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Impact of climate change on hydrological extremes in the Yangtze River Basin, China

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Abstract The recent (1970–1999) and future (2070–2099) climates under the SRES A1B scenario, simulated by the regional climate model RegCM4.0 driven with lateral boundary conditions from the ECHAM5 general circulation model, are utilized to force a large-scale hydrological model for assessing the hydrological response to climate changes in the Yangtze River Basin, China. The variable infiltration capacity model (VIC) is utilized to simulate various hydrological components for examining the changes in streamflow at various locations throughout the Yangtze River Basin. In the end of the twenty-first century, most of the Yangtze River Basin stands out as "hotspots" of climate change in China, with an annual temperature increase of approximately 3.5 °C, an increase of annual precipitation in North and a decrease in South. Runoff in the upper reach of Yangtze River is projected to increase throughout the year in the future, especially in spring when the increase will be approximately 30 %. Runoff from the catchments in the northern part of Yangtze River will increase by approximately 10 %, whereas that in the southern part will decrease, especially in the dry season, following precipitation changes. The frequency of extreme floods at three mainstream stations (Cuntan, Yichang, and Datong) is projected to increase significantly. The original extreme floods with return periods of 50, 20, and 10 years will change into floods with return periods of no more than 20, 10, and 5 years. The projected increase in extreme floods will have significant impacts on water resources management and flood control systems in the Yangtze River Basin.

Keywords Climate change · Hydrological extremes · RegCM4.0 · VIC · Yangtze River Basin

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1 Introduction

Temperature, precipitation, and water vapor patterns are predicted to change significantly by the end of the twenty-first century according to the Fourth and Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007, 2013). Anthropogenic global climate change and human activities have significantly affected different hydrological processes, and resulted in changes in the spatial and temporal distribution of water resources at both global and local scales (Christensen et al. 2004; Jha and Gassman 2014; Wang 2005; Yang et al. 2008, 2010, 2012; Yu et al. 2014). Considering that water is an essential resource, the changes in the hydrological cycle will have serious impacts on ecological, social, and economic situations (Horrevoets et al. 2004; Poff et al. 1997). Changes in global streamflow are still unclear and no significant changes have been found based on observational data over the second half of the twentieth century (Alkama et al. 2013; Dai et al. 2009; Walling and Fang 2003), although some studies have identified robust trends over some

specific regions (Krakauer and Fung 2008; Stahl et al. 2010). Projecting the future climate and assessing its possible impact on water resources are critical for the basin level and national planning of flood control, hydropower production, agricultural irrigation, and ecosystem preservation. Many studies on the impacts of climate change on hydrological regimes have been conducted (Chiew et al. 2009; Etchevers et al. 2002; Mkankam Kamga 2001; Senatore et al. 2011; Shabalova et al. 2003). These studies usually used a three-step process that consists of (1) implementing global climate models (GCMs), the most commonly used tools for future climate predictions, under different greenhouse gases emission scenarios; (2) using statistical or dynamical approaches (i.e., regional climate models, RCMs) to downscale the GCM output and provide fine-resolution climate parameters for hydrological simulations; and (3) implementing hydrological models to simulate the changes in hydrological regimes at watershed scales (Xu et al. 2005).

Yangtze River is the largest river in China and the third largest river in the world. It is also one of the most important rivers in the history, culture, and economy of China. However, frequent floods in the Yangtze River Basin inflicted considerable loss of lives and property (Ge et al. 2013). In the last century, Yangtze River Basin experienced significant warming in terms of annual average temperatures and temperature extremes (Sang et al. 2013; Wang et al. 2014), while no obvious trend was found in annual mean precipitation. However, distinct decreases in the number of rain days and increase in precipitation intensity were observed over most part of the Yangtze River Basin (Gu et al. 2014; Guo et al. 2013; Huang et al. 2013; Su et al. 2006; Zhang et al. 2014). The trend of annual discharge has been examined by several researchers, and the results indicated that the trend is not significant and is unevenly distributed spatially, with a decrease in the upper reach, and an increase in middle and lower reaches of the Yangtze River Basin (Chen et al. 2014; Zhang et al. 2006, 2009). Because large dams and reservoirs built along the Yangtze River during the last 50 years dramatically change the seasonal streamflow rates (Lai et al. 2014; Zhou et al. 2014), trends in seasonal streamflow can be affected greatly by these human activities (Dai et al. 2009). Exploring the future changes in the Yangtze River Basin is important for strategic adjustment in this area. Xu et al. (2009) analyzed future projections of climate extreme derived from an ensemble of GCMs, and found increases of temperature extremes and heavy precipitation events in the Yangtze River Basin. Wang et al. (2012) state that simulations used VIC model with climate scenarios generated by PRECIS regional climate model indicate southeast China may experience greater rainfall and runoff in the coming decades. Ju et al. (2014) applied the artificial neural network model with eight selected GCMs to study the impacts of climate change in the Yangtze River Basin, and the results show that the likelihood of extreme floods tend to increase in the future.

Most previous climate change impact assessment studies on hydrological processes of Yangtze River Basin focused on the seasonal or monthly water resources, and many of them used future climate information directly from GCMs to drive hydrological models. It is well known that the changes of extreme hydrological events would have more profound and immediate impacts on agriculture, economy, and human health than the seasonal or monthly changes (Arnell 2011; Easterling et al. 2000). So the primary concern of this study was on the impact of future climate change on extreme hydrological events based on the coupling of a high-resolution regional climate model and a distributed hydrological model. The objectives of this study are (1) to investigate climate change across the Yangtze River Basin by using projections of a global climate model ECHAM5 downscaled by a regional climate model RegCM4.0, (2) to assess hydrological changes in the Yangtze River Basin by integrating the regional climate model and a distributed hydrological model VIC, and (3) to explore the likely impacts of climate change on extreme hydrological events.

The study area and available data are described in the next section. The methods employed to study the impact of climate change on hydrological processes, including the regional climate model, the bias correction method, and the distributed hydrological model are described in Sect. 3. The results of future climate projection and hydrological impact, especially the changes in the frequency of extreme hydrological events, are addressed in Sect. 4. The summary and conclusions are presented in Sect. 5.

2 Study area and available data

The Yangtze River originates from the Tibetan Plateau and flows across southwest, central, and eastern China for 6,300 km before emptying into the sea (Fig. 1). The basin has a gently sloping topography that drops from above 5,000 m to sea level. The basin lies in southern China between latitudes 24°N and 36°N and longitudes 90°E and 122.5°E and covers an area of approximately 1.8×10^6 km^2. Most sections of the basin are situated within a subtropical warm-wet zone and affected heavily by monsoon climate; however, the Yangtze River source region is in the dry, frigid, high-altitude zone. Annual precipitation varies between 300 and 2,000 mm and appears to diminish from southeast to northwest. Most of the precipitation falls in the wet season between April and October.

