H. XU and Y. Luo.: Climate change impacts and uncertainties in river discharge in two climate regions in China

Authors’ response to comments by reviewers

We greatly appreciate the editors and all the anonymous reviewers’ valuable interactive comments on the manuscript. We have attempted to address every point raised by them. The following are our point-point replies, with reference to the order of the comments by the reviewers.

Anonymous Referee #1:

We appreciate the Referee #1’s comments and suggestions on our manuscript. Our responses are as follows.

Comment 1: Uncertainty assessment is of utmost importance for climate impact studies. Current paper assesses the uncertainty caused by climatic scenarios, but has not given enough consideration on the uncertainty resulted from parameterization process of hydrological model. In section 2.2.1, it was pointed out Nash-Sutcliffe efficiency of SWAT model are only reached 0.44 and 0.57; 0.64 and 0.67 for two river basins for simulation of monthly runoff. Therefore, it was needed to take uncertainty from model performance into account.

Response 1: We have clearly stated the reason why we just quantify the uncertainty constrained by GCMs in the final manuscript in Line 10-12, Line 18, and Line 24-25 Page 2. We also have indicated the method and threshold used in hydrological model calibration in the final manuscript in Line 5-6 and Line 10-15 Page 6.

Comment 2: With the deepening of our understanding on climate change and its possible triggers, emission scenarios have been updated several times, such as IS92, SRES, RCPS and SSPS. Current paper projects the possible changes of hydrological regime in two river basins based on SRES A1B for three time periods (2020s, 2050s and 2080s). My suggestion to authors is to update their research results by referring IPCC AR5 report.

Response 2: We have clarified the reason that emission scenarios selected and datasets used in this study in the final manuscript from Line 28 Page 3 to Line 2 Page 4.

Anonymous Referee #2:

We greatly appreciate the Referee #2’s detailed comments and suggestions on our manuscript, that really helpful for us to improve the current manuscript, and that for future scientific paper organizing. Our responses are as follows.

Comment 1: Section 2.2.1: Because the two catchments investigated are located at the semi-arid climate region and the subtropical humid climate region, respectively, whether the SWAT model is suitable for two different climate regions? It is better to add more detailed descriptions on model development.

Response 1: We have added detailed descriptions on model development in the final manuscript in

Line 7-11 Page 5.

Comment 2: Lines 10-13,

Page 7104: Which kind of data series were used for model validation? 1961-1997 and 1961-1994? or 1991-1997 and 1991-1994?

Response 2: We have corrected this in the final manuscript in Line 4-5 Page 6.

Comment 3: Titles of the section 3.1.1 and 3.1.2 are more suitable for "Changes of annual: : :: : :" and "Changes of seasonal: : :: : :"

Response 3: We have changed the titles to "3.1.1 Changes of annual temperature and precipitation", "3.1.2 Changes of seasonal temperature and precipitation", and also have changed the title to "3.2.1 Changes of average hydrograph", "3.2.2 Changes of annual and seasonal river discharge"

Comment 4: Section 3.2.3: Extreme discharge analyzed in this paper is the annual mean discharge. It is better to use daily flow data for extreme events. Because short time scale data is more representative for extreme events.

Response 4: The extreme discharge analyzed in this paper is based on simulated monthly mean discharge. The techniques adopted for downscaling in this study do not account for projected changes in the intensity of rainfall at daily timescales. So the simulated daily flow is not used for extreme events analyzed in this study.

Comment 5: Line 24, Page 7110: Q50 is usually described for a 50th percentile value rather than a mean value. Therefore, it needs to be clarified whether the 50th percentile or the mean value is used in this study?

Response 5: Q50 is the median flow with the monthly mean flow exceeded in 50% of months over the simulated 30-yr period. We have corrected mean flow to Q50 or "median flow" throughout all the final manuscripts in Line 11 Page 1, Line 9 Page 2, Line 17, 19, 21, 23 Page 12, and Line 6-8 , 14 Page 16.

Technical corrections: 1. Line 15, Page 7106: "Huangfuchan" should be "Huangfuchuan"; 2. Figure 7: Please add units for the x axis.

Response: We have corrected the first one according suggestion in Line 15 Page 8, and revised the figure title as "Figure7. Extreme flows changes for 7 GCMs projections under 2020s, 2050s and 2080s time horizons for River Huangfuchuan (left) and River Xiangxi (right) (% difference from 1961–1990 baseline) for Q05, Q50 and Q95 flows (i.e. exceedance in % of months over the simulated 30-yr period)" in Page 27.

J. Ngaina (Referee)

General comments: The study has assessed the impacts of climate change on river discharge in two catchments representing different climate regions in China using downscaled multiple (7) Global Climate Models (GCMs) applied to semi-distributed hydrological models Soil Water Assessment Tools (SWAT). The study has stated the problem, methodology and results clearly to support its conclusion. The study gives valuable insights towards understanding the impacts of climate change on river discharge in different climate regions. To further improve the readability of the paper, the authors should consider breaking most of the sentences that are very long to into multiple sentences and also recheck grammatical errors resulting from slight omissions.

Response: We have tried our best to reorganize the long sentences to multiple sentences and recheck grammatical errors in the final manuscript.

Specific comments: The current paper has assessed the uncertainty in projected discharge for three time periods (2020s, 2050s and 2080s) using seven equally weighted GCMs for the SRES A1B scenario. However, understanding on climate change has increased especially with regards to emission scenarios such as the Representative Concentration Pathways (RCPs). Further, the study has used the CMIP3 datasets against the updated CMIP5 datasets which are currently available (released in 2013) and contains more models and advanced than CMIP3 datasets. Therefore, it would be critical for authors to clearly state the criteria used to select the climate scenario (i.e. the A1B SRES scenario) and datasets used in the study. However, the results presented and assessment of uncertainty based on SRES scenario and CMIP3 datasets would not be much different even if the RCP scenarios and CMIP5 datasets were used. Although the study has utilized ClimGen as a downscaling tool, dynamical downscaling would have been ideal for this study. The conclusion has been made based using output from the multi-ensemble models. However, it would have been great to know results based on an ensemble of the 7 models.

Response: The same as we response to Anonymous Referee #1, We have clarified the reason that emission scenarios selected and datasets used in this study in the final manuscript from Line 28 Page 3 to Line 2 Page 4.

Additionally, we have already quantified the uncertainty of climate change on river discharge for more catchments in China under RCP scenarios and CMIP5 datasets recently. Basically, the finding almost like the your deduction that there are no substantial difference in results about uncertainty based on under the RCP scenarios and CMIP5 datasets comparing with that presented and assessment in this manuscript.

Considering the downscaling method, we didn’t get sufficient climate projections based dynamic downscaling method forcing by multi-GCMs for the simulation in our manuscript. Fortunately, we are excited to know that more climate projections are available recently from CORDEX (A COordinated Regional climate Downscaling EXperiment) by dynamic downscaling method. We would like use the climate projection based on dynamical downscaling in our future research.

We have plotted the projected temperature, precipitation and discharge of ensemble of the 7 models in Figure 4 and Figure 8.

Technical corrections

- Line 7, (page 7100): "We assessed" should be changed to "The study assessed". The use of "we" should also be adjusted throughout the manuscript e.g. Line 14 (page 7100), Line 11 (page 7102), Line 18 (page 7103) etc.

- Line 14, (page 7100): " -29 to 139 " should be changed to "-29 to 139 %"
- Line 21 to Line 25, (page 7101): Provide references to the cited work. References should also provided to all cited literature in the manuscript e.g Line 4 to line 10, (page 7102 that starts with "In a previous study"), Line 6 (page 7103, which starts with "The River Xiangxi lies") etc.
- Line 25, (Page 7104): The sentence " ... used in this study seven GCMs were from ..." should be rewritten for clarity e.g. " ... used in this study utilized seven GCMs from ... "
- Line 1, (Section 5, conclusion): "assesse" should be changed to "assessed"

Response: We have corrected the final manuscript according to suggestion.

S. Rwigi (Referee)

General comment: In my review report, I have as much as possible tried to answer the following questions as honestly as I can.

Response: We really appreciate your valuable interactive comments and supports about the manuscript, that really helpful for us to improve the current manuscript, and that for future scientific paper organizing. Our responses are as follows.

Comment 1: Does the paper address relevant scientific questions within the scope of HESS? The paper has made a bold attempt to address scientific questions within the scope of HESS. It has addressed the important question of the impacts of climate change on water resources. Bearing in mind that water is a critical component in economic as well as social development, I consider this paper relevant.

Comment 2: Does the paper present novel concepts, ideas, tools, or data? The paper has comprehensively described the input data to the hydrological model together with their sources. The concept of model calibration is well stated in section 2.2.1. The concept of climate scenarios, projections and uncertainties is fairly well brought out in section 2.2.2.

Comment 3: Are substantial conclusions reached? The paper has reached substantial conclusions well backed by the results. It has concluded that climate change has obvious impacts on river discharge in terms of both mean and extreme flows.

Comment 4: Are the scientific methods and assumptions valid and clearly outlined? The paper has fairly well outlined the calibration method of the hydrological model and the need to use multiple climate models when predicting future climate for use in impacts studies.

