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Spatial-temporal changes in river runoff and terrestrial ecosystem water retention under 1.5℃ and 2℃ warming scenarios across China

Ran Zhai[1,2], Fulu Tao[1,2,3,*], Zhihui Xu[4]

[1] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
[3] Natural Resources Institute Finland (Luke), FI-00790 Helsinki, Finland
[4] Information Center of Yellow River Conservancy Commission, Zhengzhou 450004, China

Correspondence to: Fulu Tao (taofl@igsnrr.ac.cn)

Abstract. The Paris Agreement set a long-term temperature goal of holding the global average temperature increase to below 2.0℃ above pre-industrial levels, and pursuing efforts to limit this to 1.5℃, it is therefore important to understand the impacts of climate change under 1.5℃ and 2.0℃ warming scenarios for climate adaptation and mitigation. Here, climate scenarios by four Global Circulation Models (GCMs) for the baseline (2006-2015), 1.5℃ and 2.0℃ warming scenarios (2106-2115) were used to drive the validated Variable Infiltration Capacity (VIC) hydrological model to investigate the impacts of global warming on river runoff and Terrestrial Ecosystem Water Retention (TEWR) in China. The trends in annual mean temperature, precipitation, river runoff and TEWR were analysed at the grid and basin scale. Results showed that there were large uncertainties in climate scenarios from the different GCMs, which led to large uncertainties in the impact assessment. The differences among the four GCMs were larger than differences between the two warming scenarios. The interannual variability of river runoff increased notably in areas where it was projected to increase, and the interannual variability increased notably from 1.5℃ warming scenario to 2.0℃ warming scenario. By contrast, TEWR would remain relatively stable. Both extreme low and high river runoff would increase under the two warming scenarios in most areas in China, with high river runoff increasing more. And the risk of extreme river runoff events would be higher under 2.0℃ warming scenario than under 1.5℃ warming scenario in term of both extent and intensity. River runoff was significantly positively correlated to precipitation, while increase in maximum temperature would generally cause river runoff to decrease through increasing evapotranspiration. Likewise, precipitation also played a dominant role in affecting TEWR. Our findings highlight climate change mitigation and adaptation should be taken to reduce the risks of hydrological extreme events.

1 Introduction

The global average surface temperature increased by 0.85℃ from 1880 to 2012, and the beginning of the 21st century has been the warmest on record (IPCC, 2013). In 2015, the Paris Agreement set a long-term temperature goal of holding the global average temperature increase to below 2.0℃ above pre-industrial levels, and pursuing efforts to limit this to 1.5℃, because the risks and impacts of climate change were thought to decrease significantly under global warming of 1.5℃ than 2.0℃ (Schleussner et al., 2016). This calls for spatial explicitly climate change impact assessment on multiple sectors under global warming of 1.5℃ and 2.0℃. Up to now, impact assessment under 1.5℃ and 2.0℃ warming scenarios has been rare, but urgently needed for climate adaptation and mitigation.

Global warming is likely to have major impacts on hydrological cycle (Huntington, 2006;Milliman et al., 2008;Arnell and Gosling, 2013), such as changing precipitation pattern and increasing risks of extreme hydrological events (Wang et al., 2012;Zhang et al., 2016). China is vulnerable to future climate change, the impacts of climate change on water resources in China has been of key concern (Piao et al., 2010;Leng et al., 2015). Hydrological models have been routinely used to investigate the impacts of climate change on water resources, driven by climate scenarios from GCMs. Several previous studies had assessed climate change impacts on water resources in some river basins over China (e.g, Chen et al., 2012; Li et al., 2013; Zhang et al., 2016). For example, with the Xin-anjiang model and HBV model in Qingjiang Watershed, Chen et al. (2012) showed river runoff would be firstly decreased during 2011-2040 and then increased under A2 and B2 scenarios relative to baseline period (1962-1990). Using the SIMHYD and GR4J rainfall-runoff models, driven by climate scenarios from 20 GCMs, mean river runoff was projected to increase by most of the GCMs under a 1.0℃ increase in the global average surface air temperature across the Yarlung Tsangpo River basin (Li et al., 2013). Using the Soil and Water Assessment Tool (SWAT), Zhang et al. (2016) showed that future river runoff under RCP2.6 and RCP4.5 scenarios would not change much, but increased significantly under RCP8.5 scenario from three different GCMs (BCC-CSM1.1, CanESM2, and NorESM1-M) in the Xin River basin of China. However, climate change impact on water resources for the whole China has rarely been investigated. Using the VIC model, Wang et al. (2012) showed the total amount of annual river runoff over China would increase by approximately 3-10% by 2050 under A2, B2, and A1B emissions scenarios, however with uneven distribution, relative to 1961-1990. Using the VIC model driven by climate scenarios from five GCMs under RCP8.5 emission scenario, Leng et al. (2015) showed that climate change could increase water-related risks across China in the 21st century because of projected decrease in river runoff and increase in interannual variability. The changes in river runoff and hydrological extreme events under 1.5℃ and 2.0℃ warming scenarios across China have not been investigated yet. Because of vast territory and large amount of population, it is important to understand the spatial explicitly changes in water resources under 1.5℃ and 2.0℃ warming scenarios in China.

