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Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the River Yangtze and Yellow Basins, China

H. Xu[1], **R. G. Taylor**[2], **and Y. Xu**[3]

[1]National Climate Center, Laboratory for Climate Studies of China Meteorological Administration, Beijing 100081, China
[2]Department of Geography, University College London, Gower Street, London WC1E 6BT, UK
[3]State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

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Correspondence to: H. Xu (xuhm@cma.gov.cn)

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Abstract

Quantitative evaluations of the impacts of climate change on water resources are primarily constrained by uncertainty in climate projections from GCMs. In this study we assess uncertainty in the impacts of climate change on river discharge in two catchments of the River Yangtze and Yellow Basins that feature contrasting climate regimes (humid and semi-arid). Specifically we quantify uncertainty associated with GCM structure from a subset of CMIP3 AR4 GCMs (HadCM3, HadGEM1, CCSM3.0, IPSL, ECHAM5, CSIRO, CGCM3.1), SRES emissions scenarios (A1B, A2, B1, B2) and prescribed increases in global mean air temperature ($1\,^{\circ}$C to $6\,^{\circ}$C). Climate projections, applied to semi-distributed hydrological models (SWAT 2005) in both catchments, indicate trends toward warmer and wetter conditions. For prescribed warming scenarios of $1\,^{\circ}$C to $6\,^{\circ}$C, linear increases in mean annual river discharge, relative to baseline (1961–1990), for the River Xiangxi and River Huangfuchuan are +9% and 11% per $+1\,^{\circ}$C, respectively. Intra-annual changes include increases in flood (Q05) discharges for both rivers as well as a shift in the timing of flood discharges from summer to autumn and a rise (24 to 93%) in dry season (Q95) discharge for the River Xiangxi. Differences in projections of mean annual river discharge between SRES emission scenarios using HadCM3 are comparatively minor for the River Xiangxi (13% to 17% rise from baseline) but substantial (73% to 121%) for the River Huangfuchuan. With one minor exception of a slight (–2%) decrease in river discharge projected using HadGEM1 for the River Xiangxi, mean annual river discharge is projected to increase in both catchments under both the SRES A1B emission scenario and 2° rise in global mean air temperature using all AR4 GCMs on the CMIP3 subset. For the River Xiangxi, there is great uncertainty associated with GCM structure in the magnitude of the rise in flood (Q05) discharges (–1% to 41% under SRES A1B and –3% to 41% under 2°global warming) and dry season (Q95) discharges (2% to 55% under SRES A1B and 2% to 39% under 2° global warming). For the River Huangfuchuan, all GCMs project a rise in the Q05 flow but there is substantial uncertainty in the magnitude of this rise (7% to 70% under SRES

A1B and 2% to 57% under 2° global warming). Greatest differences in the projected hydrologic changes are associated with GCMs in both catchments than emission scenarios and climate sensitivity. Critically, estimated uncertainty in projections of mean annual flows is less than that calculated for extreme (Q05, Q95) flows. This research suggest that the common approach of reporting of climate change impacts on river in terms of mean annual flows may mask the magnitude of uncertainty in flows of most importance to water managers.

1 Introduction

Global warming induced by rising concentrations of greenhouse gases is changing global climate patterns (Bates et al., 2008). Warming of the atmosphere observed over several decades is associated with the changes in hydrological systems globally and at the basin scale. These changes include: precipitation patterns and extremes; the amount and generation of river flow; the frequency and intensity of flood and drought; and, by extension, the quantity and quality of freshwater resources (Juen et al., 2007; Xu and Singh, 2004). The magnitude and spatial distribution of changes in climate combined with characteristics of specific basin determine which impacts are the most important at regional scale (Menzel, 2002; Matondo et al., 2004; Wilby et al., 2006; Hagg et al., 2007).

China, similar to many parts of the world, is experiencing the consequences of climate change, through rising air temperatures, changes in the distribution and amount of precipitation, and changes in extreme climatic conditions. Such changes in climate have been linked to an increased occurrence of flood events in southern China and more frequent droughts in Northern China (Wang et al., 2005). The most important and direct impact of climate change is changes to the availability of water resources. Previous research indicates that the discharge of large rivers in China has decreased since 1950 with more frequent drought and flood events (Zhang et al., 2007; Wang et al., 2008).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
7, 6823–6850, 2010

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The River Yangtze and River Yellow are historically, culturally, and economically of critical importance to Southern and Northern China. The River Yangtze is 6300 km long and has a basin area 1.8 million km^2 which primarily experiences a subtropical, monsoon climate. The River Yellow is 5464 km long and has a basin area of 0.8 million km^2, that mainly comprises arid and semi-arid environments. The contrasting climates and landscapes of these basins give rise to very different hydrological regimes. The inter-comparison of responses in both basins to climate change is, therefore, expected to be indicative of many regions in China.

Mean annual precipitation in the River Yangtze basin is about 1070 mm and mean annual river discharge is ~976 km^3, equivalent to a specific discharge of 542 mm. Annual per capita water availability decreased from 2700 m^3 in 1980 to 2100 m^3 in 2005. Previous studies (Zhang et al., 2006, 2008; Jiang et al., 2007) show that there has not been a significant change in annual precipitation but an increase in the number of extreme (10th percentile) precipitation events is observed (Su et al., 2008). Greater variability in precipitation has intensified floods and prolonged droughts. Spatial and seasonal changes in precipitation have also been observed. Increased precipitation has been detected in middle and lower reaches of River Yangtze in summer whereas a decrease in precipitation is observed in the upper reaches of the basin near the Three Gorges Dam site in autumn (Xu et al., 2008). Although no significant trend was detected for annual runoff in Yangtze River basin during 1961–2000, a significant positive trend in flood discharges was found in the middle and lower basin over the same period.