Response: For point 1 to 4, the great supports from the reviewer really encourage us both for the revision of the manuscript and for future scientific paper organizing.

Comment 5: Are the results sufficient to support the interpretations and conclusions? The results, as presented, are fairly sufficient to support the interpretation and conclusions made in the paper. The paper should however make it clear that the streamflow discussed in the results is coming from the hydrological model and not from the GCMs as the paper seems to imply.

GCMs are only providing input data to the hydrological model (SWAT). This needs to come out clearly.

Response: We have changed the title to “3.2 Projected discharge based on hydrological model” in the final manuscript.

Comment 6: Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? In my view, the description of the experiment is sufficiently complete but not precise. There is need to describe the method used to calibrate SWAT model and the criterion used to assess the performance of the calibrated model.

Response: The same as we response to Anonymous Referee #1,We have indicated the method and threshold used in hydrological model calibration in the final manuscript in Line 5-6 and Line 10-15 Page 6.

Comment 7: Do the authors give proper credit to related work and clearly indicate their own new/original contribution? In my view, the authors have given proper credit to related work. They need however, to come out more clearly on their own contribution.

Response: We have added the necessary references (See references part) in the final manuscript and tried to make more clearly on their own contribution in the final manuscript.

Comment 8: Does the title clearly reflect the contents of the paper? Yes.

Comment 9: Does the abstract provide a concise and complete summary? Yes.

Response: many thanks for the support from Point 8-9

Comment 10: Is the overall presentation well structured and clear? The overall presentation is well structured and clear. In my view however, section 2.2.1 has some contradiction. The authors state that they used an already calibrated SWAT model of both rivers Huangfuchuan and Xiangxi in the opening paragraph. But in line 10, they suddenly change and describe how the model was calibrated. It is my considered opinion that the results of the model calibration presented in this section should be presented in section 3.

Response: This study is made based on previous calibrated SWAT model. We think some details of the models, the data they employed, how they were calibrated, and their performance could make the current paper "stands on its own". But we don’t want move the part to section3.

Comment 11: Is the language fluent and precise? The English language has issues of grammar which interferes with the flow and readability. There is need to check on the grammar in order to improve the quality of the paper.

Response: We have checked on the grammar in the final manuscript.

Comment 12: Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Most of the abbreviations, symbols and units used in this paper are well defined. There are a few cases however, that need improvement. Ensure that you state the names in full the first time they appear before using abbreviation e.g. United States (US) page 7103 line 18.

Response: We have US to “United States” in Line 6 Page5 in the final manuscripts.

Comment 13: Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? I suggest that section 2.2.1 on hydrological model calibration be modified. The authors should stick to the use of and already calibrated model or discuss the calibration methods but not both. Use of both is confusing to the reader. Section 3.1.3 on uncertainties in temperature and precipitation projections should be summarized to at most one page. Section 4 on discussion is too long and should also be summarized to at most one page. The first paragraph of section 5-conclusions should be deleted. It is not part of the conclusion but fits very well in the summary.

Response: We have indicated the method and threshold used in hydrological model calibration in the final manuscript in Line 5-6 and Line 10-15 Page 6. We have tried our best to summarize section 3.1.3 (Line 6-21, 28-29 Page 10; Line 1-2, 9-13 Page 11) and section 4 (Line 21-23, 26-19 Page 13; Line 1 Page 14) in the final manuscript and have deleted the first paragraph in section5 in Line 24-27 Page 15.

Comment 14: Are the number and quality of references appropriate? The paper has some recent references, sufficient number of references, and a good number sufficiently authoritative references, I therefore, consider the number and quality of references appropriate.

Comment 15: Is the amount and quality of supplementary material appropriate? In my view, the amount and quality of supplementary material used in the paper is fairly appropriate.

Response: Many thanks for point 14-15. The great supports from the reviewer really encourage us both for the further revision of the manuscript and for future scientific paper organizing.

Climate change and its impacts on river discharge in two climate regions in China

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Abstract

Understanding the heterogeneity of climate change and its impacts on annual and seasonal discharge, and the difference between ~~mean~~ median flow and extreme flow in different climate regions is of utmost importance to successful water management. To quantify the spatial and temporal heterogeneity of climate change impacts on hydrological processes, this study simulated river discharge in the River Huangfuchuan in semi-arid northern China and the River Xiangxi in humid southern China. ~~We~~ The study assessed the uncertainty in projected discharge for three time periods (2020s, 2050s and 2080s) using seven equally weighted GCMs for the SRES A1B scenario.

Climate projections that were applied to semi-distributed hydrological models Soil Water Assessment Tools (SWAT) in both catchments showed trends toward warmer and wetter conditions, particularly for the River Huangfuchuan. Results based on seven GCMs' projections indicated -1.1 to 8.6 ℃ and 0.3 to 7.0 ℃ changes in seasonal temperature and -29 to 139 % and -32 to 85 % changes in seasonal precipitation in River Huangfuchuan and River Xiangxi, respectively. The largest increases in temperature and precipitation in both catchments were projected in the spring and winter seasons. The main projected hydrologic impact was a more pronounced increase in annual discharge in the River Huangfuchuan than in the River

Xiangxi. Most of the GCMs projected increased discharge in all seasons, especially in spring, although the magnitude of these increases varied between GCMs. Peak flows was projected to appear earlier than usual in River Huangfuchuan and later than usual in River Xiangxi. While the GCMs were fairly consistent in projecting increased extreme flows in both catchments~~, the increases~~ ~~were~~ with ~~of~~ varying magnitude compared to ~~mean~~ median flows. For River Huangfuchuan in the 2080s, median flow changed from -2 to 304 %, compared to a -1 to 145 % change in high flow (Q05 exceedence threshold). For River Xiangxi, low flow (Q95 exceedence threshold) changed from -1 to 77 % and high flow changed from -1 to 62 %, while median~~mean~~ flow changed from -4 to 23 %. The uncertainty analysis provided an improved understanding of future hydrologic behavior in the watershed. Furthermore, this study indicated that the uncertainty constrained by GCMs was critical and should always be considered in analysis of climate change impacts and adaptation.

Key words: climate change; climate region; catchment; discharge; uncertainty

1. Introduction

The impacts of climate and hydrological changes cover all spatial scales, from local to global (Lahmer et al., 2001; Coulthard et al., 2005). There is now substantial evidence indicating that over the most recent decades, the global hydrological cycle has already been responding to observed global warming (Bates et al., 2008), which includes increasing atmospheric water vapor content and changing precipitation pattern. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (Jiménez Cisneros et al., 2014). To some extent, global climate change has also changed the availability of water resource in China. The precipitation, evaporation, and discharge of China’s main rivers and lakes have changed to varying degrees. But in general, the measured discharges of northern rivers such as the Haihe, Yellow, and Liaohe have decreased (Second National Assessment Report for Climate Change, 2011). In contrast, the water cycle in southern China is significantly different from that of northern China (Liu et al., 2004). Moreover, there is evidence that water cycle will likely intensify further. So exploring the impacts of projected climate change on river discharge in the south and north China will be an interesting topic.

Global Climate Models (GCMs) are useful tools for simulating climate system and developing climate change research, which generate possible future climate scenarios. Within the IPCC AR5 water sector, most hydrological projection studies use the precipitation and temperature downscaled from GCMs to driven hydrological models. From these studies, it is abundantly clear that climate change has the potential to substantially impact water resource. It emerges the uncertainties in projected changes to river runoff constrained by the uncertainties in regional climate projection. Generally, GCMs are considered to be the largest source of uncertainty for quantifying the impacts of climate change revealed by several previous researches (Rowell., 2006; Prudhomme and Davies., 2009; Wilby and Harris., 2006; Xu et al., 2011). Considering the usefulness of climate scenarios for the decision-making and substantial uncertainties in climate projection, better quantifying uncertainties is helpful to reduce the future risk and adopt adaptive water management.

In a previous study, two typical sub-catchments River Huangfuchuan of the Yellow River and River Xiangxi of Yangtze River~~s~~ were selected as study areas for quantitative evaluation of the projected impacts and multi-source uncertainties of climate change on river discharge for the 2050s (Xu et al., 2011). The results indicated a consistent trend toward warmer and wetter conditions and increased river discharge in both catchments. Substantially larger increases in river discharge relative to baseline were consistently projected for the semi-arid River Huangfuchuan catchment in northern China compared to the subtropical humid River Xiangxi catchment in southern China. In this paper, ~~we~~ the study focused on the greatest source of uncertainty from GCMs individually and analyzed the changes in air temperature, precipitation, and river discharge of the two catchments in the early (2020s), middle (2050s), and late 21st century (2080s). The climate projection used in this study was based on ~~using~~ seven GCMs under the SRES A1B emission scenario within the CMIP3 structure. SRES scenario are based on assumptions about driving forces such as patterns of economic and population growth, technology development, and other factors and SRES A1B are widely used in climate change analysis and decision making in China. ~~We~~ The study focused on extreme flow, constraining uncertainty in the projected river discharges, and examining the contrasts between the southern and northern catchments.