Terrestrial Ecosystem Water Retention (TEWR) is one of important processes affecting river runoff yield. With the rapid growth of population and economy, ecosystem degradation and ecosystem services have increasingly become a hot topic. TEWR is one of important ecosystem services (Gong et al., 2017;Xu et al., 2017). Different methods have been used to quantify TEWR. One of popular methods is based on terrestrial ecosystem water balance, the capacity of TEWR is the difference between the amount of precipitation and the sum of runoff and evapotranspiration (Ouyang et al., 2016;Xu et al., 2017). It is of great importance to evaluate TEWR service under changing climate for ecosystem and water resource management (Tao et al., 2003).

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To our knowledge, this study is the first to investigate the changes in river runoff and TEWR service across China under 1.5℃ and 2.0℃ warming scenarios, as well as the differences between the two warming scenarios. The objectives of this study are 1) to investigate the characteristics of expected changes in temperature and precipitation under 1.5℃ and 2.0℃ warming scenarios; 2) to investigate the changes in river runoff, hydrological extremes, and TEWR across China under 1.5℃ and 2.0℃ warming scenarios at the grid scale and basin scale; 3) to evaluate the dominant factors for changes in river runoff and TEWR under warming climate.

2 Materials and methods

2.1 Study domain

There are ten main basins in China (Fig.1), including the Songhua River basin (SHR), Liao River basin (LR), Northwest River basins (NWR), Hai River basin (HR), and Yellow River basin (YR) in the northern China; the Yangtze River basin (YTR), Huai River basin (HuR), Southeast River basins (SER), Southwest River basins (SWR), and Pearl River basin (PR) in the southern China (Leng et al., 2015;Liu et al., 2017b). The temperature increases from north to south, and precipitation increases gradually from northwest to southeast (Xie et al., 2007). Mean annual river runoff for China is around 284 mm based on synchronous runoff data for a 50-year period from 1956-2005 (Wang et al., 2012). However, water resource is unevenly distributed spatially and seasonally. In most areas, there are more than 70% of total river runoff in the flood season from June to October (Wang et al., 2012). Water is more abundant in the southern China than the northern China (Piao et al., 2010).

2.2 Model description

A large-scale semi-distributed hydrological model, VIC, was applied in this study. It divided China into 0.5°×0.5° grids with three layers of soil. The soil and vegetation situation in each grid were considered in the model. The total runoff consists of surface runoff and base flow (Wang et al., 2012), a conceptual surface runoff model with Philip infiltration formulation is used to generate runoff from the first and second layers (Liang and Xie, 2001;Xie et al., 2003). ARNO method is used to describe base flow, which only happens in the third layer of soil (Todini, 1996). A routing model is used to calculate runoff in each catchment after running VIC model (Lohmann et al., 1996).