Mean annual precipitation in Yellow River is 470 mm and mean annual river discharge is ~58 km^3, equivalent to a specific discharge of 73 mm. The basin can be classified as water scarce as this river discharge represents annual per capita water availability of less than 1000 m^3 (Pereira et al., 2007). Previous studies (Fu et al., 2004; Liu et al., 2008; Huang et al., 2009) indicate trends toward higher air temperatures in the River Yellow basin during the past 50 years. Fu et al. (2004) find no significant trend in annual precipitation from 1951 to 1998 whereas others (Xu et al., 2006; Liu et al., 2008; Huang et al., 2009) indicate precipitation has decreased over slightly different

HESSD
7, 6823–6850, 2010

time periods (1961–2006, 1957–2006, and 1951–2000). Declines are especially apparent in spring, summer and autumn as well as preferentially in the southeastern part of the basin. These decreases are calculated after allowing for human uses (Fu et al., 2004; Wang et al., 2006). Applying climate projections generated from 4 GCMs (HadCM3, CGCM2, CCSR and CSIRO) for one emission scenario (SRES B2), Xu et al. (2008) estimate a reduction mean annual streamflow over the period 2010 to 2099 in a headwater catchment of the Yellow River Basin.

Current understanding of impacts of climate change on water resources is complicated by uncertainty in both climate projections and the simulation of hydrological responses to climate perturbations (Prudhomme et al., 2003; Treut et al., 2008; Minvill et al., 2008). The main objective of this study is to quantify uncertainty in climate change impacts on river discharge, in two sub-catchments of the River Yangtze and Yellow Basins under contrasting climate regimes (semi-arid, humid). The hydrologic model used here is Soil and Water Assessment Tool (SWAT) model, which is a physically based semi-distributed hydrological model that operates on a daily time step. Baseline climate derives from detrended monthly CRU TS3.0 datasets (Mitchell and Jones, 2005) for the period during 1961–2005, which were used for calibrating and validating SWAT model. We quantify uncertainty in projections of climate change on river discharge by applying a range of climate scenarios using different GCMs (subset of IPCC AR4 GCMs), emission scenarios (SRES A1B, A2, B1, B2) and prescribed increases in global mean air temperature (1 to 6 °C), including the 2 °C threshold of "dangerous" climate change (Todd et al., 2010). Daily climate datasets used to drive SWAT model were generated by a weather generator (Arnell, 2003).

HESSD
7, 6823–6850, 2010

2 Study area and datasets

2.1 Basin description

The River Xiangxi and River Huangfuchuan were selected as meso-scale catchments representative of the humid and semi-arid climates that predominate across the Rivers Yangtze and Yellow basins, respectively. River Xiangxi is one of the longest tributaries supplying the Three Gorges Reservoir (TGR) in Hubei province. Eutrophication in River Xiangxi strongly influences water quality in the TGR. The River Huangfuchuan is responsible for substantial soil erosion with annual sediment yields of ~50 million tonnes to Yellow River. The location of two sub-catchments is shown in Fig. 1; physical characteristics of both are given in Table 1. River Xiangxi is 94 km long and originates in the Shennongjia forest region with a catchment area of 3099 km^2. The River Huangfuchuan is 137 km long that encompasses the transition from the Erdos Desert to the Loess Plateau with a catchment area of 3246 km^2.

The River Xiangxi catchment lies in the subtropical region and experiences a humid climate near the Three Gorges Dam. Mean annual precipitation observed from 1961 to 2004 is 1100 mm and is characterised by a dry winter and a summer monsoon from May to September. Mean annual air temperature from 1961 to 2004 is 15.6 °C and ranges from 12 °C to 20 °C. The River Xiangxi catchment is typical of northern subtropic landscapes with high relief. Mountainous areas are covered by forests. The main agricultural crops (rice, wheat) are grown in valleys. Terraced fields are often used for corn, potatoes and tea. Limestone soils predominate in headwater areas whereas brown and yellow-brown soils occur in the lowlands. The shallow soils with low humus content promote erosion and transport of particle-bound P as well as leaching of soluble N-fractions by interflow and surface runoff. To prevent soil erosion, terraces and mulching are practised but substantial nutrient fluxes to the river contribute to eutrophication.

The River Huangfuchuan is located in semiarid climate region and farming-pastoral zone in Northern China. Mean, annual precipitation observed from 1961 to 2000 is

HESSD
7, 6823–6850, 2010

388 mm. Mean annual air temperature from 1961 to 2000 is 7.5 °C and ranges from 6.9 °C and 9.7 °C. River Huangfuchuan is representative of the "hill-gully" landscape of the northern Loess Plateau. The watershed is mainly covered by grassland or bush land with fragmentary woodland. The main agricultural crops, maize and millet, are grown in the sloping cultivated land. The soils are subject to considerable water and wind erosion. River Huangfuchuan which has experienced soil erosion and land desertification, is comparatively vulnerable to climate change.