Fig. 1 Location and topography of the Yangtze River Basin
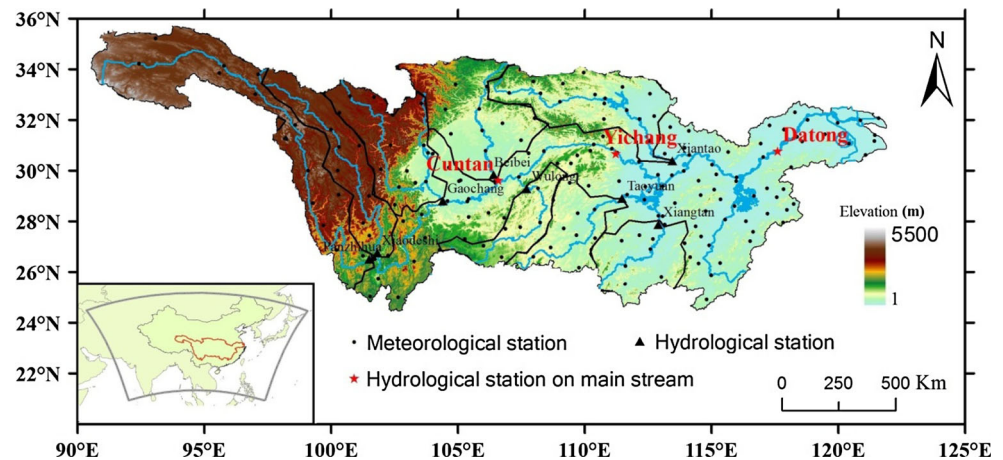
Daily rain gauge data from 187 meteorological stations in the Yangtze River Basin from 1958 to 2006 and the daily mean discharge from 11 hydrological stations (Fig. 1) from 1971 to 2000 were obtained from the China Meteorological Administration and the Hydrological Bureau of the Ministry of Water Resources. Inverse-distance squared method was adopted in this study to interpolate meteorological station data at a spatial resolution of $0.125° \times 0.125°$, which was the same as the hydrological model grid size.

3 Methods

The hydrological impact of climate change in the Yangtze River Basin was assessed with the regional climate model and hydrological model, based on the A1B SRES scenarios (IPCC 2000). The A1B scenario was characterized by a balance of economic and environmental sustainability emphasis on all energy sources (i.e., fossil and non-fossil fuels) and close to the ensemble of different scenarios. Because the low-carbon economy strategy will be adopted in China to cope with climate change and to promote China's economic growth and energy security (Jiang et al. 2010; Wang and Watson 2010), we are more interested in hydrological changes in the Yangtze River Basin under medium and low greenhouse gas emission scenarios.

Future climate changes were projected based on two experiments that used the Abdus Salam International Center for Theoretical Physics (ICTP) Regional Climate Model version 4.0 (RegCM4.0) (Elguindi et al. 2011) driven with boundary forcing from the fifth-generation atmospheric general climate model (ECHAM5) developed at the Max Planck Institute for Meteorology (Roeckner et al. 2003). One experiment is for the present (1970–1999) scenario, and the other is for the SRES A1B future scenario (2070–2099). The results of climate models often include biased representations compared with observations because

of the imperfect conceptualization, parameterization scheme, discretization, and other systematic model errors; bias correction is usually necessary (Ahmed et al. 2013; Wilby et al. 2000). To reduce the uncertainties of the climate projection scheme including only one GCM and one RCM, given the limited computing resources, the bias correction method is used as opposed to a multi-model ensemble. In this study, precipitation and 2-m temperature derived from the RegCM4 fields were corrected using a distribution transfer method (Piani et al. 2010) and a scaling method (Wood et al. 2004). The corrected fields were then employed in a macro-scale distributed hydrological model, the VIC model, to evaluate the impacts of climate change on hydrology in the Yangtze River Basin. Frequency analysis of annual maximum daily discharge was conducted with maximum of 7–15 days flood volume to examine the occurrence of flood events. The Pearson type III frequency distribution recommended by the ministry of water resources of the people's republic of China was selected for the flood frequency analysis at three stations in the main stream of Yangtze River (MWR 1993). The impacts of climate change on extreme flood events were evaluated by comparing the flood frequency between the baseline and future simulations under the A1B scenario.

3.1 Regional climate model RegCM4.0

The RegCM has been the first limited area model developed for the long-term regional climate simulation and has evolved from the first version built upon the National Center for Atmospheric Research (NCAR)-Pennsylvania State University (PSU) mesoscale model version 4(MM4) developed in 1980s (Dickinson et al. 1989; Giorgi 1990). The RegCM4.0 was released in 2010 and many physical processes had been continuously updated compared with its previous version (Giorgi et al. 2012). It includes a new land surface scheme, a mixed convection scheme, planetary

boundary layer, and so on (Elguindi et al. 2011). The new land surface scheme Community Land Model version 3.5 (CLM3.5) is a more advanced scheme which has a more comprehensive description of the land surface processes than BATS scheme in previous versions, and may improve the surface energy and water cycles simulation (Steiner et al. 2005, 2009). More details on the model RegCM4.0 can be found in Giorgi et al. (2012).

Our previous study (Gu et al. 2012), based on results of a large set of sensitivity experiments, identified a configuration of the model that performs well for simulating climate over the Yangtze River Basin. This includes a domain that covers the East and South Asia (shown in Fig. 1) with a 50 km horizontal resolution, 18 vertical levels, the CLM3.5 land surface scheme, and the MIT-EMAN convective scheme. As explained in Gu et al. (2012), the initial and boundary conditions were provided in the ECHAM5 general climate model. ECHAM5 captures the temporal variation and spatial pattern of precipitation in China (Blender and Fraedrich 2006; Li et al. 2009), and has a climate sensitivity similar to the multi-model average of all models in the Coupled Model Intercomparison Project (CMIP3) (IPCC 2007). The two experiments covered a historic period (1970–1999) and a future period (2070–2099) under the SRES A1B emission scenario.

3.2 Climate model bias correction

Systematic errors of climate models can lead to unrealistic hydrological simulations of river flow (Bergström et al. 2001; Graham et al. 2007); thus, bias correction methods must be implemented before hydrologic modeling. The commonly used bias correction methods to adjust RCM simulations include the linear scaling, local intensity scaling, power transformation, variance scaling, distribution transfer, and the delta-change approach (Teutschbein and Seibert 2012). Bias correction methods are based on the assumption that the same correction algorithm applies to both current and future climate conditions. Distribution mapping is reported to be the best correction method; it can adjust both the mean and variance of raw RCM data (Teutschbein and Seibert 2012). In this study, distribution mapping method was employed to correct the daily precipitation. Linear scaling method was employed to correct the daily temperature of the RCM output.

