

# EXTREME RIVER DISCHARGE UNDER PRESENT AND FUTURE CLIMATE CONDITIONS USING HIGH-RESOLUTION CLIMATE MODEL DATA

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This paper investigates the impact of climate change on extreme river discharge. A high-resolution climate model data was used to drive an integrated hydrological model and river discharge was simulated for the late 20<sup>th</sup> and 21<sup>st</sup> century. Flow duration curves were derived from the bias adjusted river discharge data. The 5<sup>th</sup> and 95<sup>th</sup> percentiles of flow were calculated and changes were examined for major river basins around the world. Results showed that high-flow will increase in many river basins but the low-flows may decrease or remain relatively constant. Analysis based on river basin size located in different climate regions revealed that small river basins will be impacted more than large river basins. The spatial variability of changes are also significant and it can be anticipated that the river basins in tropical and temperate climate regions fare worse in terms of decreased low-flows than those in cold and polar regions.

**Key Words:** *climate change, river discharge, low-flows*

## 1. INTRODUCTION

Climate change leads to changes in all domains of the global freshwater system and trends of change in some of the domains have already been observed during the last decades<sup>1)</sup>. Increase in global average temperature due to warming of earth is expected to intensify the natural water cycle, however, the effects on the hydrological cycles are still uncertain<sup>2)</sup>. This is likely to result in a shift in peak streamflow from spring to winter in many areas with lower flows in summer and autumn. Flood magnitude and frequency are likely to increase in most regions and volumes of low-flows are likely to decrease in others<sup>1),3)</sup>. Model projected results have

shown that the increasing temperature trend will continue further. In the warmer world evaporation into the atmosphere as well as the water-holding capacity of the atmosphere increases resulting in favorable conditions for increased climate variability with more intense precipitation and more droughts<sup>4)</sup>. The hydrological cycle will thus be intensified with changing pattern of precipitation which may increase in one season and decrease in another<sup>5),6)</sup>.

Due to the intensification of the hydrological cycle precipitation will increase on average; however, substantial variations in spatial as well as seasonal changes in the precipitation pattern are anticipated<sup>6)</sup>. Changes in both precipitation and

evaporation are expected as a result of climate change, and so changes in streamflow are also anticipated. Change in river runoff is determined by the relative magnitude of changes and other factors including the ability of soil to absorb and hold moisture. Therefore, river discharge may increase in some regions due to increased precipitation while in other regions, increased precipitation may be offset by increased evapotranspiration with no substantial change in river runoff. Many studies have shown that the annual mean river discharge will increase in many regions, particularly in the high latitudes<sup>7),8)</sup>. Most of these studies have examined the future water resources availability on the annual scale. Even though the average annual runoff gives a strong indication of water resources availability in the future, they tend to disguise the information on how variability of flow regimes will affect the availability of water resources with respect to time. Indeed, monthly and daily flows are of great practical importance from the point of view of water resources management, e.g., hydropower development<sup>9),10)</sup>, and the well-being of the aquatic ecosystem. Therefore, it is important to understand how climate change will affect the temporal variability of flow in sub-annual scale. Here we simulated daily river discharge at the global scale using high-resolution climate forcing data and analyze the impact of climate change on the extreme flows. Flow duration curves are prepared for major river basins and change in high-flows ( $Q_5$ ) and low-flows ( $Q_{95}$ ) are analyzed. Finally, the variability of change in extreme flows in different climate regions and different river basins is examined.

## 2. MODEL, DATA AND METHODS

### (1) The Hydrological Model

The hydrological model used here is an integrated global water resources assessment model developed by Hanasaki *et al.*<sup>11),12)</sup> which simulates daily water flow globally at a spatial resolution of  $1^\circ \times 1^\circ$  (longitude and latitude). The model simulates both the natural and anthropogenic water flow; however, in this study we ran the model in natural cycle mode in which the surface hydrology module is coupled with river routing model. All anthropogenic water cycle modules were deactivated because it was out of scope of this study to gather necessary data for the future. The surface hydrology module is based on a bucket model<sup>13),14)</sup> and calculates the energy and water budget including snow. Details of model formulations and calibration can be found at Hanasaki *et al.*<sup>11)</sup>. The river routing model is the Total Runoff Integrating Pathways (TRIP)<sup>15)</sup>. It consists of  $1^\circ \times 1^\circ$  digital river