2.2 Available data

Spatial data used in the study include a digital elevation model (DEM), land use, soil type, and climatic data. 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: 1000 000 derive 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 7,300 soil profiles collected from all over China. Land use is an important input parameter to SWAT as it influences runoff generation (Wu and Johnston, 2007). There is, however, limited land-use data for both catchments. Modelling of baseline and projected river discharge consequently do not consider changes in land-use. The most recent land-use maps for the River Xiangxi compiled by the Hubei Land Management Bureau in the 1990s, were used to represent catchment land use. In the River Huangfuchuan, natural vegetative cover of grassland and woodland was converted to farmland from the 1950s to 1970s; restoration of artifical grassland and bush land has occurred since the late 1990s. 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 streamflow records for the Xiangshan gauging station of River Xiangxi and Huangfu gauging station of River Huangfuchuan were obtained from Water Year Book and are available for periods 1961–1994 and 1954–1997 respectively. Climate data

HESSD
7, 6823–6850, 2010

used in this study during 1961–2005 are gridded ($0.5^{\circ} \times 0.5^{\circ}$) CRU TS3.0 monthly datasets (Mitchell and Jones, 2005), which included monthly precipitation total and monthly average as well as maximum and minimum air temperatures.

3 Methodology

3.1 Hydrological model: SWAT

The Soil and Water Assessment Tool (SWAT) model is a physically based, semi-distributed, basin scale, continuous-time hydrological model that operates on a daily time step. In SWAT, basins are divided into multiple subwatersheds which are further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics. The overall hydrologic balance is simulated for each HRU including precipitation, irrigation water, infiltration, soil water redistribution, evapotranspiration, lateral subsurface flow, and return flow (Gassman et al., 2007). Applications of SWAT occur worldwide and include direct assessments of anthropogenic, climate change and other influences on a wide range of water resources. In China, SWAT has been used to simulate river discharge and sediment transport in sub-catchments of Yellow River such as Lushi and Heihe River for sediment simulation (Hao et al., 2004; Cheng et al., 2006), and in sub-catchments of Yangtze River such as Poyang Lake and small watershed in the TGR area for streamflow and soil erosion simulation (Guo et al., 2008; Shen et al., 2009)

3.2 Calibration and validation of hydrological model

Model parameterization was specified using the Arcview GIS interface for SWAT. The River Xiangxi catchment and River Huangfuchuan were divided, respectively into 10 and 13 sub-watersheds based on the DEM and the location of river gauging stations. After considering land use and soil characteristics, the River Xiangxi catchment was

HESSD
7, 6823–6850, 2010

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

divided into 195 HRUs and River Huangfuchuan was divided into 314 HRUs. Potential evapotranspiration is calculated using the Hargreaves function (Hargreaves et al., 1985); surface runoff is estimated by a modification of the SCS curve number method (USDA – NRCS, 2004), and routing processes were estimated by the Muskingum method (Neitsch et al., 2005).

The employed SWAT model had recently been calibrated and validated for the River Xiangxi using monthly river discharge observations for the periods 1970–1974 and 1976–1986 (Xu et al., 2009). In this study, SWAT models were re-calibrated to recent monthly river discharge data (1991–1994 Xiangxi; 1991-1997 Huangfuchuan) and validated for period 1961–1990. The performance of SWAT2005 was evaluated using statistical analyses to compare the quality and reliability of the predicted discharge with observed value. Summary statistics included the mean discharge (Q), coefficient of determination (R^2), and Nash-Sutcliffe efficiency (E_{ns}). The observed and modeled flow duration curve and monthly discharge for the 1961–1994 period for River Xiangxi and 1961-1997 period for River Huangfuchuan are presented in Fig. 2. The calibrated SWAT model was used in the climate scenarios modeling for the two sub-catchments.

Model performance over the calibration and validation periods is generally acceptable, with efficiencies ranging from 0.61 to 0.66 for River Huangfuchuan and 0.43 to 0.56 for River Xiangxi. The performance statics E_{ns} and R^2 are poorest for River Xiangxi in calibration period with 0.43 and 0.44, respectively. Simulated mean monthly river discharge is overestimated (37% and 6%) for the River Huangfuchuan and underestimated (6% and 7%) for the River Xiangxi over both calibration and validation periods. There is good agreement between observed and simulated flow duration curve for River Huangfuchuan, and confirmed underestimated for observed high discharge in River Xiangxi (Fig. 2a and b). The model is capable of reproducing the observed flow quite well for both catchments for the whole period as showed in Fig. 2c and d. The generally good performance over the calibration and validation periods, together with successful applications of SWAT model under different climate regions, assures the model could be used for climate change scenarios modeling. In addition to assessing

HESSD

7, 6823–6850, 2010

Quantifying uncertainty in the impacts of climate

H. Xu et al.

projected changes in mean annual river discharge, we also changes in high and low monthly runoff, expressed as Q05 and Q95, respectively, where for example, Q05 is the runoff exceeded only 5% of the time and is thus high.

3.3 Climate change scenarios

Climate projections for temperature and precipitation were generated using the ClimGen pattern-scaling technique described in Osborn (2009) and Todd et al. (2010). Scenarios were generated for (1) greenhouse-gas emission scenarios (A1B, A2, B1, B2) and (2) prescribed increases in global mean temperature of 1, 2, 3, 4, 5, and 6 °C using the UKMO HadCM3 GCM as well as (3) A1B emission scenario and prescribed warming of 2 °C ("dangerous" climate change) using six additional GCMs from the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset: CCCMA CGCM31, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM30, and UKMO HadGEM1.

