A new approach to flood risk assessment in Asia-Pacific region based on MRI-AGCM outputs

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Abstract:

Climate change is anticipated to escalate flood impacts, and thus it is important to assess flood risk closely in terms of extent and location. This study aimed to assess present and future flood risks, particularly flood risk change, over the Asia-Pacific region with consideration of climate change impacts by using a topography-based analysis method. By analyzing the output of the super-high-resolution global atmospheric general circulation model, it was found that future flood risk will increase in response to extreme rainfall under climate change. Results of this study also indicated that flood risk will further increase in the far future (2075–2099) than in the near future (2015–2039). Analyses of inundation area and flood inundation depth (FID) also showed upward trends; most of flood plains in the Asia-Pacific region may experience a 0–50cm increase in FID.

KEYWORDS climate change; flood risk; MRI-AGCM; Asia-Pacific region; FID

INTRODUCTION

There is a worldwide concern of increasing flood risks under anticipated climate change. Both the frequency and magnitude of flood hazards are expected to increase due to climate changes as a result of greenhouse gas-induced changes in temperature, radiation, rainfall, soil moisture and many other atmospheric factors (IPCC AR4, 2007; Petrow *et al.*, 2001; Schiermeier, 2011), which will directly contribute to increasing flood disaster risk (Parry *et al.*, 2001; Schipper and Pelling, 2006; Mirza, 2011). Moreover, Hirabayashi and Kanae (2009) emphasized that flood-affected population may well be larger at the global level considering a critical level of projected temperatures in the future. The Asia-Pacific region is particularly vulnerable to the impacts of natural disasters (World Bank, 2005). During 2000–2011, 9 of the top 10 countries with the highest number of water-related disaster deaths were in Asia (EM-DAT, 2012). Moreover, in 2003 alone, about 315-million of population was affected by tropical cyclones and floods (UNDP, 2004). Similar estimates were also provided by the Water World Assessment Program report (WWAP, 2009). Considering these circumstances, flood risk should be assessed not only from a single perspective of hazard intensity, but also from multiple viewpoints of hazards,

damage and other socio-economic factors.

Flood risk has been studied as one of the major impacts of climate changes. However, closer examination is needed with different methods and climate scenarios to obtain more detailed information on the potential changes in flood risk, as well as the extent and location of inundated areas. Previous research has confirmed a possible increase in flood risk, but few studies have utilized global- or continental-scale inundation models under climate change. In an attempt to fill this gap, Kwak *et al.* (2011) developed a simple method for assessing the inundation depth based on topographical analyses.

Future flood risk also needs to be assessed in terms of different climate change scenarios. Simulations based on different scenarios produce different projections in future flood risk. Recently, a global climate model with a high horizontal grid resolution of about 20 km has been developed by the Japan Meteorological Agency (JMA). This model improves the simulation of regional-scale atmospheric processes and local climate due to better representation of topographical effects and physical processes (Mizuta *et al.*, 2006; Kusunoki *et al.*, 2011).

This study aimed to assess present and future flood inundation areas over the Asia-Pacific region under climate change by using a topography-based analysis method. More specifically, this study investigated to what extent the potential inundation area may change and where in the Asia-Pacific region such flood risk may increase under future climate change condition. In addition, the flood risk change from the present to future was compared for two precipitation datasets MRI-AGCM3.1S and 3.2S. The output from 20-km resolution AGCM simulations (MRI-AGCM3.1S and 3.2S) was used. This study allows us to project potential future flood risk in relation to the future climate change.

GLOBAL DATASET

Figure 1 shows an overview of a dataset and study flow for computing potential inundation area by using the global dataset in this study.

MRI-AGCM3.1S and 3.2S

MRI-AGCM3.1S and 3.2S are the precipitation data used in this study to produce discharge data for each study period of time: Present (daily data from 1980 to 2004), Near Future (daily data from 2015 to 2039) and Far Future (daily data from 2075 to 2099) (Kitoh *et al.*, 2009). MRI-AGCM3.1S

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is the output of a super high-resolution global atmospheric general circulation model on the Earth Simulator (Mizuta *et al.*, 2006), jointly developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI), with a horizontal grid size of about 20 km and 60 vertical layers (top 0.1 hPa). MRI-AGCM3.2S is a slightly revised version of MRI-AGCM3.1S with improvement particularly in the frequency of tropical cyclones in the western North Pacific and seasonal change of the East Asian Summer Monsoon by changing the parameters shown in Table I (Mizuta *et al.*, 2012). Table I lists the difference in the specification between MRI-AGCM3.1S and MRI-AGCM3.2S. Inomata *et al.* (2011) corrected the bias of MRI-AGCM precipitation datasets by using grid-based APHRODITE daily precipitation datasets estimated from a rain-gauge-observation network.