The RegCM4.0 simulations and observation data were interpolated to the one-eighth degree geographical grid in VIC with the inverse distance weighting technique. The distribution transfer between the simulated and observed daily precipitation was completed at each grid. Gamma distribution is often assumed to be suitable for the daily rainfall distribution (Block et al. 2009; Piani et al. 2010).

The cumulative distribution function of gamma distribution is defined as

$$\mathrm{cdf}(x) = \int_0^x \frac{\mathrm{e}^{\left(-\frac{x}{\theta}\right)} x^{(k-1)}}{\Gamma(k)\theta^k} \, \mathrm{d}x + \mathrm{cdf}(0) \tag{1}$$

$$\Gamma(k) = \int_0^{+\infty} t^{k-1} \mathrm{e}^{-t} \mathrm{d}t$$

where x is the daily precipitation, cdf(0) is the fraction of days with no precipitation, and k and θ are the form and scaling parameter, respectively.

One of the most common biases of RCM output is the overestimation of the number of rainy days. The number of rainy days was adjusted by applying a precipitation threshold. The values of the threshold depend on the difference in the performance of RCM at each grid. After correcting the number of rainy days, the daily precipitation data from RCM and observation were fitted by Gamma distribution to determine the parameters with the best fit (k and θ). The transfer function $x_{\mathrm{sim}} = f(x_{\mathrm{obs}})$ follows the equation $\mathrm{cdf}_{\mathrm{sim}}(x_{\mathrm{sim}}) = \mathrm{cdf}_{\mathrm{obs}}(x_{\mathrm{obs}})$.

Unlike daily precipitation, the climate models express the daily temperature in terms of mean, minimum, and maximum temperatures. However, if these three variables are corrected independently by the distribution function transformation, large relative errors in the daily temperature range may result (Thrasher et al. 2012). A sample linear scaling method was thus utilized to reduce the bias by the same correction coefficient. The correction coefficient for temperature at each grid was calculated based on the differences between the observed and simulated temperatures, which is defined by

$$k_{T\mathrm{month}} = \sum_{\mathrm{year}=1970}^{1999} \sum_{\mathrm{day}=1}^{28,29,30,31} \mathrm{OBS}_{\mathrm{year,month,day}}(i,j)$$
$$- \sum_{\mathrm{year}=1970}^{1999} \sum_{\mathrm{day}=1}^{28,29,30,31} \mathrm{RCM}_{\mathrm{year,month,day}}(i,j) \tag{2}$$

where RCM and OBS indicate the temperature at a given day (day, month, year) from the RegCM4.0 simulation and observation, respectively.

3.3 Distributed hydrological model VIC

The land surface scheme in climate models (both GCMs and RCMs) includes the representation of terrestrial hydrology, but often with substantial simplifications that may not be suitable for some hydrological studies (Bergström et al. 2001). For this reason, the VIC model was employed to study the various hydrological processes in the Yangtze River Basin. The VIC model is a semi-distributed, physically based, macro-scale surface water

and energy balance hydrological model (Cherkauer et al. 2003; Liang et al. 1994, 1996). The subgrid-scale spatial variability in infiltration, vegetation/land cover, and precipitation was represented by a mosaic approach. The model employs one vegetation layer, two snow layers, and three soil layers, with moisture and energy fluxes, are exchanged between layers. VIC employs a separate routing scheme to simulate the delayed streamflow from the generated runoff within a grid cell (Lohmann et al. 1998). The global 1 km land cover classification dataset (Hansen et al. 2000) and the global 10 km soil dataset (Reynolds et al. 2000) were utilized for each grid to define the soil and vegetation parameters in the VIC model. The model has been applied in a number of large river basins worldwide (Hidalgo et al. 2013; Nijssen et al. 1997; Raje et al. 2014; Su et al. 2005; Tang et al. 2010; Yong et al. 2013), including the Yangtze River Basin in China (Ferreira et al. 2013; Zhang et al. 2013; Zhou et al. 2006).

4 Results

The hydrological effects of climate change were investigated based on output from RegCM4.0 and VIC. The RegCM4.0 performance over the Asia domain and the projected future changes were documented in Gu el al. (2012). Here we provide a more detailed assessment of the RegCM4.0 performance and projected future climate changes for the Yangtze River Basin, followed by the hydrological changes simulated by VIC model.

4.1 RegCM4.0 model validation

The meteorological fields simulated by using RegCM4.0 were evaluated against observed data during the control period 1970–1999. Figure 2 shows the seasonal cycle of temperature and precipitation for the control period within the Yangtze River Basin obtained from RegCM4.0

simulations and observations. RegCM4.0 captured the overall seasonality of temperature and precipitation fairly well. However, the model underestimated the temperature in most months. During the winter season, the difference exceeds 2 °C. For precipitation bias, a significant overestimation (percentage wise) of precipitation was observed in February and December. Obvious underestimation was observed in September and October. In terms of the absolute amount, obvious overestimation was observed in July and August; obvious underestimation was observed in September and October.

The spatial pattern of the simulated thirty year average annual mean 2 m temperature is in close agreement with that of the observed data (Fig. 3). The most noticeable bias was found in the upstream of Yangtze River Basin located in the high-elevation Tibetan Plateau region, where the model underestimated the annual mean temperature by 5 °C. The model performance for precipitation was not as good as that for temperature; however, the major features of the spatial pattern were well captured. The model overestimated precipitation in the upstream section, especially in the southwest region (overestimated by more than 50 %) of the Yangtze River Basin. The model also underestimated precipitation by approximately 20 to 30 % in the east of the Yangtze River Basin.

4.2 Bias correction for RegCM4.0

The accuracy of precipitation estimation with RegCM4.0 was improved significantly after bias correction (Fig. 4). There were relatively large errors in several areas in the RegCM4.0 precipitation simulation. For example, the model overestimated precipitation in the source region of the Yangtze River, overestimated precipitation in the southern part of the upper Yangtze River and simulated a false heavy rainfall center, and underestimated precipitation in several areas in the middle and lower reaches of the Yangtze River. Most of the biases in these areas were