4 Results

4.1 Uncertainty in the magnitude of prescribed increases in global mean air temperature

Figure 3a indicates that for the chosen sub-basins precipitation is projected by HadCM3 to increase at a near-linear rate with a rise in global mean air temperature of 1 °C to 6 °C. Annual precipitation is projected to increase, relative to baseline, by 6% to 35% for the River Xiangxi and 9% to 53% for the River Huangfuchuan. Along with linear increases in precipitation, preferential increases in air temperature relative to global mean are also projected (e.g. 8.5 °C in River Xiangxi and 9.1 °C in River Huangfuchuan for a 6 °C rise in global mean air temperature (Fig. 3a).

Mean annual river discharge is estimated to increase in both the River Xiangxi and Huangfuchuan catchments under prescribed increases in global mean air temperature

HESSD
7, 6823–6850, 2010

projected by HadCM3 (Fig. 3b). Increases in mean annual river discharge with rising air temperatures are, however, non-linear (Fig. 3c). Under rises of 1 °C to 3 °C, the trend in rising river discharge for the River Xiangxi is lower than that estimated for warming of 4 °C to 6 °C; the reverse is observed for the River Huangfuchuan. Substantial changes in intra-annual river discharge are associated with the non-linear response in annual river discharge to increasing global mean air temperature. Monthly flow is projected to increase in all months and there is a shift in flood season (high flows) from summer to autumn for River Xiangxi. The low (Q95) flow increases dramatically (24% to 93%) for the River Xiangxi and the high (Q05) flow increases substantially (13% to 64%) but in a non-linear fashion for the River Huangfuchuan.

4.2 Uncertainty associated with different SRES emissions scenarios

Fig.4a shows the changes in mean climate projected by HadCM3 for each of the 4 SRES scenarios (A1B, B1, B2, A2) in both study catchments. Increases in mean annual temperature range from 2.5° to 3.4° for the River Xiangxi and from 2.7° to 3.6 ° for the River Huangfuchuan. The highest increases occur under the A1B emission scenario for both basins. Projected precipitation increases by ~10% with little variance between emission scenarios for River Xiangxi. For the River Huangfuchuan, precipitation is projected to increases by 20 to 28% relative to baseline with slightly greater differences between the 4 emission scenarios. These projected changes in climate give rise to substantially different increases in river discharge (Fig. 4b). The magnitude of changes for annual discharge varies from 13 to 17% for the River Xiangxi and from 73 to 121% for the River Huangfuchuan. The projected monthly discharge under different SRES emission scenarios, for River Huangfuchuan increase throughout the year (Fig. 4c), and there is only minor uncertainty in the magnitude for this rise in the Q05 flow (10% to 17%) and the Q95flow (45% to 55%) for River Xiangxi whereas high (Q05) flows increase considerably (70 to 90%) for the River Huangfuchuan.

HESSD
7, 6823–6850, 2010

4.3 Uncertainty in GCM structure for SRES A1B emission scenario

Figure 5a shows the projected climate change under the A1B emission scenario for the priority subset of 7 AR4 GCMs. The projected annual mean temperature increases for all GCMs under SRES A1B but ranges from approximately 2° (CSIRO, HadGEM1 and CCSM3.0 GCM) to 3.4° (HadCM3, IPSL and ECHAM5 GCM) for the River Xiangxi and from ~2.2° (CSIRO and CCSM3.0 GCM) to 3.8° (HadCM3 and ECHAM5 GCM) for the River Huangfuchuan. Projected changes in mean annual precipitation for the River Xiangxi are minor (< ±2% from baseline) for 3 GCMs (CCSM3.0, CSIRO, ECHAM5) but show moderate increases of 7 to 12% for 4 GCMs (HadCM3, CGCM31, HadGEM1, IPSL). Projected changes in mean annual precipitation for the River Huangfuchuan are minor (<5% from baseline) for 2 GCMs (CSIRO, ECHAM5), moderate (12 to 17% from baseline) for 4 GCMs (CCSM3.0, HadGEM1, CGCM31, IPSL) and substantial (27%) for HadCM3. In contrast, there is considerably less variation in projected increase in annual mean temperature for both basins. Projected changes in precipitation between basins show large differences. For example, the CCSM3.0 GCM projects a decrease in precipitation of −2% for River Xiangxi and an increase in precipitation of +17% for the River Huangfuchuan. Indeed, this trend is robust as all GCMs project greater increases in precipitation for the River Huangfuchuan than the River Xiangxi.

Following precipitation projections, hydrological modeling shows a consistent increase in river discharge for the two sub-basins though with substantial disparities between GCMs. HadGEM1 is the only GCM projecting a decrease in annual mean discharge (Fig. 5b). For the River Xiangxi, the ensemble mean (of GCMs) is an increase of 9% in mean annual river discharge; HadGEM1 projects a decrease of −2% in annual discharge whereas the other GCMs project increases ranging from 2% to 17%. For the River Huangfuchuan, the ensemble mean is an increase of 34% in mean annual river discharge. HadCM3 projects the largest increase in mean annual discharge (73 %); the other GCMs project increases ranging from 11% to 42%.