2.3 Data

Bias-corrected climate datasets for this study were from the project “Half a degree Additional warming, Prognosis and Projected Impacts” (HAPPI). It provides climate data to assess how the climate, especially extreme weather, might be different from the current days in the world under 1.5℃ and 2.0℃ warmer than pre-industrial conditions (Mitchell et al., 2017). Large ensembles of simulations (>50 members) for three time periods have been produced after being bias corrected using the ISIMIP2b bias correction approach (Frieler et al., 2016), from four GCMs up to now, including ECHAM6-3-LR, MIROC5, NorESM1-HAPPI, and CAM4-2degree (Table 1) (http://portal.nersc.gov/c20c/data/ClimateAnalytics/). The first time period was from 2006 to 2015 which is the most recently observed 10-year, the second time period was from 2106 to 2115 under 1.5℃ and 2.0℃ warming scenarios, respectively. Each simulation within an time period was different from the others in its initial weather state (Mitchell et al., 2017). Table 1 showed the available ensemble members in each GCM under current period from 2006 to 2015, and 1.5℃ and 2.0℃ warming scenarios from 2106 to 2115.

The daily weather data from 1961 to 1979 was obtained from China Meteorological Administration (CMA). 1 km land cover data was from the University of Maryland (http://glcfapp.glcf.umd.edu:8080/esdi/index.jsp). 1 km soil texture data (China Soil Map Based Harmonized World Soil Database (v1.1)), and 1km Digital Elevation Model dataset were obtained from the Cold and Arid Regions Sciences Data Center at Lanzhou (http://westdc.westgis.ac.cn). These data were used to build the VIC model. The NASA Shuttle Radar Topographic Mission (SRTM) 90 m Digital Elevation Data (http://srtm.csi.cgiar.org/) was used to extract each catchment. Monthly river runoff observation data from 1961 to 1979, obtained from the hydrological year book of China and local water resources department, were used for calibrating and validating the VIC model. A detailed description was presented in Zhai and Tao (2017).

2.4 VIC model parameters calibration and validation

Monthly river runoff data from 1961-1979 was used to calibrate and validate the VIC model (Wang et al., 2012;Liu et al., 2017b). Seven parameters in the VIC model needed to be calibrated because it was difficult to obtain. We divided 1961-1979 into three periods, including preheating period (1961-1962), calibration period (1963-1969), and validation period (1970-1979) in each catchment. The VIC model was run at daily time step and the results were aggregated to monthly time step at each catchment for calibrating and validating parameters. The relative error ($BIAS$; %) and the Nash-Sutcliffe efficiency coefficient (NSE) were used to calibrate and validate the parameters:

1) The $BIAS$ (%) represents the error between simulated ($\overline{Q}_s$) and observed mean monthly runoff ($\overline{Q}_o$):

$$BIAS = (\overline{Q}_s - \overline{Q}_o) / \overline{Q}_o , \tag{1}$$

2) The NSE (Nash and Sutcliffe, 1970) represents the matching degree between the simulated and observed runoff:

$$NSE = \frac{\sum (Q_{i,o} - \overline{Q}_o)^2 - \sum (Q_{i,o} - Q_{i,s})^2}{\sum (Q_{i,o} - \overline{Q}_o)^2} , \tag{2}$$

Where, $Q_{i,o}$ and $Q_{i,s}$ are the observed monthly runoff (mm) and the simulated monthly runoff (mm) at the month *i*, and $\overline{Q}_o$ is the mean observed monthly runoff (mm). A good simulation result will have NSE close to 1 and $BIAS$ approach to 0.

2.5 Quantification of TEWR service

In this study, considering the input water and output water of a certain grid, we adopted the following equation to calculate the total amount of TEWR capacity (Ouyang et al., 2016;Xu et al., 2017).

$$W = P - ET - R \,, \tag{3}$$

Where, W represents TEWR (mm), P represents precipitation (mm), ET represents evapotranspiration (mm), and R represents river runoff (mm).