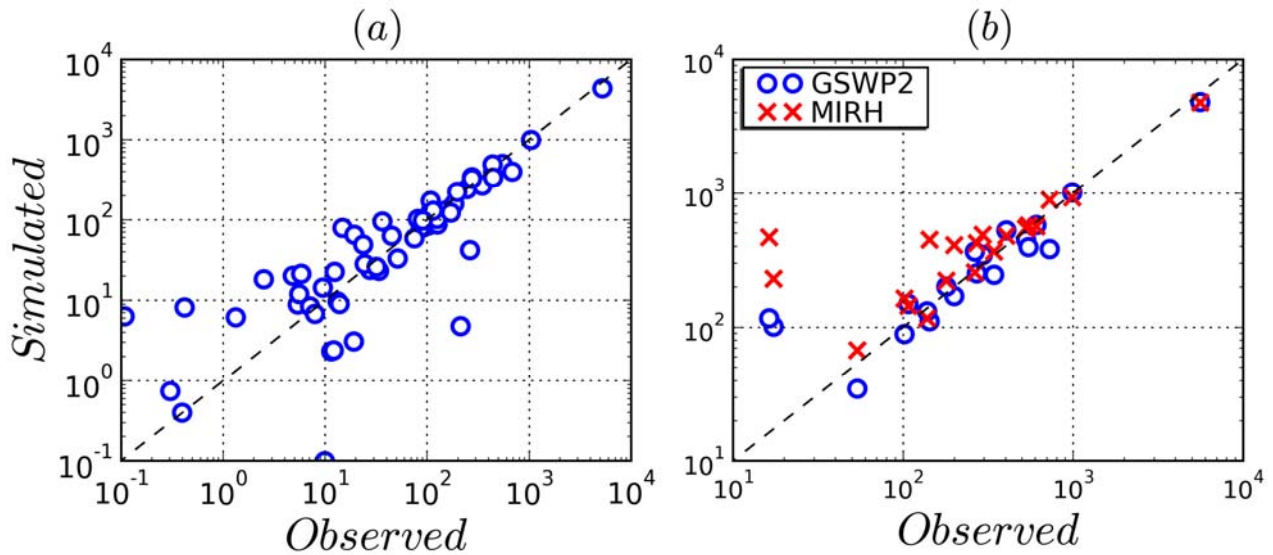
map and routes the river discharge from the runoff generated in each grid and isolates each river basins and inter-basin transport through river channels and collects the routed discharge to the river mouth. A constant flow velocity of 0.5 m/s is used globally.