HESSD
7, 6823–6850, 2010

Relative to projected changes in mean annual river discharge, there is less consistency in projections of intra-annual river discharge in both catchments (Fig. 5c). For River Xiangxi, all GCMs project a rise in the low (Q95) flow but they range from 2% to 55%. There is also a near-uniform rise (HadGEM1 excepted) in projections of high (Q05) flows but substantial uncertainty in the magnitude of these rises for the River Xiangxi (−1% to 41%) and River Huangfuchuan (7% to 70%).

4.4 Uncertainty in GCM structure for 2° rise in global mean air temperature

Uncertainty in projected changes in climate under a 2° rise in global mean air temperature associated with the priority subset of AR4 GCMs is shown in Fig. 6a. Preferential increases in mean, annual temperature are evident in both the River Xiangxi and River Huangfuchuan. The rise ranges from 2.2° for the HadGEM1 GCM to 2.8° for the IPSL GCM in River Xiangxi. For the River Huangfuchuan, the rise ranges from 2.3° for CGCM31 GCM to 3.0° for HadCM3 GCM. Differences between GCMs in projections of mean annual precipitation are greater than that for temperature. Projected changes in mean annual precipitation, relative to baseline, vary from a −2% decrease for HadGEM1 to 12% increase for HadCM3 in River Xiangxi and from a 1% to 19% increases for ECHAM5 and CCSM3.0 GCMs, respectively for the River Huangfuchuan.

An increase in mean annual river discharge in both basins under a 2 °C rise in global mean air temperature is a robust projection using all GCMs (Fig. 6b) except HadGEM1 (slight decrease). For the River Xiangxi, the ensemble mean projection (of GCMs) is an increase in mean annual discharge of 10% relative to baseline and ranges from 2.5% for ECHAM5 to 19% for CCSM3.0. For the River Huangfuchuan, the ensemble mean projection is a 33 % increase in mean annual river discharge which ranges from 9% for ECHAM5 to 60% for CCSM3.0. Projected intra-annual (seasonal) changes in river discharge for the River Huangfuchuan indicate an earlier (July) peak flow relative to baseline (August) for CGCM31 and HadCM3 and an increase in peak discharges in July for the other GCMs (Fig. 6c). All GCMs project a rise in the Q05 flow but there is uncertainty in the magnitude of this rise (2% to 57%) for River Huangfuchuan. For the

River Xiangxi, there is no consistent trend for projected seasonal discharges across the 7 GCMs (Fig. 6c). All GCMs with one exception (HadGEM1) project a rise in the Q05 flow with the uncertainty from −3% to 41%, while the Q95 flow increase from 2% to 39%.

5 Discussion

The assessment of the impacts of climate change on river discharge in a humid subtropical sub-basin of the River Yangtze and a semi-arid temperate sub-basin of the River Yellow reveals near-uniformity in projections of greater mean annual river discharge. There is, however, substantial uncertainty in the magnitude of projected increases in river discharge that is primarily associated with GCM structure, magnitude of global warming, and emission scenarios. The greatest uncertainty in the projected changes in river discharge stems from the choice of GCM from the priority subset of seven AR4 GCMs. With the exception of projections of a slight (−2%) decrease in river discharge from HadGEM1, mean annual river discharge increases under both the SRES A1B emission scenario and 2° rise in global mean air temperature irrespective of the applied GCM. This finding is unique among the catchments examined on five continents reporting in this special issue (Arnell, 2010; Hughes et al., 2010; Kingston and Taylor, 2010; Kingston et al., 2010; Nobrega et al., 2010; Thorne, 2010). Differences in hydrological projections between the SRES emission scenarios projected by HadCM3 are comparatively minor (13 to 17% increase relative to baseline) for the River Xiangxi but substantial for the River Huangfuchuan (73 to 121% increase relative to baseline). The differences result primarily from differences in projections of precipitation in both basins.

Warmer and wetter scenarios for the River Huangfuchuan are projected to increase river discharge substantially which, if properly managed, could serve to alleviate current water scarcity. The projected increase in peak flows (Q05) in the River Huangfuchuan serves to exacerbate soil erosion. The general increase in peak flow (Q05) and low flow (Q95) in River Xiangxi is expected to increase the transportation of non-point source pollution and sediment to river channel by runoff, whereas the increased flow could dilute point source pollution, improve environmental flow (Shao et al., 2008; Li et al., 2009). Although the purpose of this paper was not to simulate the impacts of the changes in the hydrology on freshwater ecosystem, some inferences can be drawn with respect to issues such as the management of water resource for maintaining acceptable environmental quality. Increasing flow in have strong implications for management of water resource in both catchments, while the increase in mean flow will increase the available water resource but the increased peak flow (Q05) in both basins will increase flood frequency and flood risk. Therefore, adaption measures need to consider projected changes in both mean and extreme (Q05, Q95) flows and uncertainties therein.