BTOP model parameters

The BTOP distributed hydrological model used in this study was originally developed by Takeuchi *et al.* (1999) for the purpose of hydrological simulations over large river basins (Takeuchi *et al.*, 2008; Shrestha *et al.*, 2007; Hapuarachchi *et al.*, 2011). For calculating inundation

depths, the study used the Manning's roughness coefficient (n_0), the local channel slope (I_f) width (B_f) and the maximum daily discharge (Q_{max}) of the BTOP model with the Muskingum-Cunge method (Cunge, 1969). The BTOP discharge datasets were created for this study from MRI-AGCM3.1S and 3.2S.

HydroSHEDS

The Shuttle Elevation Derivatives at multiple Scale (HydroSHEDS) is produced by the NASA's Shuttle Radar Topography Mission (SRTM) (Farr *et al.*, 2007) in a consistent format for regional- and global-scale applications (Lehner *et al.*, 2006). The elevation layers, i.e., DEM (digital elevation model), are based on a combination of the original SRTM-3 and the digital terrain elevation data (DTED-1) of SRTM. In this study, DEM, main streams and flow directions were used to calculate potential inundation areas at 15 arc-second resolution (approximately 500 meters at the equator).

LandScan 2009

The study employed population data derived from the LandScan2009 Global Population Database at 30 arc seconds (1 km or finer), developed by the Oak Ridge National Laboratory (ORNL) for the United States Department of Defense (DoD). The LandScan is the finest population data available which describe both distribution and dynamics (day and night) of human population by using geospatial and temporal modeling for a high degree of location accuracy (Budhendra *et al.*, 2007).

METHODOLOGY

Study area

As the target study area, the Asia-Pacific region between 50N-10S and 65E-150 E (32,000,000 km²) was selected. This area covers about 21% of the world's land area with large rivers such as Ganges, Indus, Chang Jiang and Mekong. This region is extremely prone to flood disasters, especially the areas affected by Asian monsoons and typhoons/cyclones.

Definition of flood risk

Many factors are involved in defining flood risk. In this study, as described in the introduction, the authors defined flood risk ($RISK_{flood}$) as follows:

Figure 1. Integrated analysis flowchart for computing potential inundation area.

Table I. Specifications of the new and previous versions of MRI-AGCM projection

	MRI-AGCM3.1S	MRI-AGCM3.2S
Horizontal resolution	TL959 (20 km, 1920 × 960)	
Vertical levels	60 (top at 0.1 hPa)	64 (top at 0.01 hPa)
Time step	6 minutes	10 minutes
Cumulus convection	Prognostic Arakawa-Schubert (1974)	Yoshimura (2005)
Cloud	Smith (1990)	Tiedtke (1993)
Radiation	Shibata and Aoki (1989)	JMA (2007)
Gravity wave drag	Shibata and Uchiyama (1992)	Iwasaki <i>et al.</i> (1989)
Land surface		Hirai <i>et al.</i> (2007)
Boundary layer		Mellor and Yamada (level 2) (1974)
Aerosol (direct)	Sulfate aerosol	Five species

$$RISK_{flood} = function (Hazard_{flood}, EXP_{population}, Vul_{basic}) \quad (1)$$

where $RISK_{flood}$ is the flood risk of the area, $Hazard_{flood}$ is the potential inundation area, $EXP_{population}$ is the maximum number of affected people in the inundation area, and Vul_{basic} is the basic vulnerability of the inundation area. This definition of flood risk has been widely adopted in other studies (Crichton, 1999; UNDP, 2004; ADRC, 2005). In this study, the potential inundation area was calculated by the annual maximum daily river discharge with a 1/50 probability of occurrence (50-year flood). The flood risk of the inundation area was simulated by assuming the maximum value for the vulnerability factor due to unavailability of data such as coping capacity, resilience, and susceptibility.