2.6 Analysis

The climate scenarios from the GCMs of ECHAM6-3-LR, MIROC5, NorESM1-HAPPI, CAM4-2degree were input to drive the VIC hydrological model. Each GCM had output three climate change scenarios: baseline period from 2006-2015, the 1.5℃ warming scenario from 2106-2115, and the 2.0℃ warming scenario from 2106-2115. For the GCM of ECHAM6-3-LR, NorESM1-HAPPI, and CAM4-2degree, we had 200 simulations (10 years × 20 ensembles) for the baseline period, 1.5℃ and 2.0 ℃ warming scenarios, respectively. For the GCM of MIROC5, we had 100 simulations (10 years × 10 ensembles) for the baseline period, the 1.5℃ and 2.0℃ warming scenarios, respectively. Changes in annual mean temperature and annual precipitation were calculated using each ensemble for future 10 years period (2106-2115) under 1.5℃ and 2.0 ℃ warming scenarios relative to the corresponding ensemble for the baseline period (2006-2015). Changes in annual mean and standard variation (SD) as a measure of interannual variability were used to analyse the impacts of climate change on river runoff and TEWR across China. We computed the changes in annual mean and SD of runoff and TEWR as the relative differences between the simulations using each ensemble for future 10 years period (2106-2115) under 1.5℃ and 2.0 ℃ warming scenarios relative to the simulations using the corresponding ensemble for the baseline period (2006-2015). For each warming scenario in every GCM, we adopted the median value of the changes among ensembles, which should be the most likely result avoiding abnormal value (Tao and Zhang, 2011). We also calculated the median value of runoff change and TEWR change among all 70 ensembles under the four GCMs of each grid. Then we calculated probability density functions of river runoff change and TEWR change through the median value from all 70 ensembles in every grid in the ten main basins across China under 1.5℃ and 2.0℃ warming scenarios (2106-2115) relative to the baseline period (2006-2015). The basin mean was calculated by averaging the values for the individual grid cells within the basin for each ensemble of a GCM.

Two annual river runoff quantiles Q_{10} (low flow) and Q_{90} (high flow) were used to evaluate the risks of hydrological extremes. We used all ensemble simulations in the baseline period in 2006-2015, in 2106-2115 under 1.5℃ warming scenario, and in 2106-2115 under 2.0℃ warming scenario to evaluate the changes in low runoff and high runoff. Therefore, there were 700 years data (10 years × 3 GCMs × 20 ensembles + 10 years × 1 GCM × 10 ensembles = 700) for baseline period in 2006-2015, 1.5℃ warming scenario in 2106-2115, and 2.0℃ warming scenario in 2106-2115, respectively.

Pearson Correlation Coefficient (r) was used to analyse the dominant factors affecting runoff and TEWR:

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$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}, \tag{4}$$

Where, n represents sample size, including four GCMs, two warming scenarios relative to the baseline in each GCM, 20 or 10 ensembles in each warming scenario, 10 years in each ensemble, so there are 1400 samples (10 years × 3 GCMs × 20 ensembles × 2 warming scenarios + 10 years × 1 GCM × 10 ensembles × 2 warming scenarios = 1400) in each grid. x_i and y_i are variable change values under 1.5℃ and 2.0℃ warming scenarios (2106-2115) relative to the baseline period (2006-2015) in each data set, and $\bar{x}$, $\bar{y}$ are mean change value of each variable in each grid.

3 Result

3.1 VIC model parameters calibration and validation

The VIC model was calibrated and validated in ten catchments located in different main basins in China (Fig. 1), and then the calibrated parameters were applied in all the grids located in the same basin. The NSE values of monthly runoff were above 0.70 in eight catchments in the calibration period, while the NSE values were above 0.70 in seven catchments in the validation period (Table 2). Except the Xiahui catchment, the $BIAS$ values in all catchments were between -15% and 15%, which indicated the model simulated monthly runoff fairly well. Generally, the VIC model performed better in catchments located in the southern China where there were more precipitation and runoff compared with catchments located in the northern China. The NSE values for the Sanjiangkou, Xixian, Yangkou, Zhongaiqiao and Changle catchment in the southern China were all more than 0.75, and the $BIAS$ values were between -10% and 10%.