Fig. 2 Comparison between simulated data of RegCM4.0 and observed data: *a* precipitation (*filled bars*, mm/ month) and *b* temperature (*solid and dashed lines*, °C)
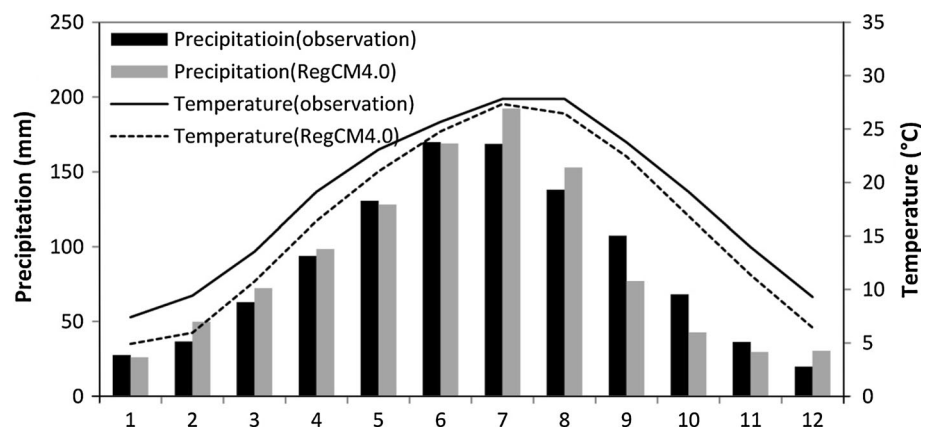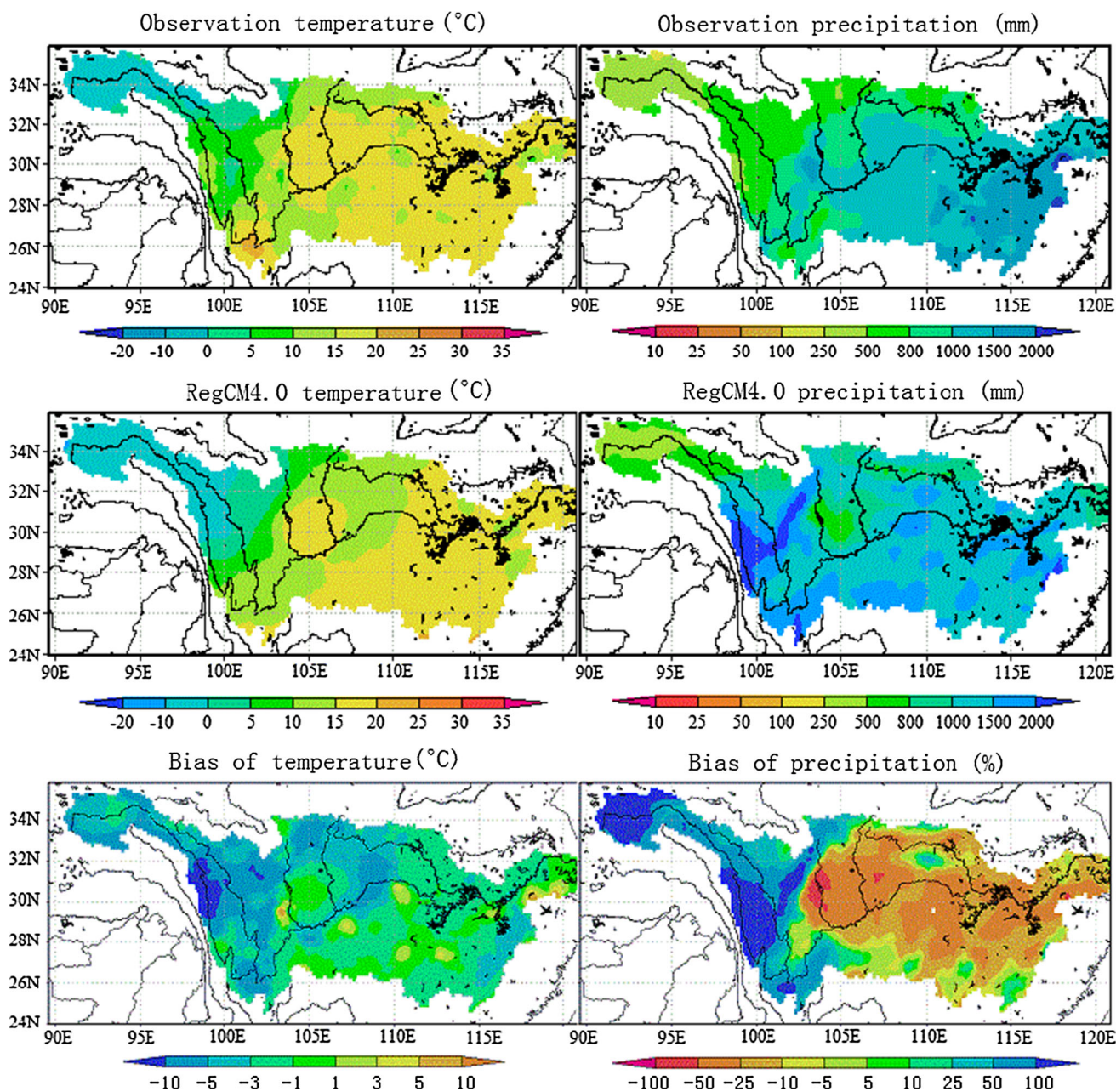
Fig. 3 Thirty-year average 2 m temperature (*left column*) and precipitation (*right column*): from observation data (*upper panels*), from RegCM4.0 in the control period (*middle panels*), and the difference between the two (*lower panels*)

removed after bias correction in precipitation; this result demonstrates the effectiveness of the distribution transfer method for precipitation correction.

The biases of temperature were adjusted with the linear-scaling approach, which were operated with monthly correction values based on the differences between observation and simulation. Therefore, the historical RegCM4.0 simulations after bias correction would agree well in terms of average annual mean temperature by definition. But this did not mean all biases of temperature had been removed.

For example, the bias of the daily temperature range was not considered in this method. Nonetheless, the same bias correction methods for temperature and precipitation were used in the future temperature projection.

4.3 VIC model calibration and validation

Most of the parameters of the VIC model can be determined based on land surface information (i.e., topography, soil, and vegetation); however, several parameters must be