Procedure

Figure 1 shows the outline of the procedure of this study. Input data at each grid cell adjusted to the employed GIS were calculated from the original data given at original grid cell. The following steps describe the preparation of necessary data to finally compare Present, Near Future and Far Future flood risks.

Step 1: Derivation of relative elevation model (REM)

To calculate flood risk according to the definition above, data for $Hazard_{flood}$ need to be prepared. In this study, the authors used flood inundation depth (FID) for this hazard factor. As shown in Figure 2, the relative elevation model (REM) of each cell is needed in order to obtain FID. The REM of an individual cell in the study area was derived from the elevation difference between the cell and its nearest downstream given river channel cell (target cell), based on the HydroSHEDS data (Figure 2(1)) by using the aforementioned topography-based method (Kwak *et al.*,

2010). Figure 2(2) shows a sample case of calculating the REM of the cells around a given river channel cell. In this case, the elevations of the river channel cell (target cell) and cell A* are 30 m and 31 m, respectively; thus, the REM of cell A* is +1 m. Accordingly, REM are determined for other cells.

However, REM is only capable of expressing depth with the accuracy of 1 m due to the limitation of HydroSHED15S/DEM. Improvement is necessary for REM to achieve a depth accuracy of less than 1 m by applying linear interpolation. Also, the DEM data are not capable of expressing main-stream banks (including artificial embankments), which also affects the accuracy of the FID model.

Step 2: Production of H_{max}

H_{max} was set as the maximum river water depth of the 50-year flood calculated based on MRI-AGCM 3.1S or 3.2S. H_{max} was calculated only for river channel cells. This dataset was produced by transforming from the BTOP discharge data by using Manning's steady, uniform flow resistance formula below (Chow *et al.*, 1988; Hapuarachchi *et al.*, 2011):

$$H_{max} = \{Q_{max} \times n_0 / (B_f \times I_f^{1/2})\}^{0.6} \quad (2)$$

Step 3: Calculation of FID

After determining H_{max} for each river channel cells, FID was calculated for each cell as the difference between H_{max} and REM ($FID = H_{max} - REM$). FID indicates the potential flood inundation depth of a given cell when H_{max} is greater than the REM of that cell ($REM < H_{max}$). In the case of $REM \geq H_{max}$, FID was not calculated because it means that no flooding is expected to occur over such cells.

Figure 2(3) illustrates how FID was derived for cells around a given river channel cell. The floodwater flows into the next cell with the lowest REM among those adjacent to the previous one.

Step 4: Calculation and comparison of $RISK_{flood}$

Finally, the potential flood risk of each flooded cell was determined by applying the calculated FID, as well as the hazard and exposure factors, to equation (1). In this study, the exposure factor was a function of the geographic distribution of population per square kilometers exposed to a given flood inundation area, based on the LandScan dataset.

The authors performed time-slice simulation for three different periods of time by repeating the procedure above to obtain flood risks in the respective cases of Present, Near Future and Far Future, and then compared them between MRI-AGCM3.1S and 3.2S for possible flood-risk change.

To this end, differential FID was calculated by subtracting the FID in Present from the FID in Near Future or Far Future. With the calculated flood risk in Present used as the benchmark, potential flood risk changes in Near Future and Far Future were estimated.

RESULTS

Figure 3 shows the overall results of this study. Figure 3a and b are the maps of 50-year flood inundation comparing Present, Near Future and Far Future of MRI-AGCM3.1S projection while Figure 3c and d for Present, Near Future and Far Future of MRI-AGCM3.2S. Table II shows the projected inundation area and population in flood risk areas,

Figure 2. Schematic diagram of the simple algorithm for computing potential flood inundation depths by using DEM, flow direction and river network in step 1. In Step 3 FID, the floodwaters in the target cell can overflow to its surrounding cells in 8 directions, depending on their DEM values.

Figure 3. Potential inundation areas in the Asia-Pacific region (50N-10S, 65E-150E), cases of Near Future and Far Future based on (a) and (b) of MRI-AGCM3.1S or (c) and (d) of MRI-AGCM3.2S. In the most of the potential inundation area (a, c and d), the inundation depth increase (differential FID) between 0 cm and 50 cm compared with the present flood. On the other hand, in Near Future (b), a differential FID of less than zero meters is clearly visible over the potential inundation area.