### (2) Forcing data

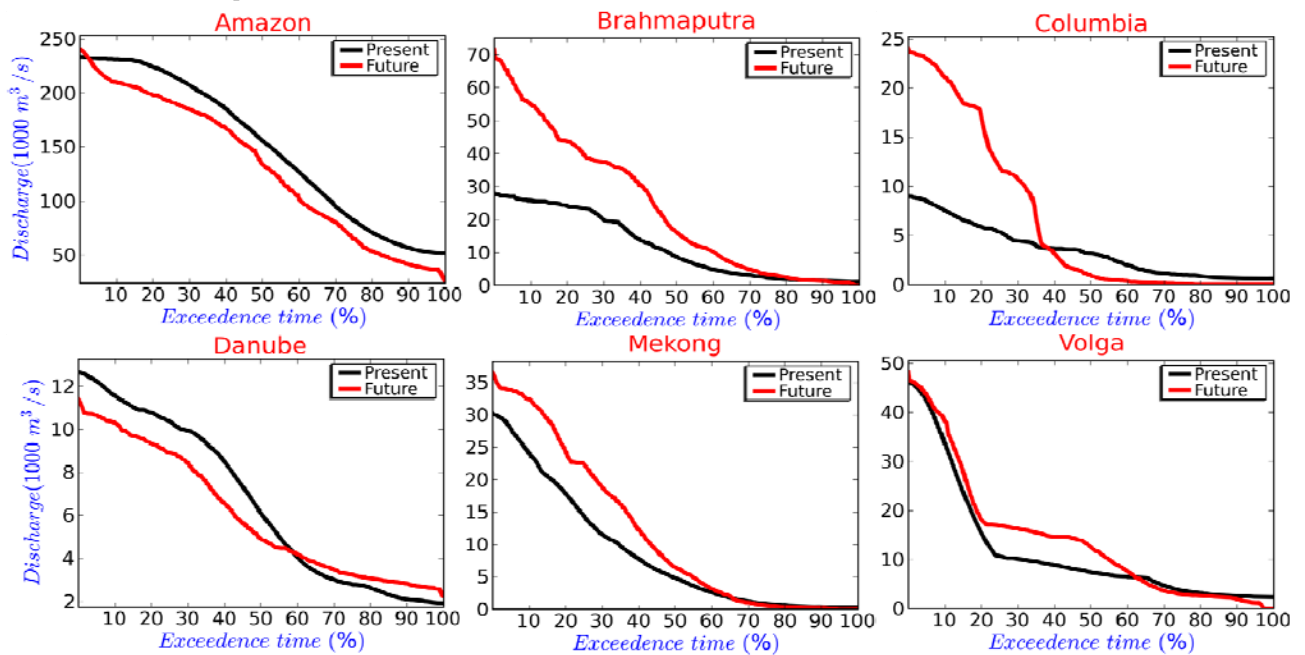
Three sets of meteorological forcing data were used to drive the Integrated Model. First, we used the meteorological forcing data produced by the second Global Soil Wetness Project (hereafter, GSWP2). Here we use the seven input meteorological components namely, precipitation, air temperature, surface air pressure, specific humidity, wind speed, downward shortwave radiation and downward long wave radiation produced for the baseline experiment version 1 (B1). These data cover 10 year period (1986 – 1995) and are available at 3-h time intervals for  $1^\circ \times 1^\circ$  (longitude and latitude) global grids. Second, we used the meteorological forcing data for the late 20<sup>th</sup> century (1971-2000) from a high-resolution climate model called the MIROC<sup>16)</sup>. MIROC data consists of all meteorological forcing components that are provided by the GSWP2 at the same temporal resolution. Third, we used the meteorological forcing data for the late 21<sup>st</sup> century (2071-2100) as projected by the same climate model for A1B emissions scenarios of the IPCC<sup>17)</sup>. All data from MIROC were regridded to  $1^\circ \times 1^\circ$  (longitude and latitude) from the original spatial resolution of T106 ( $\sim 1.25^\circ \times 1.25^\circ$ ).

### (3) Methods

A conventional method was adopted to estimate current and future river discharge at the global scale. The hydrological model was run with three sets of aforementioned meteorological forcing datasets at a spatial resolution of  $1^\circ \times 1^\circ$  (longitude and latitude). The model simulates daily river runoff which is then used to drive the river routing model. First a control simulation was made for a period of 1986 – 1995 using the GSWP2 forcing data. Then the 20<sup>th</sup> and 21<sup>st</sup> century river discharge was simulated using MIROC input forcing data. Scenarios representing the current climate and future climate were derived by assuming 30 year time slice of 1971-2000 and 2071-2100 respectively. Thus, average daily river discharge was calculated by taking 30 year mean for both the baseline and future scenarios. Then the future river discharge was adjusted for model biases with reference to the river discharge obtained from the control simulation using GSWP2 forcing data. Finally, daily flow duration curves were derived from the daily streamflows and changes in low-flows and high-flows were calculated.