Fig. 4 Average annual rainfall
in the historical period from
RCM before bias correction (**a**),
after bias correction (**b**), and
observation (**c**)
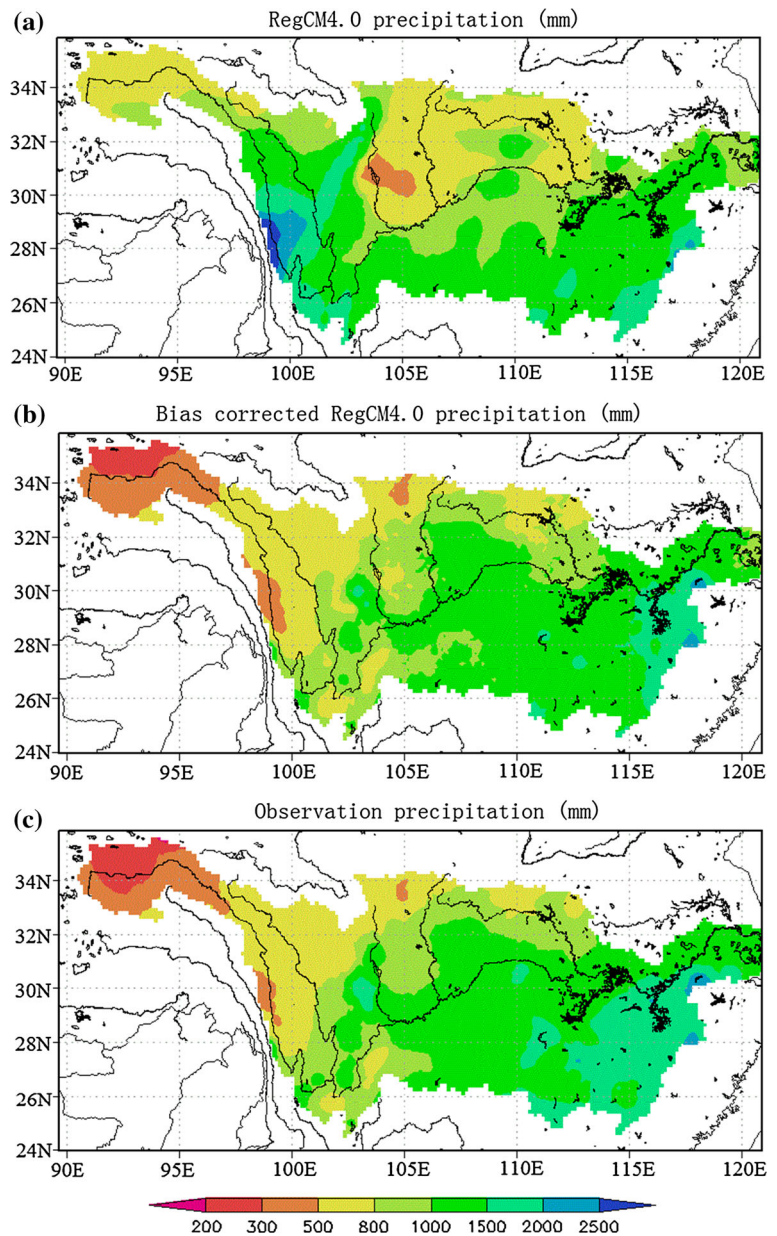
determined through calibrations. Random autostart simplex method was employed in model calibration. The parameters in the different catchments of the Yangtze River Basin were calibrated to reflect parameter heterogeneity in the entire basin. The VIC model was calibrated and validated with observed daily hydrographs from 11 catchments (divided by the hydrological stations in Fig. 1) in the Yangtze River Basin. Two indicators that reflect the performance of VIC model were selected and defined as

Volume error (VE):

$$VE = \overline{(Q_{sim}} - \overline{Q_{obs}})/\overline{Q_{obs}} \times 100\,\% \qquad (3)$$

Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970):

$$NSE = 1 - \left[\sum_{t=1}^{N} \left(Q_{sim,t} - Q_{obs,t} \right)^2 \Big/ \sum_{t=1}^{N} \left(Q_{obs,t} - \overline{Q_{obs}} \right)^2 \right] \qquad (4)$$

where $\overline{Q_{sim}}$ and $\overline{Q_{obs}}$ are the simulated and observed average streamflows over the period; $Q_{sim,t}$ and $Q_{obs,t}$ are the simulated and observed streamflows at time t; and N is the number of time steps in the period. VE reflects the agreement between the simulated and observed runoff volume, and NSE indicates the overall agreement of the shape of the hydrograph in the period. The optimal values for VE and NSE criteria are close to zero and 1, respectively.

Table 1 Characteristics of the 11 catchments and results of the calibration and validation

Catchment	River	Lon	Lat	Area ($*10^4$ km²)	Calibration (1970–1979)		Validation (1980–1989)	
					VE (%)	NSE	VE (%)	NSE
Panzhihua	Jinshajiang	99°56′	26°54′	23.3	−5.8	0.80	−6.5	0.81
Xiaodeshi	Yalongjiang	101°50′	26°45′	11.8	−3.5	0.95	−3.8	0.90
Gaochang	Minjiang	104°25′	28°48′	13.5	−4.0	0.93	−5.1	0.87
Beibei	Jialingjiang	106°25′	29°50′	15.8	4.0	0.89	3.2	0.84
Wulong	Wujiang	107°43′	29°17′	8.3	−6.6	0.71	−2.8	0.76
Xiantao	Hanjiang	113°28′	30°23′	14.4	4.2	0.61	5.9	0.72
Taoyuan	Yuanjiang	111°29′	28°54′	8.5	−6.6	0.82	−7.2	0.78
Xiangtan	Xiangjiang	112°55′	27°52′	8.2	−0.9	0.91	−3.8	0.92
Cuntan	Yangtze	106°36′	29°37′	86.7	−3.2	0.88	−4.3	0.87
Yichang	Yangtze	111°14′	30°40′	100.6	−1.7	0.83	−4.7	0.84
Datong	Yangtze	117°37′	30°46′	170.5	−0.8	0.81	−3.8	0.78

The observed streamflows for the period of 1970–1979 were used for calibration, and those from 1980 to 1989 were used for the validation of the model in 11 catchments of the Yangtze River Basin. Table 1 shows the characteristics of the 11 catchments and the calibration and validation results. The values of VE and NSE over the validation period vary from −7.2 to 5.9 %, and 0.72 to 0.92, respectively. The parameters are therefore effective for river flow simulation in the Yangtze River Basin. Under the assumption that the parameter in the VIC model will not change with the future climate change, the same parameters can be used for hydrological simulation in future period.

4.4 Future climate changes projected by RegCM4.0

Figure 5 shows the predicted changes in the bias-corrected 30-year average temperature and precipitation. The predicted increase in annual average temperature is higher than 3.5 °C in most areas. The largest increase (4–4.5 °C) is predicted to be in the source region of the Yangtze River Basin, especially in autumn and winter. The center region is another "hotspot" where the future temperature is predicted to increase more significantly in summer and autumn. Annual precipitation is predicted to increase in the northern region and decrease in the southern region of Yangtze River's mainstream. The upper reach of the Yangtze River Basin will have the most significant (more than 30 %) increase in precipitation during spring and summer. Precipitation will decrease by more than 10 % in the eastern and southern regions of the Yangtze River Basin in autumn and winter; this estimation indicates that droughts will become more common in dry season.

4.5 Future changes in runoff

Future hydrological changes were assessed based on output from VIC driven with the bias-corrected climate output from RegCM4.0. To demonstrate the impact of bias correction on model results, Fig. 6 shows the discharge of three main-stream hydrological stations simulated by using VIC model driven by the original and the bias-corrected output from RegCM4.0, for the control period 1970–1999 and future period 2070–2099. Without the bias correction, the model overestimates both the peak streamflow and the base flow in control period. The relative errors of mean annual runoff during this period simulated by using VIC model driven by the original outputs of RegCM4.0 were 60.3, 37.9, and −17.1 %. These errors were reduced to −2.5, −10.4, and −5.6 % after the bias-corrected climate was used. When the same bias correction method was used to drive future hydrologic simulations, a similar effect is found, with reductions in the future base flow and peak flow (Fig. 6, right column).