Table II. Potential 50-year flood inundation area in the Asia-Pacific region based on the BTOP model using the bias-corrected precipitation of MRI-AGCM3.1S or 3.2S

Potential inundation area	MRI-AGCM3.2 (Bias correction)			MRI-AGCM3.1 (Bias correction)		
	Hazard area (km ²)	Area (km ²) where FID increases	Area (%) where FID increases over 50 cm	Hazard area (km ²)	Area (km ²) where FID increases	Area (%) where FID increases over 50 cm
SFAC (2075–2099)	1,880,000	1,490,000	+21.2	1,850,000	1,500,000	+17.8
SNAC (2015–2039)	1,840,000	1,230,000	+ 8.9	1,793,000	990,000	+ 5.6
SPAC (1980–2004)	1,810,000			1,786,000		

as well as their rate of changes, in Present, Near Future and Far Future projected by the cases of MRI-AGCM3.1S and 3.2S.

The projected 50-year flood inundation area increases from Present to Far Future in both cases (MRI-AGCM3.1S: 1.78 million km² to 1.85 million km²; MRI-AGCM3.2S: 1.81 million km² to 1.88 million km²) (Table II), but the potential flood hotspots where FID increases more than 1 m in Far Future (red cells in Figure 3) increase at a greater rate of 21.2% with MRI-AGCM3.2S compared with 17.8% with 3.1S.

Table II also shows the respective rates of flood-risk change from Present to Far Future for both AGCM cases. Overall, these results are mutually consistent in that increased rainfall is likely to contribute to higher flood risk, and that greater flood risk is expected toward Far Future. It is also interesting that, in Figure 3a, the flood risk in Near Future stays at the same level as Present or shows a potential decrease. The yellow cells showing the negative differential FIDs are clearly visible over the potential flood area. This is due to a decrease in extreme rainfall projected in the case of MRI-AGCM3.1S. Since MRI-AGCM3.2S is a projection

with more extreme rainfall than 3.1S, this result suggests that flood risk may show a greater increase if climate change results in more extreme rainfall.

Additionally, in an attempt to estimate affected people in the case of a 50-year flood based on the two global rainfall datasets, the authors found that, with both datasets, the number of affected people may also increase at a greater rate of 6.1% (approximately 35.1 million people) with MRI-AGCM3.2S from Present to Far Future, compared with 4.9% (approximately 27.9 million people) with 3.1S.

Furthermore, it may be worth noticing that flood risk hotspots spread mainly in the downstream areas of the following rivers: Indus (Pakistan), Ganges (North of India), Chang Jiang (eastern China), Ayeyarwady (Myanmar), lower Mekong (Cambodia and Viet Nam), and Amur (China) in monsoon Asia, as shown in Figure 3a and b.

CONCLUSION

In this study, the authors developed the simple topography-based analysis method for flood risk assessment

over the Asia-Pacific region under climate change. Flood risk assessment was conducted using a 20-km resolution global atmospheric model outputs, focusing on the assessment of Present, Near Future and Future flood risks, particularly changes of flood inundation area according to FID, over the Asia-Pacific region with consideration of climate change impacts. The study found that flood risk may show a greater increase if climate change results in more extreme rainfall. In the future climate simulation by MRI-AGCM3.2S, the change of flood risk is consistent with extreme rainfall. Analyses were conducted by dataset and time period in terms of flood-risk area, affected population and their change rates. Their results showed an upward trend.

For future regional flood risk assessment, improvement is necessary to increase accuracy in identification of flood inundation area by calibrating local hydro-geomorphological parameters. In addition, the BTOP outputs of flood time-series, which are the basis of this analysis, need further improvement in the processes of, for example, evapo-transpiration and snowmelt mechanisms. Furthermore, the study should be extended to basins less than 5,000 km² and mega deltas located in coastal areas.

Finally, the prospective change of flood risk should be examined more closely under various climate change scenarios. In addition, large-scale assessment results, such as those of this study, should be validated through smaller-scale assessment, for example, by studying a specific local river basin.

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SUPPLEMENT

Supplement 1. Relationship between precipitation and maximum daily discharge related to flood risk.

Figure S1. Differences (=Far Future–Present) of Top 0.5% bias-corrected daily precipitation (a) and maximum daily discharge projected (b) in the case of MRI-AGCM3.2S.

Figure S2. Enlarged version of Figure 3c showing difference FID (=Far Future–Present) based on MRI-AGCM3.2S.

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