3.2 Climate change across China under 1.5℃ and 2.0℃ warming scenarios

The median values of the changes in annual mean temperature and annual precipitation under the two warming scenarios for each GCM and all the four GCMs were shown in Fig. 2 and Fig. 3, respectively. Generally, the ECHAM6-3-LR and CAM4-2degree projected a relatively small increase in annual mean temperature (Fig. 2a,d,f,i). The MIROC5 projected a relatively large increase in annual mean temperature in comparison with other GCMs (Fig. 2b,g). As for annual precipitation, the ECHAM6-3-LR projected a decrease in precipitation over large areas across China under 1.5℃ warming scenario, and the decreasing trends reduced in the northeastern China and northwestern China, and increased in the Yellow River basin, Huai River basin, Yangtze River basin, and Southwest River basins under 2.0℃ warming scenario (Fig.3a,f). In contrast, the MIROC5, NorESM1-HAPPI and CAM4-2degree projected an increase in precipitation over large areas across China under both 1.5℃ and 2.0℃ warming scenarios. In particular, the MIROC5 projected the largest increase in precipitation by more than 20% in large areas in the southern China (Fig. 3b,g). Nearly all the four GCMs projected that precipitation decreased more (or increased less) in most areas located in the northwestern China than other areas in China (Fig. 3). In contrast, precipitation was projected to increase more (or decrease less) in the southeastern China (Fig. 3). There were large differences among the projections by the four different GCMs, suggesting a large uncertainty from climate change projection. Take all the 70 ensembles of the four GCMs as a whole, annual mean temperature was projected to increase more in the northern China and the middle and lower reaches of the Yangtze River basin than other areas (Fig. 2e,j). And annual precipitation was projected to increase more in the southeastern China under 1.5℃ warming scenario, and the increasing trend was projected to narrow down in the Yangtze River basin and extend to some areas located in the northern China under 2.0℃ warming scenario (Fig. 3e,j).

3.3 Changes in river runoff across China under 1.5℃ and 2.0℃ warming scenarios

There was significant difference in projected change in river runoff using the VIC model driven by the four different GCMs (Fig. 4). The projected river runoff pattern was consistent with that of precipitation generally, suggesting precipitation change played a dominant role in runoff change. For example, under 1.5℃ and 2.0℃ warming scenarios by the ECHAM6-3-LR, river runoff was projected to decrease in most areas across China (Fig. 4a,f) due to the projected decrease in precipitation (Fig. 3a,f). By contrast, using the climate scenarios by the MIROC5, river runoff was projected to increase most (Fig. 4b,g) due to the projected increase in precipitation (Fig. 3b,g). In addition, increase in temperature would lead to increase in evapotranspiration (Fig. A1), which resulted in decrease in river runoff. For example, under 1.5℃ warming scenario by the CAM4-2degree, precipitation would increase in most areas but the magnitude of increase was small, river runoff was projected to decrease in large areas in the Hai River basin, Yellow River basin, Huai River basin, and the source regions of the Yellow River basin and Yangtze River basin (Fig.4d). Using the climate scenarios by the MIROC5 and NorESM1-HAPPI, river runoff was projected to increase in most areas across China (Fig. 4b,c,g,h), suggesting the positive effects of precipitation increase should exceed the negative effects of temperature increase. For the median change across all the 70 ensembles in the four GCMs, river runoff was projected to increase in large areas in China, especially in the Yellow River basin, Huai River basin, and Pearl River basin (Fig. 4e,j). By contrast, river runoff was projected to decrease in areas located in the Northwest River basins (NWR) under 1.5℃ warming scenario and the source regions of the Yellow River basin and the Yangtze River basin under 2.0℃ warming scenario (Fig. 4e,j).

For each GCM, the median changes in SD among the ensembles under 1.5℃ and 2.0℃ warming scenarios were presented (Fig. 5). The standard deviation was projected to increase notably in areas where the annual river runoff increased notably, for all the four GCMs. Furthermore, the SD of the simulated river runoff increased more under 2.0℃ warming scenario than that under 1.5℃ warming scenario generally (Fig. 5), suggesting that interannual variation of river runoff would increase with climate warming.

3.4 Changes in hydrological extremes across China under 1.5°C and 2.0°C warming scenarios

Both low river runoff (Q_{10}) and high river runoff (Q_{90}) were projected to increase in large areas across China, although decrease in some areas in the Northwest River basins and the source regions of the Yellow River basin and the Yangtze River basin (Fig. 6). High river runoff was expected to increase much more (or decrease less) than low river runoff in most areas (Fig. 6). In some areas in the Northwest River basins, Songhua River basin and the source regions of the Yellow River basin and the Yangtze River basin, low river runoff was projected to decrease under both 1.5°C and 2.0°C warming scenarios (Fig. 6a,b). The areas with low river runoff decreasing were projected to enlarge under 2.0°C warming scenario (Fig. 6a,b) around the source regions of the Yellow River basin and the Yangtze River basin, suggesting much more drought risks under 2.0°C warming scenario than under 1.5°C warming scenario. And the low river runoff increased less under 2.0°C warming scenario than 1.5°C warming scenario (Fig. 6a,b). The areas with high river runoff increasing were projected to enlarge under 2.0°C warming scenario than 1.5°C warming scenario (Fig. 6c,d). The intensity was also expected to increase in most areas across China, especially in the Huai River basin (Fig. 6c,d), suggesting flood risks would increase under 2.0°C warming scenario. In contrast, high river runoff in some areas in the source regions of the Yellow River basin and the Yangtze River basin was expected to decrease, and decreased more under 2.0°C warming scenario than 1.5°C warming scenario (Fig. 6c,d). Generally, high river runoff was expected to increase more than low river runoff in most areas across China, and the risks of extreme high river runoff and low river runoff were expected to increase under 2.0°C warming scenario than 1.5°C warming scenario.