2. Study areas and methodology

2.1 Characteristics of study areas

The River Huangfuchuan is a primary catchment in the middle reaches of the Yellow River. The River Xiangxi is the first tributary supplying the Three Gorges Dam (Fig. 1). In addition to their being located in different climate regions, these two catchments also have different climate conditions and historical climate change trends (Xu et al., 2011).

The River Huangfuchuan is located in northern China, has a semi-arid climate, and is primarily a pastoral farming region. The mean annual temperature is 7.5 ℃, and increased at a rate of 0.24 ℃ ~~per~~ decade^{-1} from 1961 to 2010. The mean annual precipitation is 388 mm, but decreased over the period of 1961–2000, and increased over 2001–2010 at a rate of 0.87 mm decade^{-1} (Gao et al., 2005; Sun et al., 2012). The mean annual runoff was 42.4 mm for 1956–2005, with a range of 74 mm in the 1950s to 28 mm in the 1990s (Wang et al., 2009, 2012). Given the impacts of soil erosion, ecological water shortage, land desertification, flooding, and human water use, the River Huangfuchuan is very sensitive to global change (Yang et al., 2004).

The River Xiangxi lies in a subtropical humid climate region. Mean, minimum, and maximum annual air temperature from 1961 to 2008 was 17.0, 12.7, and 22.9 ℃, respectively. Minimum and maximum annual temperatures have increased over this period, especially since the 1980s. Mean annual precipitation during this period was 992 mm with a slight decrease in recent years. The mean annual runoff was 688 mm for 1961–2005, with a decrease from 733 mm in the 1960s to 552 mm in the 1990s (Jin et al., 1996). Due to land shortage, the natural vegetation has been progressively converted to farmland, exposing large areas of soil and leading to serious erosion and water loss (~~Jin et al., 1996; ~~Jiang et al., 2002).

2.2 Methodology

2.2.1 Hydrological model calibration and validation

The hydrological model used in this study was the Soil-Water-Assessment-Tool (SWAT) model developed by the ~~US -~~- United States Department of Agriculture (USDA)~~,~~.The model ~~ which ~~has been developed with the continuation of USDA Agricultural Research Service (ARS) modeling experiences for a period of over 30 years combined with the multiple user groups from worldwide. SWAT has been used across worldwide at varying watershed scale and environmental conditions that represent a wide range of climate, soils, and landuse (Arnold et al., 2012)~~.~~. ~~We used a previously calibrated SWAT model of River Huangfuchuan and River Xiangxi (Xu et al., 2011). ~~A digital elevation model with a scale of 1: 250 000 was prepared by the China Fundamental Geographic Information Center. Spatial soil data with a scale of 1:1 000 000 was derived from Environment and Ecology Scientific Data Center of western China, National Natural Science Foundation of China. Soil properties were generated from the Soil Attribute Data Set which based on “Soil Species of China” and other sources with total information includes 7300 soil profiles collected from all over China. The most recent land-use maps for the River Xiangxi compiled by the Hubei Land Management Bureau in the 1990s and land-use records from the Inner Mongolia Autonomous Region Department of Land and Resource in the 1980s were used to represent catchment land use. Monthly climate dataset CRU TS3.0 (Mitchell and Jones, 2005) which cover the two catchments were stochastically disaggregated to daily resolution following the procedures developed by Arnell (2003) and further described by Todd et al. (2010). Station-based daily precipitation and temperature within and around the two catchments obtained from National Climate Information Center, China Meteorological Administration were used for local calibration of the daily disaggregation procedure.

Based on the input digital maps, a total of 10 and 13 sub-watersheds were generated based on dominant soil and land use for each subbasin. SWAT model was calibrated for the monthly river discharge of the Rivers Huangfuchuan and Xiangxi for a baseline period of 1961-1990, with the remaining ~~1961~~1991-1997 and ~~1961~~1991-1994 data of the Rivers Huangfuchuan and Xiangxi for validation. Firstly, the hydrological model evaluation was based on the graphical techniques with hydrographs and percent exceedance probability curves for monthly time scale. The model performed well against the monthly river discharges observed from Huangfu gauging station of River Huangfuchuan and the Xingshan gauging station of River Xiangxi, while peak flows of the River Xiangxi were very slightly underestimated~~.~~. Then, the evaluation was performed with the statistics included coefficient of determination (R^2), and Nash-Sutcliffe efficiency (Ens). Model performance was evaluated as “satisfactory” if $Ens > 0.50$ and $R^2 > 0.58$ (Moriasi et al., 2007). The performance statics Ens and R^2 are “satisfactory” except for River Xiangxi in the calibration period with 0.43 and 0.44 respectively. ~~The calibration and validation results showed that SWAT model was able to simulate the monthly discharge well, while Nash-Sutcliffe efficiency were 0.64 and 0.67 for River Huangfuchuan, and were 0.44 and 0.57 for River Xiangxi, respectively, for calibration and validation periods. The frequency distributions of simulated river discharge in both sub-catchments closely approximates those of the observed discharge records as indicated by flow duration curves, while peak flows of the River Xiangxi are very slightly underestimated.~~ More details on input datasets, model calibration and validation results can be found in Xu et al (2011).

2.2.2 Climate scenarios and hydrological projection

The climate change projection data used in this study utilized seven GCMs ~~were~~ from the CMIP-3 dataset under the SRES A1B emission scenario from 2010 to 2099, which included the following: UKMO HadCM3, UKMO HadGEM1, NCAR CCSM3.0, MPI ECHAM5, IPSL CM4, CSIRO MK3.0, and CCCMA CGCM3.1. The period from 1961 to 1990 was used as the baseline, based on CRU TS3.0 gridded (0.5° ×

0.5°) climate data. This study utilized the monthly temperature and precipitation projections from different GCMs using the ClimGen pattern-scaling technique (Osborn, 2009), which were subsequently downscaled to daily resolution. ClimGen created monthly climate scenarios through a pattern scaling approach in which climate change patterns as simulated by a suite of GCMs (Osborn, 2009), and later downscaled to daily resolution following the procedure outlined above. The baseline 1961-1990 used to represent the "present day" climatology of the study area. Climate scenarios were centered around three time periods: 2020s (2010–2039), 2050s (2040–2069), and 2080s (2070–2099), representing the early, middle and late of 21st century. The annual and seasonal changes for projected temperature and precipitation were compared with baseline period ~~from 1961 to 1990~~ for two catchments over the three time horizons.

For subsequent hydrological projections, this study adopted downscaled projection data derived from the GCMs and validated SWAT models, and projected the impact of climate change on river discharges from 2010 to 2099. The average hydrograph, annual and monthly discharge changes were calculated using 30 years of projected monthly discharge over each of the three time horizons, and then compared with the discharge simulated discharge based on CRU_TS3.0 climate data for baseline period rather than the actual observed discharge data. This technique was used to avoid systematic errors that the SWAT model would introduce in comparing the projection period with the ~~reference~~ baseline period.

The uncertainty envelope of climate projection was showed as function of each GCMs, with the assuming that each climate projection had an equal probability of occurrence. Using the result from 30-year simulations, empirical probability density functions (PDFs) of the projected annual temperature, annual precipitation, and simulated annual discharge were generated. The PDFs indicated the range of possible values for each variable and for each time horizon.

3. Results

3.1 Projected climate change

3.1.1 Changes of ~~A~~annual temperature and precipitation ~~changes~~

The mean annual temperature and precipitation projections from the seven GCMs for River Huangfuchuan and River Xiangxi ~~are~~ were shown in Fig. 2. All seven GCM projections for the River Huangfuchuan indicated warming and wetting, with air temperature rose from 1.0 to 1.8 ℃, 2.1 to 3.8 ℃ and 3.0 to 5.5 ℃ in 2020s, 2050s and 2080s, while precipitation increased by 1 to 13 %, 1 to 27 %, and 2 to 39 % respectively for the same slices. For the River Xiangxi, the GCM projections consistently showed rising temperature, with temperature rose from 0.9 to 1.7 ℃, 1.9 to 3.4 ℃, and 2.7 to 4.9 ℃ in 2020s, 2050s and 2080s, but two GCMs projected precipitation decreases (CCSM3.0 and ECHAM5), while precipitation changed from -1 to 6 %, -2 to 13 %, and -2 to 18 % respectively for the same slices.

The projected ratio of precipitation changing with temperature ranged about 7.8% ℃$^{-1}$ (CCSM3.0) to 0.3 %℃$^{-1}$ (ECHAM5) for River Huangfuchuan, with 4 GCMs projected the ratio greater than 5.8% ℃$^{-1}$, and 3 GCMs' projection less than 3.4% ℃$^{-1}$. There were 3 GCMs projected the ratio greater than 3.5 % ℃$^{-1}$ and 4 GCMs' projection less than 2.3% ℃$^{-1}$ with 2 GCMs' projection showed the precipitation decreasing with warming as mentioned before for River Xiangxi.