**Figure 1:** Comparison of observed and simulated annual mean flow in  $\text{km}^3$ : a) GSWP2 and b) GSWP2 and MIROC



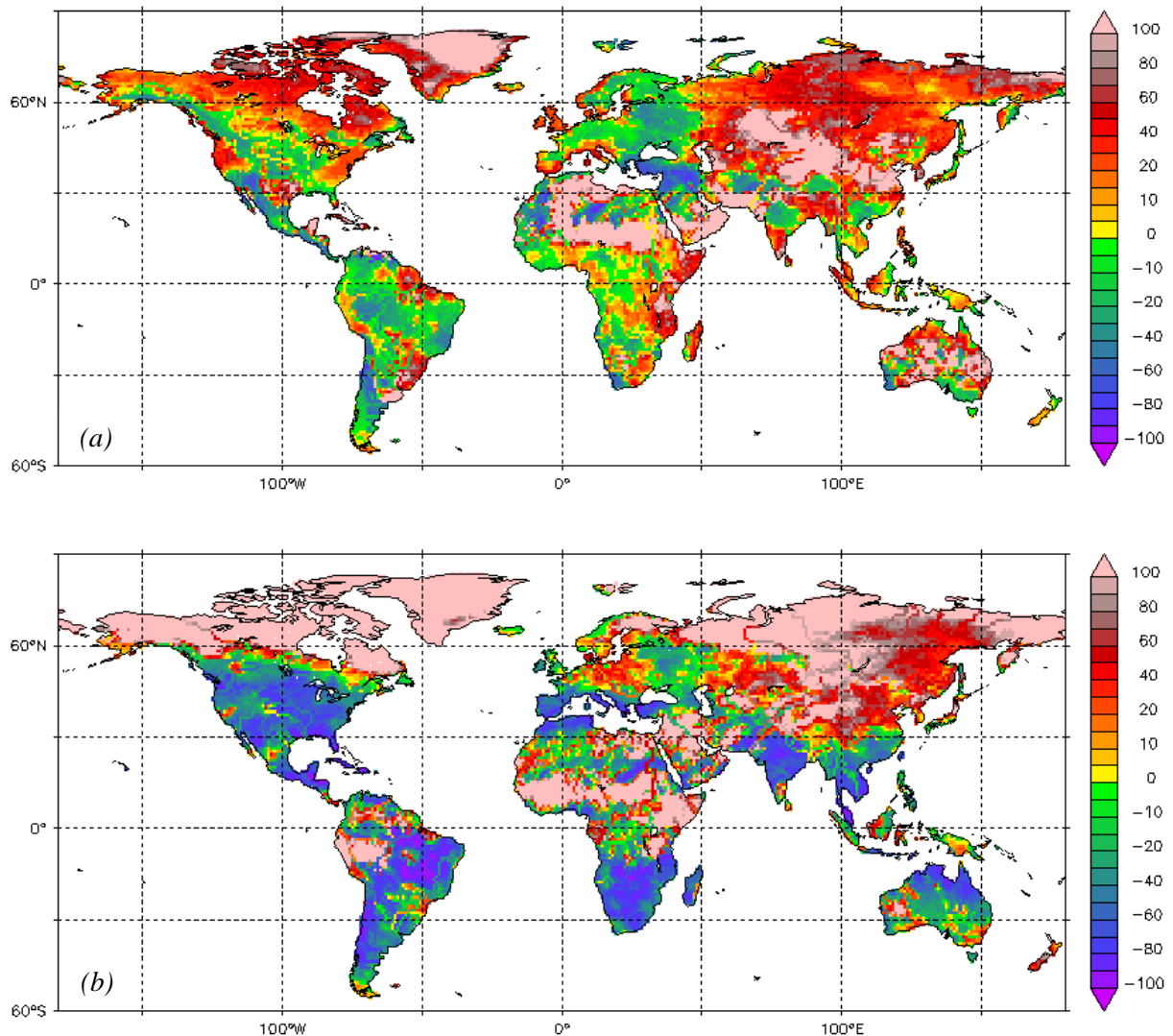
**Figure 2:** Flow duration curves for present (defined as the mean of 1986-1995, derived from GSWP2 simulation) and the future condition (defined as the mean of 2071-2100, derived from future projections) for major river basins