6 Conclusions

Uncertainty in the impact of climate change on river discharge in two representative catchments in the River Yangtze (Xiangxi) and Yellow (Huangfuchuan) basins associated with GCM structure, emissions scenarios and prescribed increases in global mean temperature has been quantified. The first notable conclusion from this work is the near-uniform consistency in the direction of the climate change signal of increased river discharge observed in both basins associated with 7 CMIP3/IPCC-AR4 GCMs, 4 SRES emissions scenarios (A1B, A2, B1, B2), and prescribed increases of 1 °C to 6 °C in global mean air temperature. Substantially greater increases in river discharge relative to baseline are consistently projected for the semi-arid, River Huangfuchuan catchment in north China compared to the sub-tropical humid, River Xiangxi catchment in south China. There is, however, substantial uncertainty in the magnitude of projected increases in river discharge resulting from climate change. The greatest source of uncertainty in hydrological projections in both catchments is GCM structure (choice of GCMs). Our results provide an indication of the relative magnitude of uncertainty

HESSD
7, 6823–6850, 2010

in current projections of hydrological change in sub-basins of the River Yangtze and Yellow, and highlight the importance of using multi-model (GCM) evaluations of climate change impacts on water resources. Although the priority subset of 7 GCMs was specifically selected to represent the expected range of uncertainty in GCM projections, uncertainty would be expected to increase if a larger number of GCMs had been employed. Similar to other studies in this issue (Arnell, 2010; Kingston and Taylor, 2010; Thorne, 2010), noted differences in projections of mean river discharge and intra-annual (seasonal) flows question the representivity of using mean flows to represent hydrological change to water managers as changes in extreme flows (e.g. Q05, Q95) are far more critical.

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HESSD
7, 6823–6850, 2010

Quantifying uncertainty in the impacts of climate

H. Xu et al.

Table 1. General information about study area.

	Huangfuchuan	Xiangxi
Location		
River system	Yellow River	Yangtze River
Latitude	39.2°~39.9° N	31.0°~31.7° N
Longitude	110.3°~111.2° E	110.5°~111.1° E
Topography		
Elevation range (m)	836–1458	100–3072
Catchment size (km^2)	3246	3099
Climate		
Climate region	Semi-arid	humid
Mean annual precipitation (mm)	388	1100
Mean annual temperature (°)	7.5	15.6
Runoff		
Annual mean (mm)	53	688

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HESSD

7, 6823–6850, 2010

Table 2. Goodness of fit for SWAT simulations in River Xiangxi and Huangfuchuan Basin (Q_{obs} and Q_{sim} are observed and simulated mean monthly discharge in $m^3 s^{-1}$).

	Huangfuchuan				Xiangxi			
	Q_{obs}	Q_{sim}	E_{ns}	R^2	Q_{obs}	Q_{sim}	E_{ns}	R^2
Calibration	3.2	4.4	0.64	0.61	34.1	32.2	0.43	0.44
Validation	4.8	5.1	0.66	0.66	40.1	37.1	0.56	0.57

HESSD
7, 6823–6850, 2010

Quantifying uncertainty in the impacts of climate

H. Xu et al.

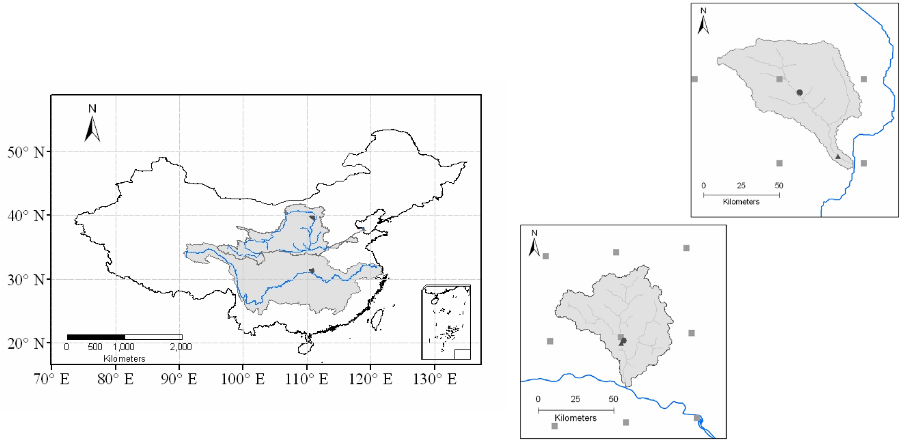

Fig. 1. Location of selected sub-catchments in the Yangtze and Yellow River Basin and climate stations (black circle), discharge stations (black triangle), and Climate Research Unit (CRU) grid nodes (grey square).

HESSD
7, 6823–6850, 2010

Quantifying uncertainty in the impacts of climate

H. Xu et al.

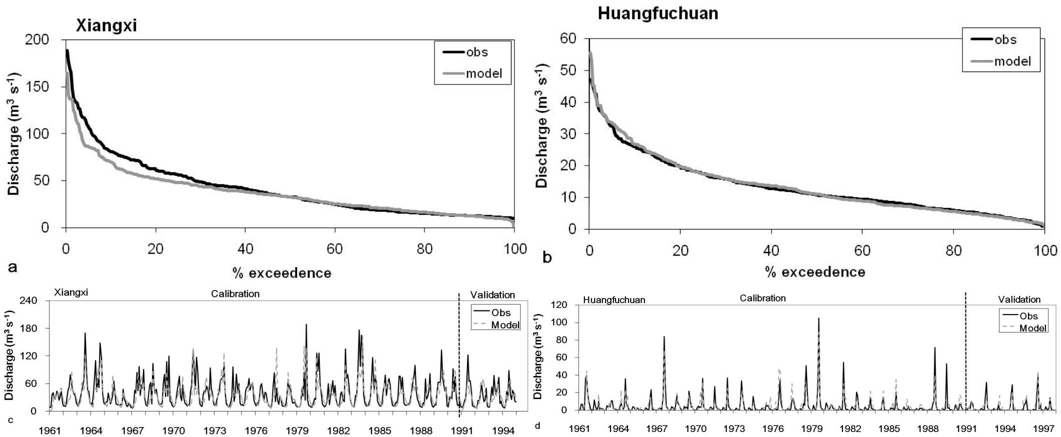

Fig. 2. Observed and simulated river discharge in River Xiangxi (1961–1994, **(a)** flow duration curve; **(c)** monthly discharge) and River Huangfuchuan (1961–1997, **(b)** flow duration curve, **(d)** monthly discharge).