3.1.2 Changes of ~~S~~seasonal temperature and precipitation ~~changes~~

The projected seasonal temperature and precipitation (Fig. 3) indicated that there was consistent warmer in winter, spring, and summer in the River Huangfuchuan, with temperature increases ranging from 0.7 to 5.3 ℃ in the 2020s and from 2.5 to 8.6 ℃ in the 2080s. Winter showed the greatest temperature rise, while several GCMs projected temperature decreasing in autumn. For the River Xiangxi, all seven GCMs projected temperature increases in all seasons, ranging from 0.3 to 2.1 ℃ in the 2020s and 1.9 to 7.0 ℃ in the 2080s. The temperature increases appeared to be greatest in autumn and least in spring. Both the estimated emissions of greenhouse gases and the total radiative forcing increase are greater at the end of 21st century than earlier of 21st century, which cause the projected temperature are larger in 2080s compare to 2020s. The projected seasonal changes are generally consistent with the projected seasonal changes in eastern Asia. The projected temperature increase are generally greater in winter and autumn compared to summer and spring in eastern Asia support by regional averages of temperature projections from a set of 21 global models for A1B scenario by CMIP3 (Christensen, 2007), and CMIP5 results support this assessment (Christensen, 2013).

There were consistent increases in projected precipitation for winter and spring across the seven GCMs, but the consistency was poorer for summer and autumn precipitation changes. The ratio of percentile precipitation changing with temperature was the highest in winter and the least in summer in both catchments. The projected seasonal precipitation increased more for the River Huangfuchuan than that of the River Xiangxi. For the River Xiangxi, seasonal mean precipitation increases in the 2020s and 2080s were 1.3 and 8.6 %, respectively, while, seasonal mean precipitation increases were 8.6 and 33.6 % for the River Huangfuchuan during the same periods. The difference in projected precipitation among GCMs increased over time horizons in each season, with the maximum range in winter and minimum range in summer among GCMs.

3.1.3 Uncertainties in temperature and precipitation projections

Based on the climate change projections, the calculated Probability Density Functions (PDFs) showed the possible ranges of temperature and precipitation changes during ~~all of~~ the three time horizons (Fig. 4). The most important findings were the increased uncertainties in projected mean annual temperature and precipitation toward the end of the 21st century. Further, the projected mean annual temperature increased in all of the GCMs, while precipitation projections showed relatively consistent increases and shifts toward extreme conditions, with the exception of ECHAM5 and CCSM3.0, which showed a decrease in the River Xiangxi. However, while the GCMs showed a consistent direction of changes in temperature and precipitation, there were large differences in the magnitudes of increase. Finally, the magnitudes of the temperature and precipitation changes in the River Huangfuchuan were more than that of the River Xiangxi, indicating that the climate change uncertainty was greater for the River Huangfuchuan.

For ~~River Huangfuchuan, the~~ projected temperature, the increase from CCSM3.0 and CSIRO showed the smallest magnitude with about 1.0℃ and 3.0℃ for River Huangfuchuan, and 0.9℃ and 2.8℃ for River xiangxi for 2020s and 2080s.~~,~~ ~~while~~ ~~t~~The projected warming from ECHMM5 and HadCM3 were at the other end of the spectrum for River Huangfuchuan~~,~~ with increase of 1.8℃ and 5.3℃ for the same horizons, ~~. The middle-ground model was CCCMA, with projected increase of 1.3℃ and 3.8℃ for 2020s and 2080s horizons. For River Xiangxi, the projected temperature from CSIRO and CCSM3.0 also showed the smallest increase with the magnitude about 0.9℃ and 2.8℃ for 2020s and 2080s,~~ while the HadCM3, ECHAM5 and IPSL models were at the other end of the spectrum~~,~~ with increase of 1.7℃ and 4.9℃~~ for the same time horizons~~. ~~The middle-ground model was also CCCMA, with the projected increase of 1.4℃ and 4.2℃ for 2020s and 2080s horizons.~~

~~The projected temperature from 7 GCMs showed substantial consistency between the relative magnitudes of change associated with the different GCMs for the different time slices for an individual catchment.~~

For River Huangfuchuan, the projected precipitation from ECHAM5 and CSIRO showed the smallest increase, of less than 5.0mm and 15.0 mm for 2020s and 2080s, while the HadCM3 showed the largest increase, of about 50mm and 150mm for 2020s and 2080s. For River Xiangxi, the projected precipitation from ECHAM5 and CCSM3.0 showed decrease, of about maximum decrease 10mm and 20mm for 2020s and 2080s; while the CCCMA, and HadCM3 models showed the largest increase, of about 60mm and 190mm for 2020s and 2080s. ~~The projected precipitation change associated with the different GCMs showed consistent for an individual catchment in~~

~~three time horizons, but various not only the magnitude but also the direction between the different catchments. More precisely, t~~The projected precipitation from CCSM3.0 and ECHAM5 showed decrease for River Xiangxi while increase for River Huangfuchuan for the three horizons. Among all GCMs, HadCM3 showed substantial increase for projected precipitation for both catchments.

PDFs also showed that the mean annual temperature of the River Huangfuchuan in the 2080s was outside the natural temperature variation of the baseline with the cold years in 2080s were warmer than the warmest years for baseline. For River Xiangxi, a similar pattern was simulated in the 2050s. ~~The annual precipitation projections were very different from that of temperature. Compared to the baseline,~~ The projected precipitation from all 7 GCMs~~' projections~~ indicated that the Rivers Huangfuchuan and Xiangxi will become wetter in the future and the frequency of extreme wet and dry years will also increase compared with the baseline.

3.2 Projected ~~climate change impact on~~ discharge based on hydrological model

3.2.1 Changes of ~~A~~average hydrograph

The projected average hydrographs of the Rivers Huangfuchuan and River Xiangxi over each of the three time horizons are presented in Fig. 5. Average hydrograph shows a general increase in discharge for the Rivers Huangfuchuan and Xiangxi, with the exception of HadGEM1 and ECHAM5, which project a decrease in the River Xiangxi in summer (June to August). The projected peak discharge showed great increase and appeared earlier during the flood season in the River Huangfuchuan, while that of the River Xiangxi appeared later.

3.2.2 Changes of ~~A~~annual and seasonal river discharge ~~changes~~

The changes in projected annual and seasonal river discharges are presented in Fig. 6. The projected annual river discharge decreased for River Xiangxi in the ECHAM5 with the magnitude ranged from -1 to -1.7% during the three time horizons, and the projections from other GCMs showed an increase with the magnitude ranged from 0.3 to 7 % in the 2020s, 2 to 18 % in the 2050s, and 3 to 25 % in the 2080s. The projected annual river discharges in the River Huangfuchuan showed consistent increase across all of the GCMs with the magnitude ranged from 5 to 29 % in the 2020s, 12 to 73 % in the 2050s, and 17 to 142 % in the 2080s. The comparison between the two catchments showed that the River Huangfuchuan had substantial increase in annual river discharge than the River Xiangxi.

The changes in projected seasonal river discharge indicated the larger difference~~s~~ for both of the magnitude and direction comparing with the changes in projected annual river discharge across the GCMs with the three time horizons, especially in the River Xiangxi. The changes in projected discharge increased the most in spring for the River Huangfuchuan.

3.2.3 Changes of ~~E~~extreme discharge~~ changes~~

Fig. 7 shows the projected extreme discharges for both catchments. There was general increase in the extreme discharges (Q05 for high flow and Q95 for low flow) for both catchments in the three time horizons, and the increase in the River Huangfuchuan was more substantial than River Xiangxi. However, the changes in extreme discharge were totally different comparing that of ~~mean~~ median flow (Q50). The increase in projected high flow for the River Huangfuchuan was less than the increase in median~~mean~~ flow; with substantial uncertainty was projected for median~~mean~~ flow. However, the River Xiangxi showed an increase in projected extreme discharge that was more substantial than that of median~~mean~~ flow, with a larger range.

For the River Huangfuchuan, CSIRO was the only model that projected decreases of Q05 and ~~mean flow (~~Q50~~)~~ in the 2020s; the projected Q05 under all of the other GCMs increased over the three time horizons. The projected maximum changes in Q05 and Q50 in the River Huangfuchuan during the 2020s were 39 % ~~(~~from CGCM3.1~~)~~ and 38 % from~~(~~IPSL~~)~~, while the projected maximum changes in Q05 were 70% and 146 % from ~~(~~HadCM3~~)~~, and the projected maximum changes in Q50 were 119% and 304 % from ~~(~~HadCM3~~)~~ in the 2050s and 2080s.

For the River Xiangxi, HadGEM1, ECHAM5, and CISRO projected a slight decrease in Q50, whereas most GCMs projected an increase in extreme discharge over the three time horizons. The projected Q05 from HadGEM1 decreased during the 2050s and 2080s, while increased for the other GCMs. The maximum increase for Q05 was from the CCSM3.0, with the magnitude of 17 % (2020s), 41 % (2050s), and 63 % (2080s). The projected Q95 decreased in ECHAM5 and IPSL during the 2080s, while increased for~~t~~ other GCMs, and the maximum increase from the HadCM3 with the magnitude of 27 % (2020s), 38 % (2050s), and 77 % (2080s). The consistent and large increases in Q05 from CCSM3.0 and Q95 from HadCM3 for the three time horizons should be considered when using ~~these~~ this information for decision making.