### 3. RESULTS AND DISCUSSIONS

#### (1) River discharge simulation

We evaluated the simulated river discharge by comparing with the observed river discharge at the major river basins around the world. Observed river discharge was obtained from the Global Runoff Data Center (GRDC). About sixty rivers having basin area larger than  $150,000 \text{ km}^2$  were selected considering the fact they cover different climate regions around the world. First, annual mean for 1987 was calculated and compared. As depicted in **Fig. 1(a)** results show that the GSWP2 control run results are in strong agreement with the observed values. The correlation coefficient between the two

sets is 0.94 and the mean bias is 8%. Details of model validation can be found at Hanasaki *et al.*<sup>11)</sup>. They used a number of different forcing datasets including GSWP2-B1 and showed that the model reproduces the observed flow within plausible limits in Asia, North America, South America, Oceania, and at the global scale. Second, to check the reliability of MIROC forcing datasets, we compared the two sets of simulated results with the observed data. Here, we check five year mean from 1986 to 1990 for selected rivers for which observed discharge is available for this period. In **Fig. 1(b)** it can be seen that the MIROC forcing overestimates river discharge in most of the river basins. Therefore, it can be inferred that MIROC forcing data have



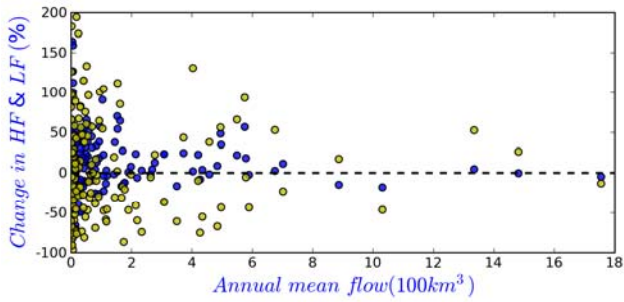
**Figure 3:** Change in extreme flows of future (defined as mean of 2071-2100) against the present condition (defined as the mean of 1971-2000) in %: a) high-flow ( $Q_5$ ) and b) low-flow ( $Q_{95}$ )

model biases and it is necessary to remove those biases before using the data for future projection. Here we correct the simulated runoff by using a simple method of bias correction as suggested by Oki *et al.*<sup>18)</sup>. In this method, difference between the future scenario and the baseline scenario is first calculated, which is the change in river runoff as projected by the GCM. The change is then added to the observed runoff. Here, we use the control run simulation output instead of observed data because it is notoriously difficult to obtain observed runoff data at the global scale. It is assumed here that the control run results are reliable enough to be used for adjusting future runoff because the annual runoff volume is well simulated.

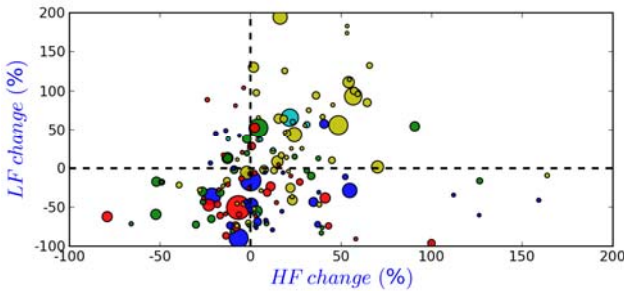
## (2) Flow duration curves

**Fig. 2** shows flow duration curves for some of the major river basins considered in this study (only

six shown). Results indicate that most of the rivers are likely to experience increased wet-season flows and decreased dry-season flows. This indicates that water resources availability will decrease during dry season which will undermine human water withdrawal as well as the environmental well-being. Flows during wet seasons may increase which however cannot be utilized unless enough storage facilities are in place. Most of the rivers in south-east Asia, southern part of the United States, Central America, and many rivers in South America will suffer from such changing flow regimes. There are some exceptions where the opposite case is likely to happen, for example in the Danube river basin. There are also other rivers in high latitude northern hemisphere where dry-season flows are likely to increase in future. This is the most favorable condition with more water in dry seasons and less flows during wet and flood seasons.



**Figure 4:** Change in extreme flows against the annual mean flow; blue and yellow circles represent  $Q_5$  &  $Q_{95}$  respectively



**Figure 5:** Change in  $Q_{95}$  vs.  $Q_5$ . Colored circles indicate rivers in different climate regions. Red: Tropics; Green: Dry; Blue: Temperate; Yellow: Cold; Cyan: Polar. Size of circle indicates river basin area.