The temperature in the entire Yangtze River Basin will increase in the future, and the uneven changes in precipitation in the temporal and spatial distributions will cause uneven changes in runoff. Therefore, the changes in runoff were estimated in different catchments within the Yangtze River Basin.

Table 2 shows the predicted future changes in temperature, precipitation, evaporation, and runoff obtained through a comparison of the climate in the control (1970–1999) and future (2070–2099) periods. Runoff will increase throughout the year; the increase will be approximately 30 % in spring in three catchments in the upper reach of the Yangtze River Basin (e.g., Panzhihua, Xiaodeshi, and Gaochang) mainly because of the 20 % increase in precipitation. In the two catchments in the northern part of the Yangtze River (Beibei and Xiantao),

Fig. 5 Predicted future changes in 2 m temperature (*left panels*) and precipitation (*right panels*): averaged annually (*top panels*) and in each of the four seasons (MAM, JJA, SON, DJF)
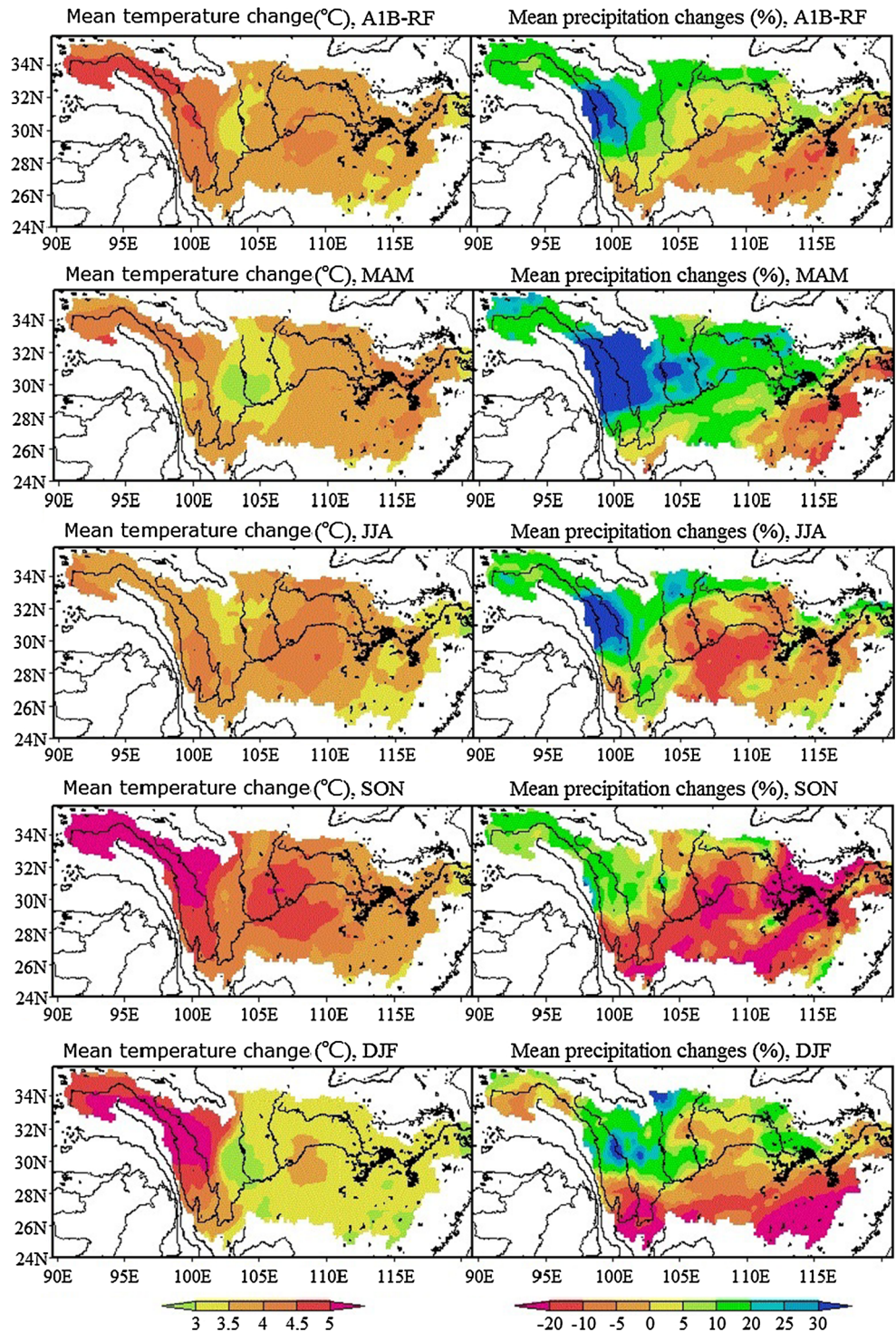
precipitation and runoff will increase by approximately 10 %, with the most significant increase appearing in spring (ranging from 15 to 20 %). The runoff in the southern regions of the Yangtze River Basin (Wulong, Taoyuan, and Xiangtan) will decrease following the decrease in precipitation, especially in the dry season (with 20–40 % decrease in winter). This situation means that

severe droughts will become increasingly common in these regions in the future.