3.2.4 Uncertainty in river discharge projections

The PDFs of the mean annual river discharges are shown in Fig. 8. There were large uncertainties in the model projections, especially toward the end of the 21st century. Some models behaved very differently than others, such as the results of HadCM3 for River Huangfuchuan and HadGEM1 for River Xiangxi. Besides the model uncertainties, projections indicated that the entire discharge distribution shifted toward more extreme events compared to the baseline period~~ from 1961 to 1990~~. Both the mean and extreme events increased for the two river basins in the future.

4. Discussions

The projected mean annual temperature of the two catchments showed a consistent increasing trend, and the magnitude increased from the 2020s to the 2080s~~, while the semi-arid River Huangfuchuan had a more consistent and substantial patterns of warming and wetting in the future~~. Most GCMs revealed near linear increases in annual precipitation and discharge in the two catchments, with the exception of projected decrease in precipitation for the River Xiangxi (CCSM3.0 and ECHAM5) (Fig. 2). ~~Fig. 6 shows that ECHAM5 is the only mode that projects decreasing mean annual discharge in the River Xiangxi. ECHAM5 is a warmer model comparing with CCSM3.0 that projects slight decrease in annual precipitation. Even if annual precipitation is on the rise, annual discharges nevertheless decrease due to rising~~

~~evapotranspiration resulting in a net water loss.~~ However, the changes in projected seasonal temperatures, precipitation and discharges in the two catchments are not univocal. The projected temperatures of the River Huangfuchuan show less increasing in autumn for all GCMs in the 2020s, but projections from four GCMs show decreasing in the 2080s. The projected seasonal precipitations vary depending on the GCM, time horizon, and on the season (Fig.3). The seasonal discharge is affected by the combination of these variables. The projected seasonal discharges in River Huangfuchuan appear increasing consistently, and with the exception of a projected decrease in summer from ECHAM5 and a decrease in autumn from CSIRO. The changes in seasonal discharge in the River Xiangxi are however much variability between GCMs. For this reason, to quantify the climate change impacts and assess the uncertainties, multiple GCMs should be used to capture the probability of future change. It has been suggested that the use of two carefully chosen climate projections (dry/hot and wet/cold projections as an example) may be sufficient (Brekke et al., 2004; Singh et al., 2006).

The projected climate changes show obvious differences in the two catchment of different climate region. The River Huangfuchuan in semi-arid northern China shows more substantial warming and wetting, with larger magnitudes of change in both temperature and precipitation. The River Xiangxi in humid southern China also shows warming, but the increase in precipitation is very slight. These results coincide with increased total annual precipitation, precipitation intensity and extreme precipitation projected for two catchments in eastern China in a future warming scenario (Feng et al., 2011). The increase in precipitation intensity and extreme precipitation is expected to be larger in the middle reaches of the Yellow River basin than that in the middle reaches of the Yangtze River basin (Jiang et al., 2011; Xu et al., 2011). Warmer and wetter scenarios for the River Huangfuchuan are projected to increase river discharge substantially, and if managed properly, this could serve to alleviate current local water shortages. However, on the basis of increasing mean discharge, the projected increase in peak flows may also exacerbate soil erosion in the area of loess plateau. The projected increase in extreme flow in River Xiangxi may be expected to increase the fluxes of nonpoint source pollution and sediment to the river channel. ~~However, increased river discharge could also serve to dilute point source pollution and increase the likelihood that target environmental flows are achieved.~~ Increasing river discharge has important implications for the management of water resources in both catchments. Increases in mean flow expand available water resources but the rise in peak flow ~~(Q05)~~ in both basins could increase flood frequency and flood risk. Therefore, adaptation measures need to consider projected changes in mean and extreme flows, as well as the associated uncertainties.

The results highlight the large uncertainty in climate change impacts due to choice of GCM. During the assessment of the climate change impacts, there are considerable difficulties in choosing appropriate GCMs considering each GCM should be treated equally in the assessment. This study use all seven of the GCMs to quantify the uncertainties and ranges of impacts on river discharge, and provide the basis for water management and further adaptations to climate change. However, ~~considering time and calculation limitations, we chose~~ choosing ~~different~~ certain GCMs in different regions according to pertinent projections is acceptable considering time and calculation limitations. For example, a single variable (temperature) could be chosen for the River Xiangxi for GCMs selection based on ~~the~~ examined the maximum and minimum temperature increases. Nevertheless, in the case of the River Huangfuchuan, the temperature-precipitation combination was more appropriate~~, and we~~ based on examined the most cold-dry and the most hot-wet extremes.

5. Conclusions

~~This study assesse the climate change and impacts of climate change on river discharge in catchments in two different climate regions in China. The projections are carried out using seven GCMs within the CMIP3 structure and uncertainties in the hydrological changes are also quantified.~~

There are obvious differences in the climate changes and in the impacts of those climate changes on river discharge in the two catchments. Compared to the catchment in the southern subtropical humid area, the catchment in the northern semi-arid area had more apparent warming and wetting, with a greater increase in river discharge. However, the seasonal changes in temperature, precipitation, and river discharge were more complicated than the annual changes, and the uncertainties were greater among the different models. Moreover, the changes in extreme flows (Q05 and Q95) were different than that of ~~mean~~ median flows (Q50). For example, in the River Huangfuchuan, the ~~mean~~ median river discharge increased greatly, but the changes in extreme flow were less than that of ~~mean~~ median discharge, so the uncertainty was relatively small. In contrast, in the River Xiangxi, the changes in extreme flows were much larger, leading to larger uncertainties. Thus, changes in extreme flows are far more critical for water managers.

This study revealed the differences between annual and seasonal river discharges in different climate regions and showed the differences between changes in extreme flows and in ~~mean~~ median river discharge. These findings have important implications for the basin-scale management of water resources in these catchments and for adaptation measures. It is insufficient to examine the impacts of climate change or evaluate adaptations based on a single global model. The uncertainties between projections from multiple GCMs must be taken into consideration.

Acknowledgements

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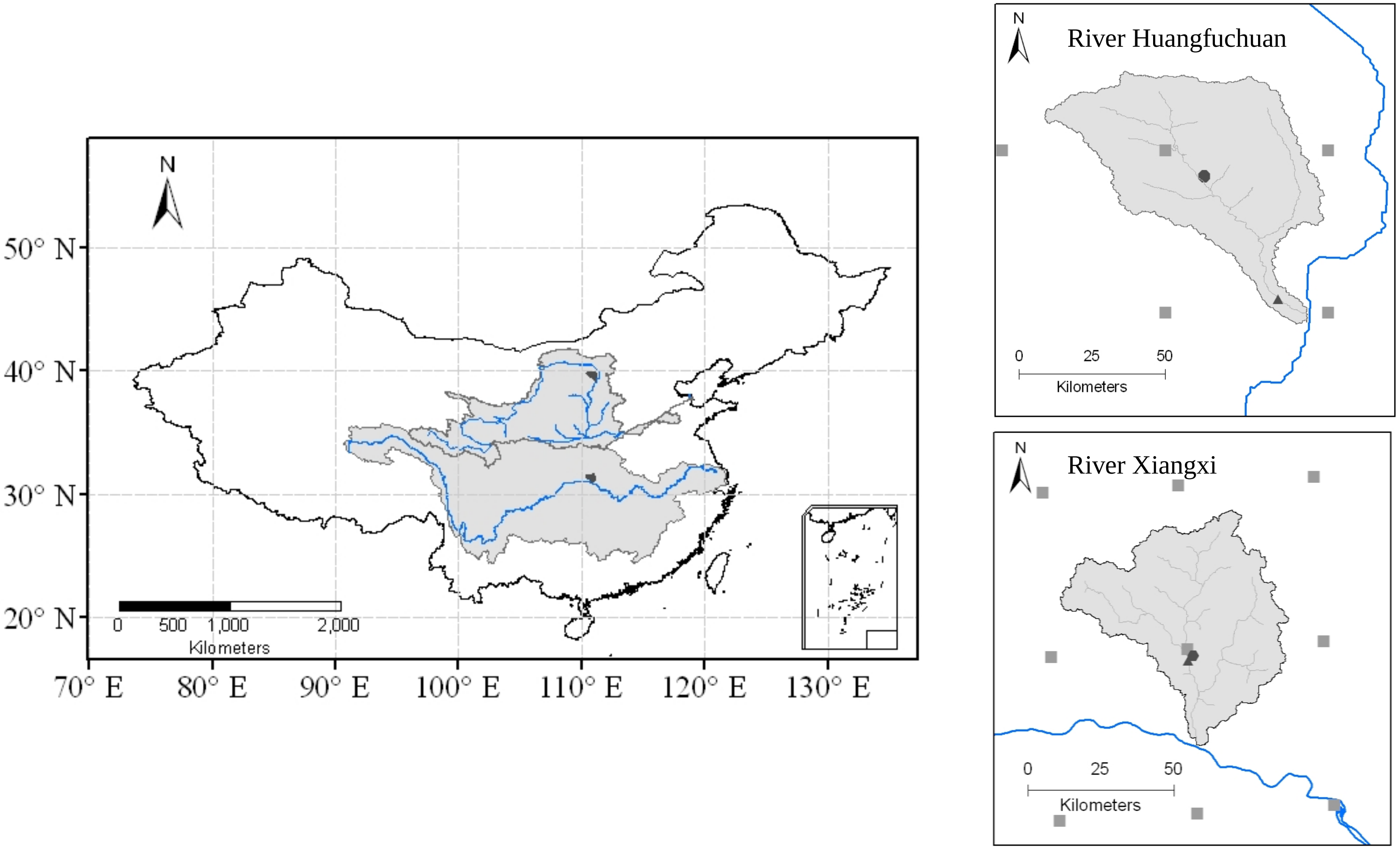

Fig. 1 Location of selected sub-catchments in the Yellow River and Yangtze ~~Basins~~ River and climate stations (black circle), discharge stations (black triangle), and Climate Research Unit (CRU) grid nodes (grey square).

