simulate runoff and inundation in the basins including high mountains with snow and glacier.

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SUPPLEMENTS

Figure S1. Change of water related disasters (1900 to 2015)
Figure S2. Changes in monthly precipitation (without/with bias correction) (Error bars/shade: Standard deviation of 25-year samples of areal mean monthly precipitation)

Figure S3. Changes in Pav (MJJAS: (a) and (b), NDJFM: (c) and (d), +/-: indicates more than 3 SST cases, △: uncertain)

Figure S4. Changes of SDII (MJJAS: (a) and (b), NDJFM: (c) and (d), +/-: indicates more than 3 SST cases, △: uncertain)

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