3.5 Changes in TEWR across China under 1.5°C and 2.0°C warming scenarios

Changes in TEWR were consistent with changes in precipitation and river runoff. With the climate scenarios by ECHAM6-3-LR, TEWR was projected to decrease in large areas in China under both 1.5°C and 2.0°C warming scenarios (Fig. 7a,f), mainly due to the projected decrease in precipitation. In addition, precipitation was not the only factor for changes in TEWR. For example, precipitation was projected to increase in the source regions of the Yellow River basin and Yangtze River basin under warming scenario by the MIROC5 (Fig. 3b,g), but TEWR there was projected to decrease (Fig. 7b,g) due to increasing evapotranspiration (Fig.A1b,g). Based on the median value of all 70 ensembles from the four GCMs, TEWR was projected to be more stable than river runoff (Fig. 4e,j, Fig. 7e,j), projected changes for most grids would range from -5% to 5%. Compared with river runoff, TEWR was projected to decrease under 2.0°C warming scenario than 1.5°C warming scenario relative to the baseline period (Fig. 4e,j, Fig. 7e,j).

As river runoff, the SD of TEWR was projected to increase notably in areas where the TEWR increased notably for all the four GCMs generally (Fig. 8). However, the SD was projected to increase in some areas where the TEWR decreased, such as the Liao River basin under 2.0°C warming scenario by the ECHAM6-3-LR (Fig. 7f, Fig. 8f). The changes in SD of TEWR were not as significant as that of river runoff. The differences among the ten main basins were not as significant as river runoff. As for the median value of the 70 ensembles, the SD of river runoff from 1.5°C (Fig. 5e) to 2.0°C (Fig.5j)

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warming scenario relative to the baseline period would increase significantly, however, the SD of TEWR was projected to increase more in most areas across China under 1.5℃ (Fig. 8e) than 2.0℃ warming scenario (Fig. 8j), suggesting TEWR would remain more stable than river runoff under a warming climate.

4 Discussion

4.1 Differences in climate variables and water resources between 1.5℃ and 2.0℃ warming scenarios by each GCM at the basin scale

To evaluate climate change and its potential impact on river runoff and TEWR at the basin scale, the annual mean temperature, annual precipitation, annual river runoff, and annual TEWR for all the 10 basins were summarized. At the basin scale, annual mean temperature increased more in the northern China than the southern China, and the differences between the northern China and southern China enlarged under 2.0℃ warming scenario than 1.5℃ warming scenario (Fig. 9a), while annual precipitation increased more in the southern China than the northern China (Fig. 9b). Generally, both river runoff and TEWR would change consistently with precipitation (Fig. 9b,c,d). Annual mean temperature increased less under the climate scenarios by ECHAM6-3-LR than the other three GCMs in most basins. Annual precipitation was projected to decrease slightly in most basins under the climate scenarios by ECHAM6-3-LR. However, precipitation was projected to increase in all basins under the climate scenarios by the other three GCMs (Fig. 9b). River runoff was projected to increase under the climate scenarios by the four GCMs, except some basins under the climate scenarios by ECHAM6-3-LR and CAM4-2degree (Fig. 9c). By contrast, TEWR was projected to decrease in more cases. According to the median value across all ensembles in the four GCMs, river runoff was projected to increase in all basins, but TEWR was projected to decrease or increase less than runoff (Fig. 9c,d). Our results showed that the differences of river runoff and TEWR between GCMs were larger than those between warming scenarios by a certain GCM. In addition, we found that the changes in river runoff and TEWR were more pronounced than those of precipitation. In this study, precipitation changes ranged from around -10% to 30%, however projected changes in river runoff and TEWR would range from -20 to 80%, -20% to 40%, respectively.