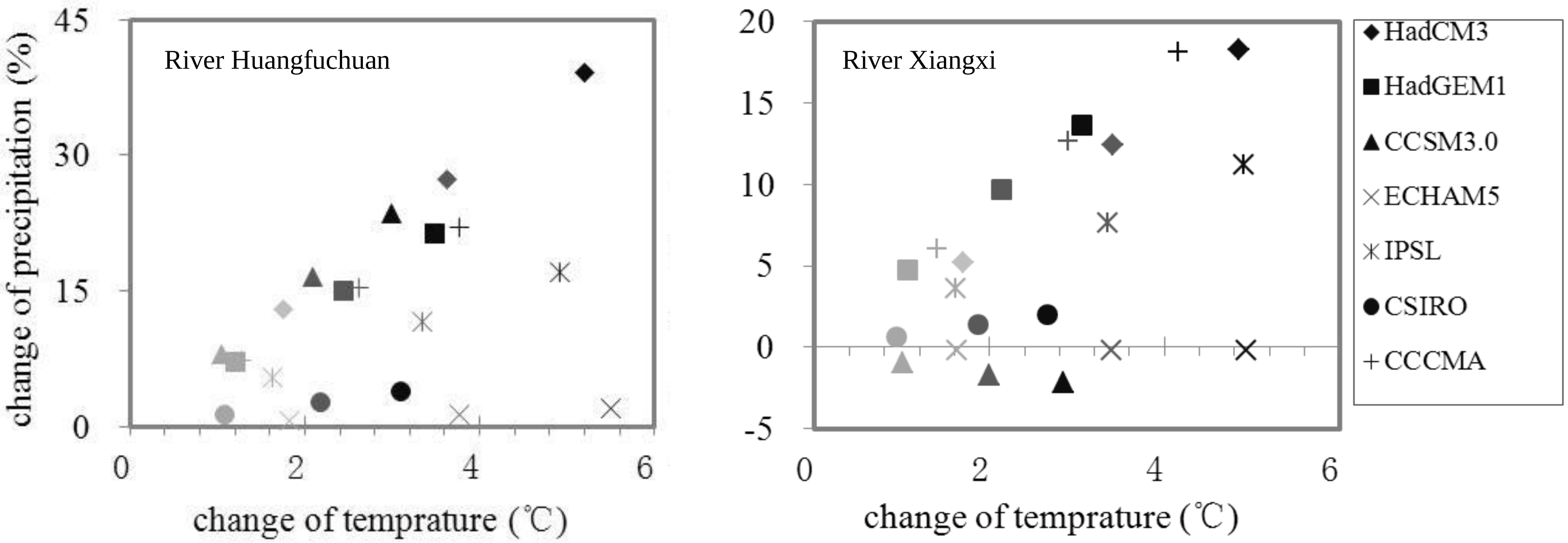

Fig. 2 Scatter plots of temperature and precipitation annual changes for seven GCMs projection under 2020s, 2050s and 2080s time horizons for River Huangfuchuan and River Xiangxi (Comparing with 1961-1990 baseline; 2020s: light grey; 2050s: dark grey; 2080s: black).

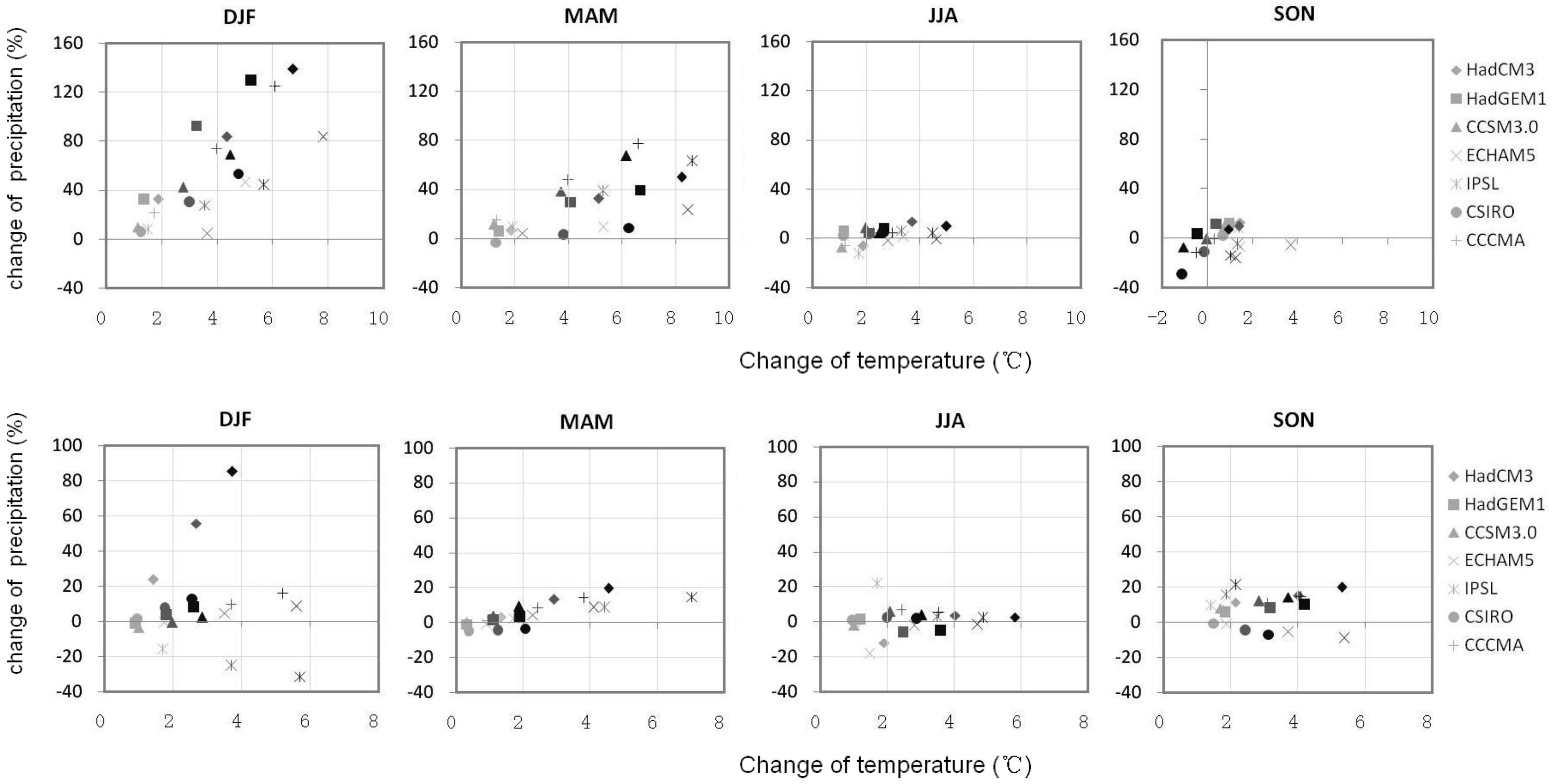

Fig. 3 Scatter plots of temperature and precipitation seasonal changes for seven GCMs projection under 2020s, 2050s and 2080s time horizons for River Huangfuchuan (u~~U~~pper) and River Xiangxi (l~~L~~ower)（Comparing with 1961-1990 baseline; 2020s: light grey; 2050s: dark grey; 2080s: black）.