HESSD

7, 6823–6850, 2010

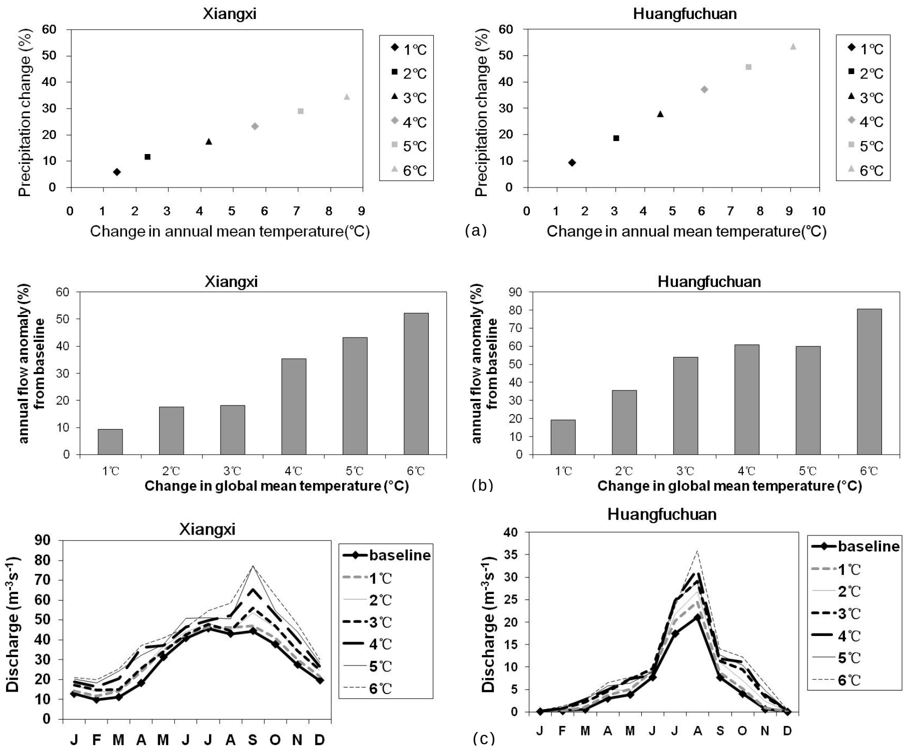

Fig. 3. (a) Projected changes in annual mean temperature (°) and annual precipitation (%), **(b)** annual and **(c)** monthly discharge for HadCM3 prescribed warming scenarios.

HESSD

7, 6823–6850, 2010

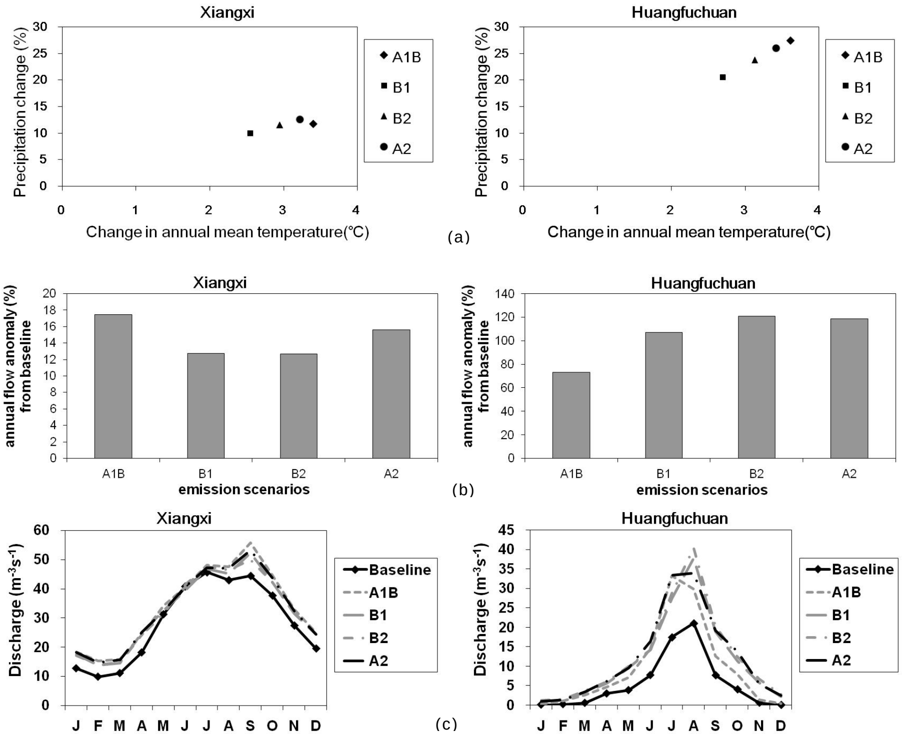

Fig. 4. (a) Projected changes in annual mean temperature (°) and annual precipitation (%), **(b)** annual and **(c)** monthly discharge for HadCM3 different emission scenarios.