4.6 Future changes in hydrological extremes

Figure 7 shows the changes in the annual maximum daily discharge (maximum of 7 and 15 days water volume at
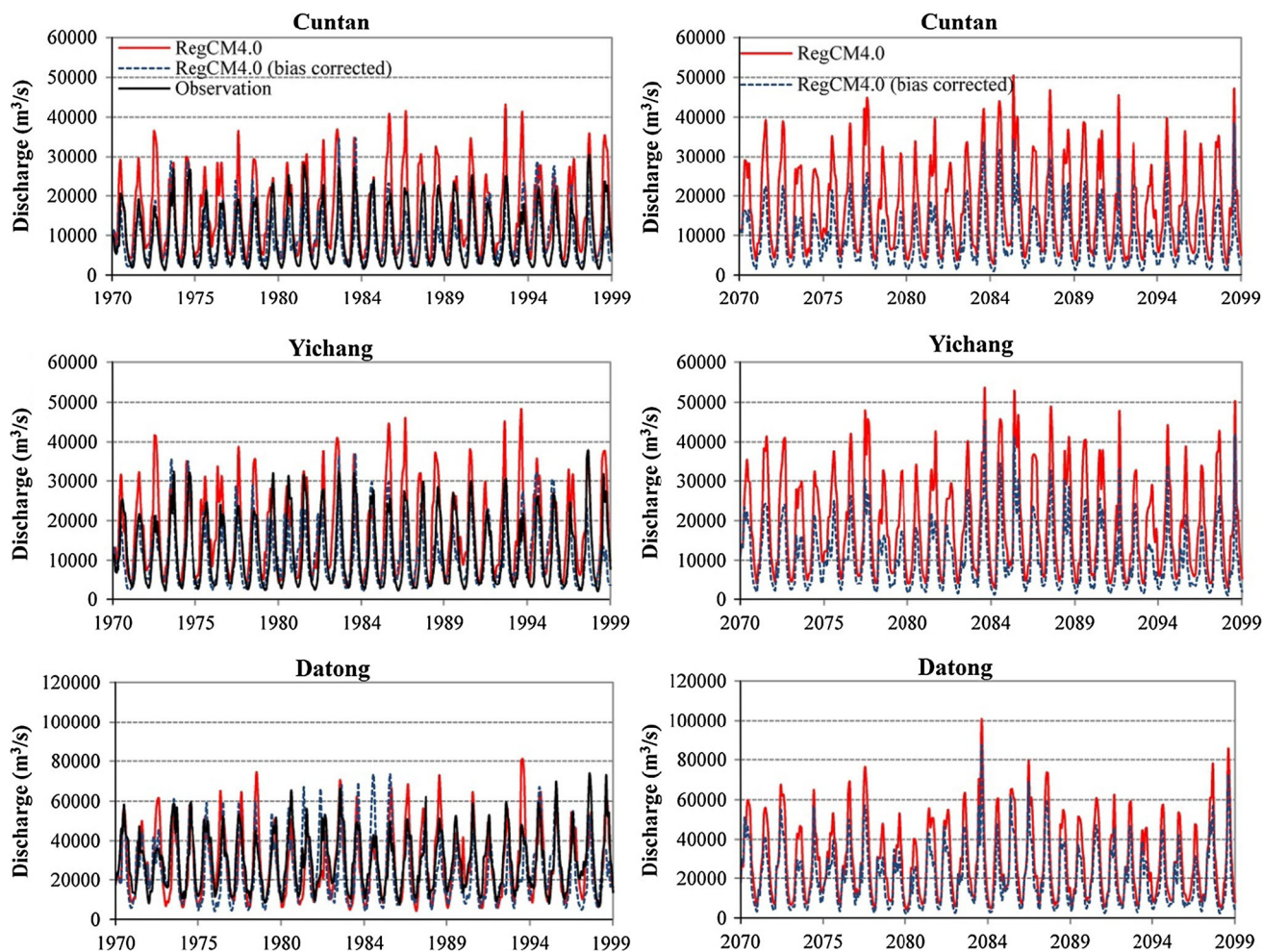
Fig. 6 The discharge of three mainstream hydrometric stations (Cuntan, Yichang, and Datong) during control period (1970–1999, *left*) and future period (2070–2099, *right*) simulated by using VIC model driven by the original and the bias-corrected output from RegCM4.0 and the observed climate data (no observation in the future period)

Cuntan station). It indicates that flood frequency and magnitude are likely to increase significantly in the future. The characteristics of extreme floods will differ by the end of the twenty-first century. For the maximum daily discharge and maximum 7 days water volume, the original extreme flood with return periods of 50, 20, and 10 years will change into floods with return periods of approximately 15, 7, and 3 years. For the maximum 15 days water volume, the original extreme flood with return periods of 50, 20, and 10 years will change into floods with the return period of approximately 10, 5, and 3 years. Analysis of the characteristics of extreme floods at Yichang and Datong stations provided similar results; thus, the results of the frequency changes in these two stations are not presented. Considering all the stations in the different regions of the Yangtze River, the climate changes have a distinct impact on the frequency of extreme floods; the floods with return periods of 50, 20, and 10 years in the present-day period

will change into floods with return periods of 10–20, 5–10 and less than 5 years in the end of twenty-first century.

An increase is projected for the selected return periods in all sub-basins. Most sub-basins will increase for flood events with a longer return period. Compared with the changes in the annual mean runoff, a more significant increase in extreme flood events is projected even in some of the sub-basins with a decreasing trend in precipitation and runoff.

5 Summary and conclusion

The outputs of the RegCM4.0 were interpolated to produce long-duration sequences of daily precipitation and temperature for the Yangtze River Basin. Bias corrections were applied to the control (1970–1999) and future (2070–2099) periods simulations. With the bias-corrected

Table 2 Projected changes between 2070–2099 and 1970–1999 in temperature (T), precipitation (P), evaporation (E), and runoff (R)

Catchment	Variable	Spring	Summer	Autumn	Winter
Panzhihua	T (°C)	4	3.9	5	4.8
	P (%)	25.8	13.8	4.1	−0.7
	E (%)	20	15.4	23.8	9
	R (%)	28.4	8.1	2.2	8
Xiaodeshi	T (°C)	3.8	3.9	4.9	4.7
	P (%)	29.7	20.4	4.6	2.8
	E (%)	16.5	16.8	25.8	1.9
	R (%)	36.2	24.3	4.6	2.8
Gaochang	T (°C)	3.3	3.5	4.5	3.8
	P (%)	31.4	12.2	3.8	16
	E (%)	19.3	8.9	19.5	5.1
	R (%)	33.4	20.9	0.9	10.9
Beibei	T (°C)	3.3	3.8	4.4	3.3
	P (%)	17.2	7.6	−3.4	8.2
	E (%)	10.2	3.8	11.1	13.1
	R (%)	15.1	15.2	1.4	0.4
Wulong	T (°C)	3.7	4.1	4.4	3.3
	P (%)	11.4	−11.7	17.6	−11
	E (%)	8.7	−2.4	1.5	6.3
	R (%)	1	−15.4	−20.4	−33.2
Xiantao	T (°C)	3.9	3.9	4.1	3.4
	P (%)	16.5	1.9	−3.6	5.4
	E (%)	11.2	1.5	6.2	19
	R (%)	19.6	3.4	1.5	12.6
Taoyuan	T (°C)	3.8	4	4.3	3.3
	P (%)	8.6	−6.5	−13.9	−8.7
	E (%)	3	−1.3	−2.4	2.2
	R (%)	−2.1	−7.1	−12.6	−22.4
Xiangtan	T (°C)	3.8	3.5	3.8	3.1
	P (%)	−4.4	−2.1	−19.6	−22.7
	E (%)	−6.1	0.2	−3.4	−6.2
	R (%)	−28.7	−7.5	−10.1	−39.3
Cuntan	T (°C)	3.6	3.8	4.7	4.1
	P (%)	21.9	11.7	0.8	0.9
	E (%)	15.4	9.8	17.8	8
	R (%)	22	13.3	0.6	0.7
Yichang	T (°C)	3.6	3.9	4.7	4
	P (%)	20.6	9.2	−0.5	−0.3
	E (%)	14.5	8.2	15.7	8
	R (%)	19.6	10.4	−0.6	−1.5
Datong	T (°C)	3.7	3.8	4.4	3.7
	P (%)	12.8	4.3	−4	−5.4
	E (%)	9.5	3.9	9.1	7.3
	R (%)	9.2	4.5	−2.1	−12

daily precipitation and temperature series, the daily discharge in 11 sub-basins of the Yangtze River Basin was simulated by using the VIC model. The impacts of climate change on hydrologic characteristics, especially on extreme hydrological events in the Yangtze River Basin, were then assessed.