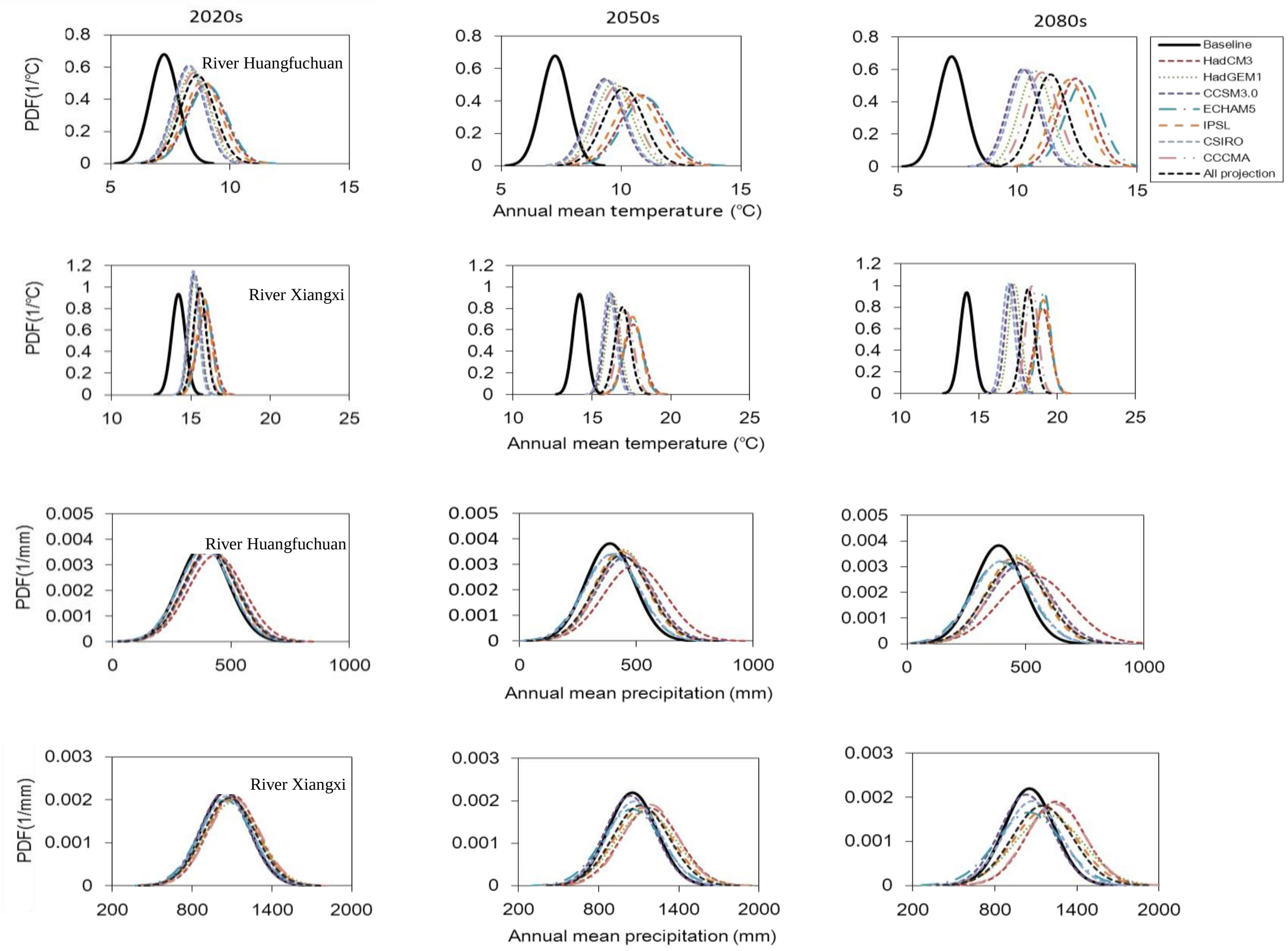

Fig. 4 Probability density functions of annual mean temperature and annual precipitation for seven GCMs projection under 2020s, 2050s and 2080s time horizons, and for the 1961–1990 baseline for River Huangfuchuan and River Xiangxi.

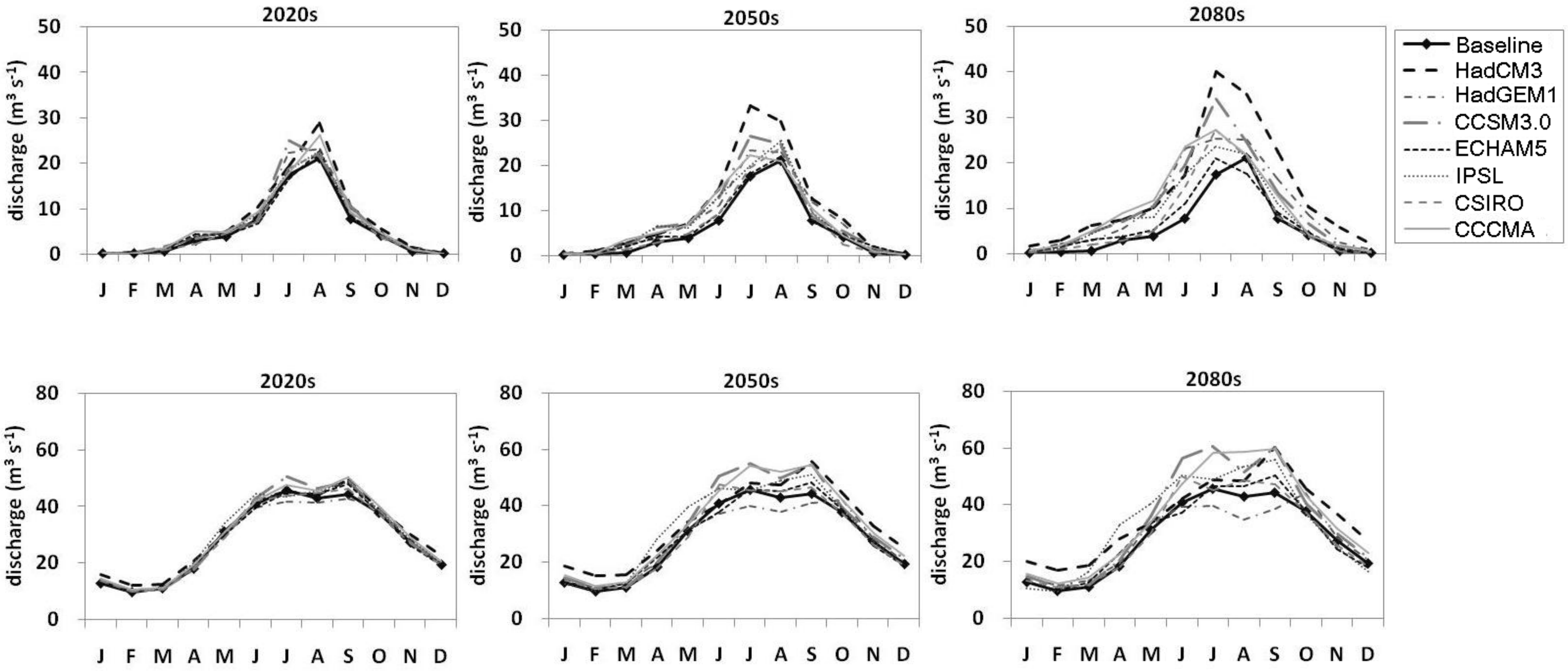

Fig. 5 Average hydrographs for seven GCMs projection under 2020s, 2050s and 2080s time horizons, and 1961-1990 baseline for River Huangfuchuan (u~~U~~pper) and River Xiangxi (~~L~~lower).