The variations of river runoff under different GCMs and warming scenarios were larger in the Huai River basin than other basins, and extremely large under the climate scenarios by MIROC5 (Fig. 9c,d), suggesting there could be larger uncertainties in the Huai River basin than other basins. The projected median annual mean precipitation and median annual mean river runoff were, respectively, about 919 mm and 204 mm during 2006 to 2015 under the climate scenarios by the MIROC5 in the Huai River basin. However, precipitation and temperature increase did not lead to a significant increase in evapotranspiration (Fig. A1b,g), More than 20% increase in precipitation would lead to a large percentage increase in river runoff because the base value in the baseline period was small.

Probability density functions of median changes of river runoff and TEWR across all ensembles in the four GCMs for all the grids in each basin were presented in Fig. A2 and A3, respectively. River runoff was projected to increase with higher probability under 2.0℃ than 1.5℃ warming scenario across China, except in the Yangtze River basin, Southeast River basins and Pearl River basin (Fig. A2), because precipitation was projected to increase less under 2.0℃ than 1.5℃ warming scenario in these basins (Fig. 9b). TEWR was projected to change less than river runoff under both 1.5℃ and 2.0℃ warming scenarios (2106-2115) compared to the baseline period (2006-2015). TEWR change was projected to decrease with higher probability under 2.0 ℃ than 1.5℃ warming scenario compared with baseline period in most basins across China (Fig. A3).

4.2 Major factors controlling changes in river runoff, and TEWR

The VIC model has four input climate variables, including precipitation, maximum temperature, minimum temperature and wind speed, the Pearson Correlation Coefficient was calculated between the projected changes in annual river runoff and the changes in climate variables, including annual precipitation (Fig. 10a), annual mean maximum temperature (Fig. 10b), annual mean minimum temperature (Fig. 10c) and annual mean wind speed (Fig. 10d). Only significant correlations were shown ($p<0.05$). Generally, the correlations between precipitation change and river runoff change were much more significant than the other three variables in China (Fig. 10). This finding is supported by some previous studies (Dan et al., 2012;Wang et al., 2016;Huang et al., 2016;Liu et al., 2017b). The correlations were smaller in the Yellow River basin, Hai River basin, and Huai River basin than other basins, even less than 0.5 for some grids in the Northwest River basins and the source regions of the Yellow River basin (Fig. 10a). This may be caused by complex topography and land type, as well as the arid condition, which prevented the amount of water to form river runoff (Liu et al., 2017a). There were significant negative correlations between annual river runoff change and annual mean maximum temperature change in most areas across China. Increasing annual maximum temperature would lead to river runoff decrease in most areas because of increasing evapotranspiration (Wang et al., 2015;Huang et al., 2016), especially in the southern China (Fig. 10b). The correlations between annual river runoff change and annual mean minimum temperature change were not significant in nearly half of the studied grids in China, which was negative at most areas in the Hai River basin, Huai River basin, the source regions of the Yellow River basin and Yangtze River basin, and some areas in the Yellow River basin, Yangtze River basin, Pearl River basin and the Northwest River basins, and positive at other areas. Increase in annual mean minimum temperature would increase melting of snow or ice in the Tibetan Plateau and high latitude areas with cold weather regime, resulting in an increase in water supply to runoff (Liu et al., 2017a). Since increase in minimum temperature was accompanied with increase in precipitation in most of the climate scenarios, there were positive correlations between minimum temperature change and runoff change at some areas. However, at other areas (e.g. Huai River basin, Hai River basin), increase in minimum temperature change would lead to decrease in runoff change, mainly caused by increasing evapotranspiration. There were significantly negative correlations between river runoff change and wind speed change at most areas. Decrease in wind speed would lead to less evapotranspiration (She et al., 2017), consequently more river runoff.