### (3) Change in extreme flows

Many studies have reported that the annual mean river discharge in many parts of the world may increase in the future<sup>7,19</sup>. While such analyses, based on annual or monthly runoff, give an indication of water resources availability in future climate conditions, they do not reflect the variations in the extreme flows in the changing climate. Therefore, we analyzed how the high-flows and low-flows will change in the future. **Fig. 3** shows the spatial distribution of change in high-flows (defined as 5% of time of a year available flow) and low-flows (defined as 95% of time of a year available flow). In the high latitude northern hemisphere both high-flows and low-flows will increase in future. However, in many parts of the southern hemisphere high-flows may increase or decrease by small amount but the low-flows are likely to decrease substantially. Regions where high-flows increase but low-flows decrease are eastern United States, some parts of Central America, southern parts of India, Australia, East Asia, Some parts of Middle East and southern Europe. In contrast, high-flows will decrease and low-flows will increase in some parts of Europe; in others both high and low-flows may increase. Results show that there is an impact of river routing in the downstream region of a river. For example, low-flows at the river mouth of Nile River and

Amazon River increase despite decrease in runoff in the neighboring grids because of the impact of upstream region where river discharge increases.

Because the changes in extreme flows are regionally diverse, we analyzed the changes for different river basins in different climate regions. We examined the changes in high-flows and low-flows in about 165 rivers which have basin area larger than  $100,000\text{km}^2$  and are located in different climate regions. As shown in **Fig. 4**, changes in extreme flows have inverse relationship with the river basin area and in many rivers high-flows increase but low-flows decrease. **Fig. 5** shows the change in high-flows and low-flows for the rivers in different climate regions. Both high-flows and low-flows increase in cold and polar regions but in tropical and temperate regions low-flows decrease and high-flows increase or remain relatively constant in some rivers. Rivers in dry regions show varying characteristics. It should be noted that the absolute amount of changes in dry regions are comparatively less due to very small annual flow volume, however, percentage changes could be high and also the bias correction causes distortion in some grids which have very low runoff.

## 4. SUMMARY AND CONCLUSIONS

Historical and future river discharge was simulated by using high-resolution climate model data. A simple bias adjustment method was applied to remove model biases from the future river runoff. Simulated daily river discharge was used to derive flow-duration curves for major river basins. Results showed that flows during dry seasons are likely to decrease while the wet-season flows may increase in many rivers. Then, different percentiles of flows were calculated and the change in 5<sup>th</sup> and 95<sup>th</sup> percentiles of flows were examined. It was found that high-flows may increase but low-flows may decrease in many parts of the world, except for the snow-dominated high latitude regions in the northern hemisphere. In the snow dominated regions, even low-flows may increase due to excessive snow melt due to global warming.

It was found that the downstream regions of some river basins are likely to be impacted by the changes in upstream regions. Therefore, change in river discharge can be different than the change in runoff along the river channels. River discharge at the river-mouth might increase due to increase in precipitation at the far upstream even though the precipitation and hence runoff in the neighboring regions may actually decrease.

Finally, we analyzed how different are the changes in extreme flows in river basins of different



size and rivers located in different climate regions. Results indicated that changes in extreme flows are more severe in smaller rivers than in the larger ones. Moreover, rivers in temperate and tropical regions are likely to fare worse due to decrease in low-flows. However, both the low-flows and high-flows may increase in many rivers in cold and polar regions.

This study revealed that the annual mean flow may increase at the global scale, however, low-flows will decrease in many regions. High-flows may increase in many regions which however cannot be fully utilized unless huge storage facilities are built. However, results presented here are entirely based on the future projections of river discharge by the climate model and bias correction method we adopted is quite simple. Applying more sophisticated bias correction methods to precipitation and temperature forcing might give more realistic river discharge for the future. Moreover, this study also has the limitation that the future projections are based on a single climate model. The authors are aware that there could be considerable differences among the results projected by different models; however, it was difficult to obtain high-temporal-resolution forcing data from different climate models. It was also out of scope of this study to use multiple land surface models to examine the capability of the models to simulate the low-flows. Therefore, examining the impact of climate change on extreme river discharge by considering all these issues might give further insight on the variability of streamflows with time.

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