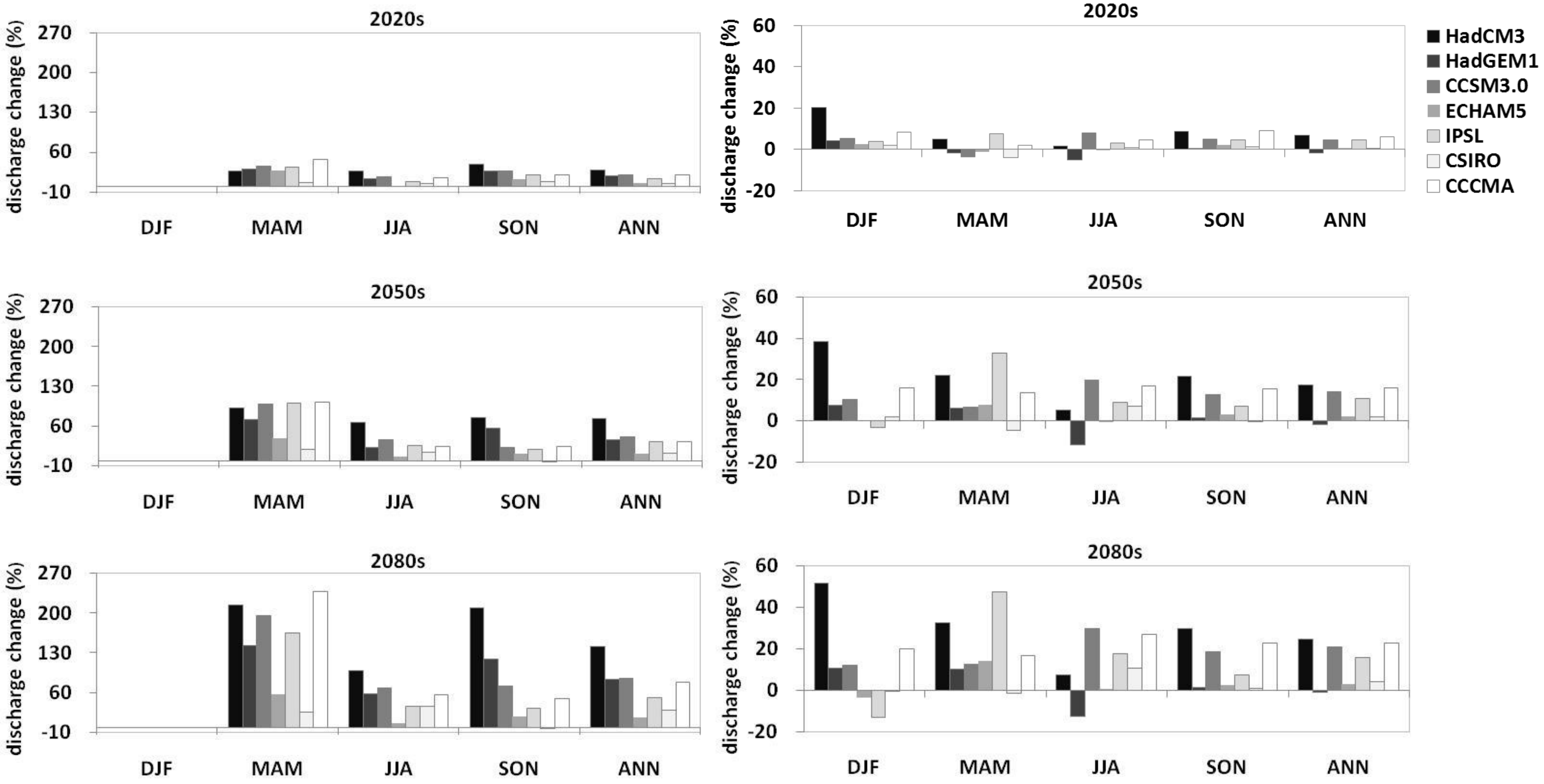

Fig. 6 Seasonal and annual discharge changes for 7 GCMs projections under 2020s, 2050s and 2080s time horizons for River Huangfuchuan (left) and River Xiangxi (right) (Comparing with 1961-1990 baseline).

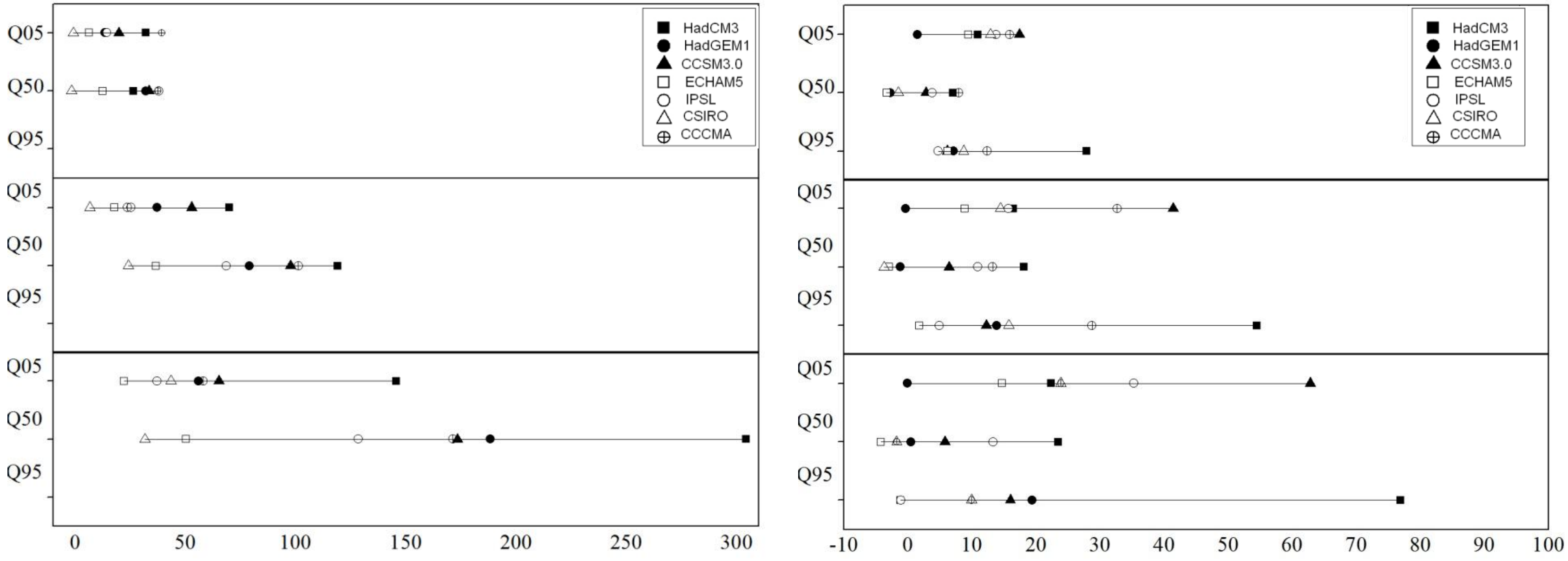

Fig. 7 Extreme flows changes for 7 GCMs projections under 2020s, 2050s and 2080s time horizons for River Huangfuchuan (left) and River Xiangxi (right) (% difference from ~~Comparing with~~ 1961-1990 baseline)~~;~~ for Q05~~: high flows;~~, Q50~~: mean flows;~~ and Q95~~: low flows~~(i.e. exceedance in % of months over the simulated 30-yr period).

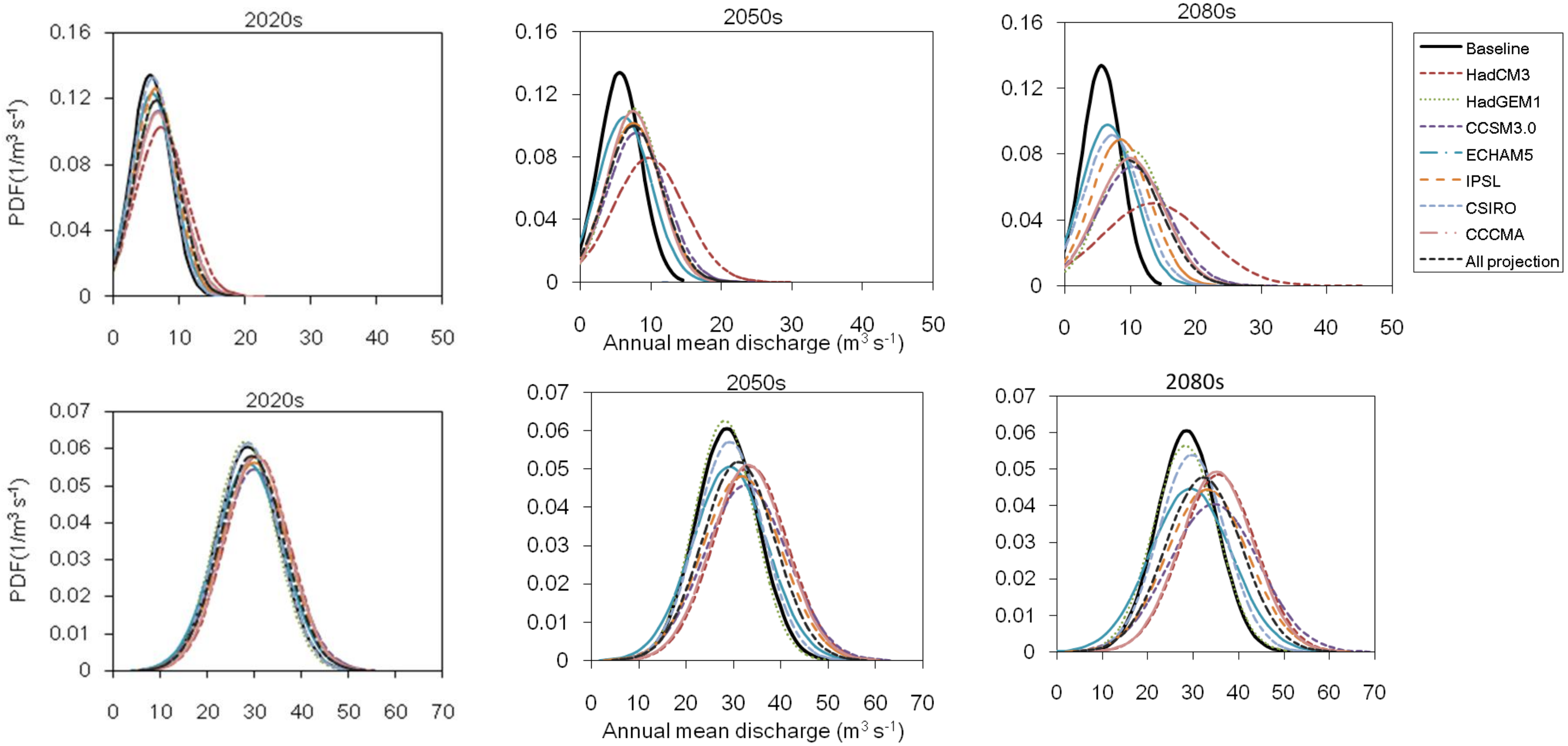

Fig. 8 Probability density functions of annual mean discharge for seven GCMs projections under 2020s, 2050s and 2080s time horizons, and for the 1961–1990 baseline for River Huangfuchuan (u~~U~~pper) and River Xiangxi (~~L~~lower).