In the future period, the annual average temperature will increase by more than 3.5 °C in most areas. The largest increase (4–4.5 °C) is predicted to exist in the source region of the Yangtze River Basin, especially in autumn and winter. The center region is another "hotspot" where the future temperature is predicted to increase more significantly in summer and autumn. This was consistent with the results of Chen et al. (2011a, b) who projected the future climate over China based on the weighted average of 28 GCMs under A1B scenario. Annual precipitation is predicted to increase in the northern region and decrease in the southern region of Yangtze River's main stream. The upper reach of the Yangtze River Basin will have the most significant (more than 30 %) increase in precipitation in spring and summer. Precipitation will decrease by more than 10 % at the eastern and southern regions of the Yangtze River Basin in autumn and winter. This prediction indicates that droughts will become increasingly common during dry seasons in this region. Huang et al. (2011) predicted that precipitation of the Yangtze River Basin would be dominated by an increasing trend based on outputs from the HadCM3 model under scenarios A2 and B2.

The future changes in temperature and precipitation will affect the future hydrological cycle. Runoff from areas in the upper reach of the Yangtze River will increase throughout the year by as much as 30 % during spring. Runoff from catchments in the northern part of the Yangtze River Basin will increase by approximately 10 %, whereas that in the southern part will decrease (especially in dry season) following the decrease in precipitation.

The impacts of climate change on extreme hydrological events are the focus of this study. The frequency changes in extreme flood characteristics at Cuntan, Yichang, and Datong stations indicate that the impacts of climate change on extreme flood events are significant under the future scenario. The original extreme floods with 50, 20, and 10 year return periods will change into floods with no more than 20, 10, and 5 year return periods. The changes in extreme flood events will have significant impacts on flood control systems. The reservoir system and hydropower stations along the Yangtze River would likely be required to spill more water because of the increase in the extreme flood events in the future.

A regional climate and hydrological model system was constructed in this study by integrating a global climate model (ECHAM5) with a regional climate model (RegCM4.0) and a distributed hydrological model (VIC) to study the impacts of climate change on water resources and extreme flood events in the Yangtze River Basin. Assessment of the uncertainties related to the GCM, RCM, emission scenario, bias correction method, and hydrological model was not conducted and is

Fig. 7 Projected changes in the annual maximum daily discharge (**a**), 7d (**b**) and 15d (**c**) water volume at Cuntan station in the Yangtze River Basin
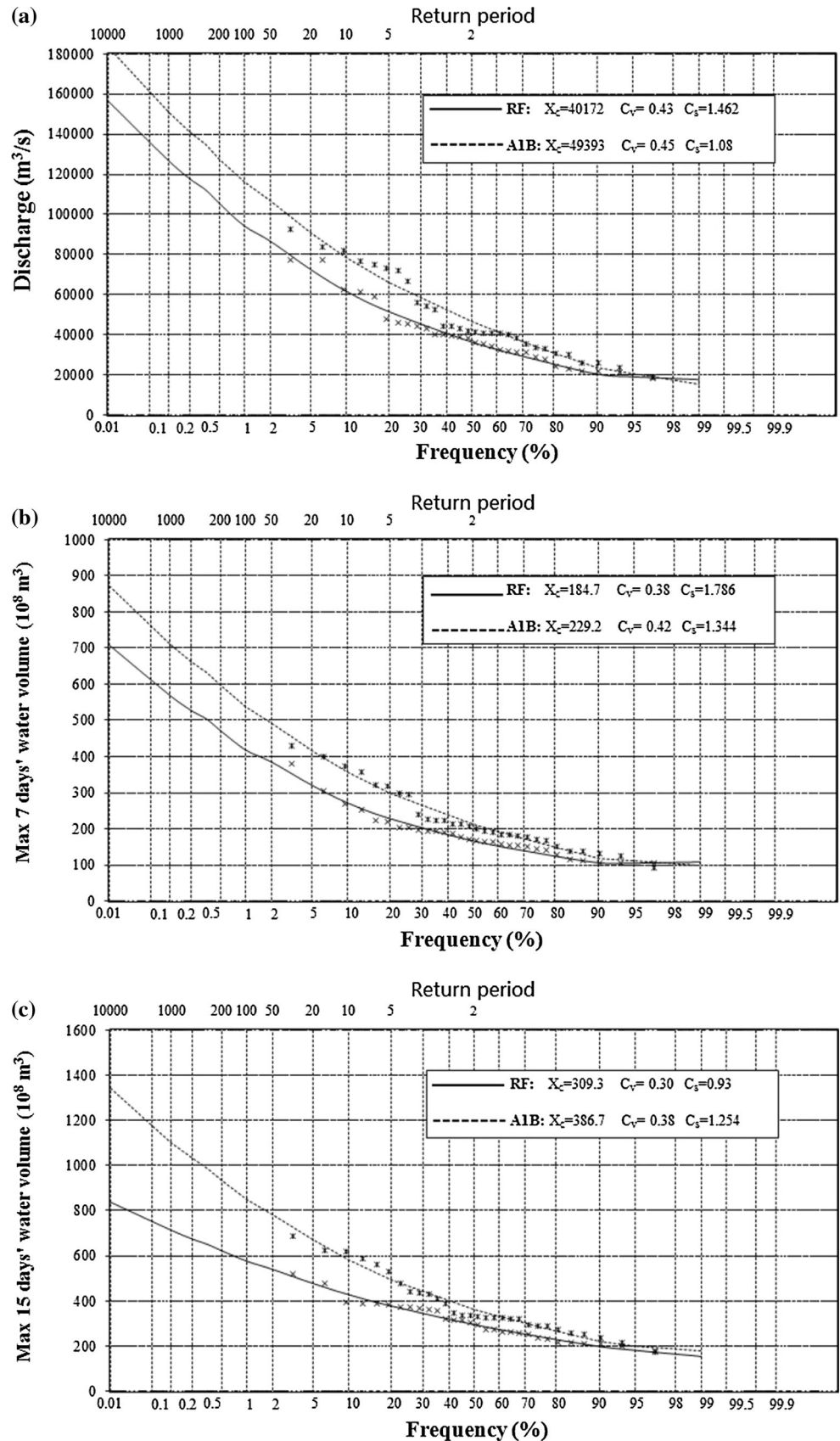
beyond the scope of this study. However, conscious choices were made to reduce the uncertainty. For example, as GCMs were recognized as the largest source of uncertainty in climate projection (Chen et al. 2011a, b; Kay et al. 2009; Woldeme-skel et al. 2012), we chose the ECHAM5 model that has a climate sensitivity close to multi-model ensemble to drive the regional climate model. We expect this study to establish a foundation for follow up research that includes comprehensive ensemble simulations to assess and address model-related uncertainties.

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