HESSD
7, 6823–6850, 2010

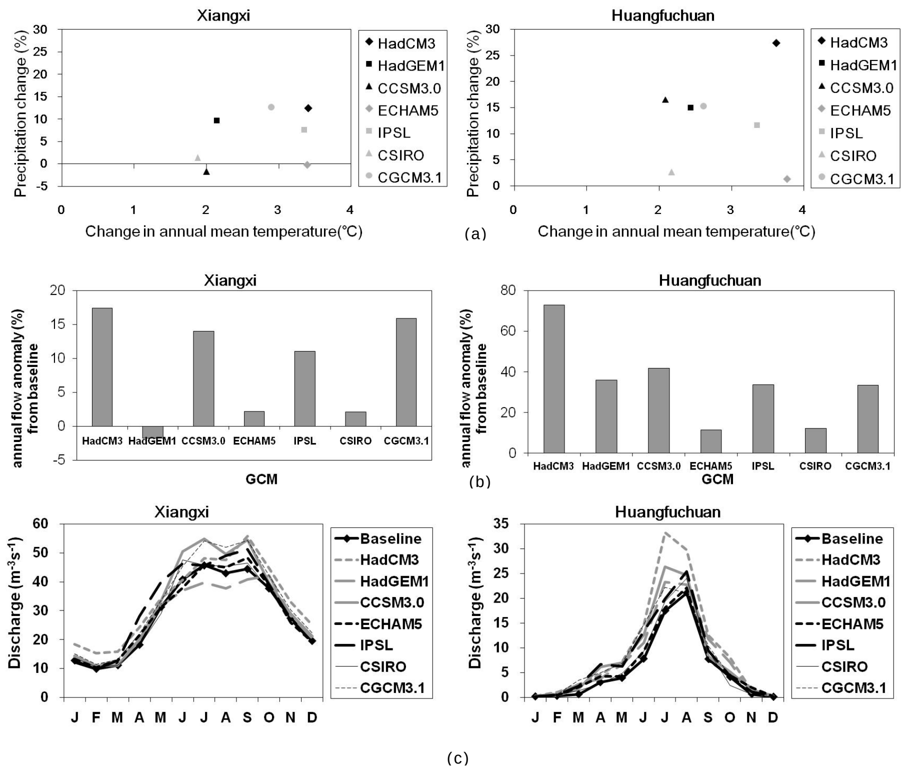

Fig. 5. **(a)** Projected changes in annual mean temperature (°) and annual precipitation (%), **(b)** annual and **(c)** monthly discharge under SRES A1B across 7 GCMs.

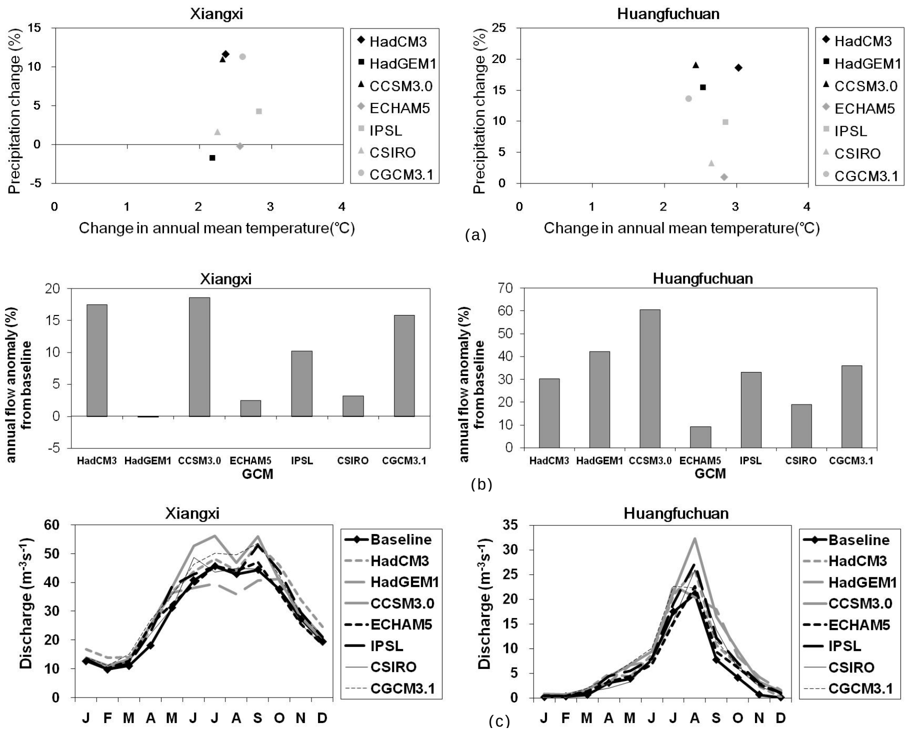

Fig. 6. (a) Projected changes in annual mean temperature (°) and annual precipitation (%), **(b)** annual and **(c)** monthly discharge under 2° warming scenarios across 7 GCMs.

HESSD
7, 6823–6850, 2010

Quantifying uncertainty in the impacts of climate

H. Xu et al.