The TEWR was calculated through three variables, including precipitation, evapotranspiration, and river runoff, we analysed the correlations between TEWR and the three variables. Like river runoff, the correlation coefficients were also more significant between annual TEWR change and annual precipitation change (Fig. 11a), which suggested that increase in precipitation change would lead to increase in TEWR change, but not as significant as the correlations between precipitation change and river runoff change (Fig. 10a). The Pearson Correlation Coefficients were smaller in the Southwest River basins than those in other basins. The correlations were nearly the same but smaller between TEWR change and river runoff change than those between TEWR change and precipitation change (Fig. 11a,c), because river runoff change and precipitation change had a strong correlation (Fig. 10a). There were negative correlations between TEWR change and evapotranspiration change in the Songhua River basin, Liao River basin, Hai River basin, Huai River basin, Southeast River basins, Pearl River basin and the source regions of the Yellow River basin and Yangtze River basin, increase in evapotranspiration change with increasing temperature change would lead to decrease in TEWR change. However, increase in evapotranspiration with increasing temperature would usually company with precipitation increasing, which led to a positive correlation between the evapotranspiration change and TEWR change at some basins.

4.3 Uncertainty analysis

The projected changes in river runoff and TEWR had a large uncertainty due to uncertainties in the climate scenarios by GCMs. It is hard to determine which GCM is better than others. Therefore, this study applied ensemble projections using multiple climate scenarios by multiple GCMs to provide a more comprehensive and robust results. Human activities also have unavoidable impacts on water resources, more and more evidence showed that the influence of human activities on water resources is significantly enhanced (Jiang and Wang, 2016;Yuan et al., 2016;Liu et al., 2017b;Zhai and Tao, 2017). Human activities such as land use/cover changes and the increase in water withdrawal will affect river runoff in the future, which is not taken into account in this study. Although increase in river runoff was projected by most climate scenarios, the river runoff may experience a decrease with the influence of human activities such as water withdrawal for life, industry and agriculture. Therefore, the impacts of human activities should be elaborated in further studies.

5 Conclusions

The validated VIC model was applied to simulate future hydrological processes driven by climate scenarios by four GCMs. There were large uncertainties in the climate scenarios by different GCMs. In general, annual mean temperature increased more in the northern China than the southern China. On the contrary, annual precipitation increased more in the southern China than the northern China. The projected changes in river runoff and TEWR were consistent with the projected changes in precipitation, which was different for different GCMs under 1.5℃ and 2.0℃ warming scenarios. Annual river runoff was projected to increase in most areas in China using climate scenarios by most of the four GCMs. The SD of river runoff was projected to increase notably in areas where annual river runoff increased notably, leading to more extreme risks. The variations of river runoff would enlarge under 2.0℃ warming scenario compared with 1.5℃ warming scenario. Furthermore, the high river runoff increased much more than the low river runoff especially in the Huai River basin, and the risks of extreme high river runoff and low river runoff would be enlarged under 2.0℃ warming scenario in comparison with 1.5℃ warming scenario. Annual TEWR was projected to change less than annual river runoff. And the variations of TEWR were more stable than those of river runoff. Multi-ensemble simulation results showed that precipitation change was the dominant factors for changes in river runoff and TEWR. Maximum temperature had a negative correlation with river runoff in most areas across China because it would increase evapotranspiration.

Our findings highlight climate change mitigation and adaptation should be taken to reduce the risks of hydrological extreme events. On one hand, mitigation climate change is of great significance, because the risks of hydrological extremes are higher under 2.0℃ than 1.5℃ warming scenario from both the increasing area and the increasing intensity. Energy-saving and emission-reduction through science and technology are helpful to reduce the concentration of greenhouse gases. On the other hand, climate change will likely continue, with increased occurrence of extreme events, particularly for the Northwest River basins, the source regions of the Yellow River basin and Yangtze River basin and Huai River basin. It is essential for government to take proper methods to cope with the risks and mitigate damages. The increasing trend in high river runoff will have major impacts on flood control systems. Operation dams and reservoirs and regional water transferring are effective ways to allocate water resources rationally both in time scale and regional scale. Although our results showed river runoff would increase in most areas across China, the total amount of population and water withdrawal would increase at the same time. Therefore, it is important to develop water-saving technology for modernized agriculture, industry and life, and increase the effective proportion of utilization of water.

Data availability

All the data is available upon request. Please contact Fulu Tao at taofl@igsnrr.ac.cn.

Acknowledgement

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Table 1. The ensemble members in each GCM used in this study.

GCM	Ensemble member		
	2006-2015	2106-2115 (+1.5℃)	2106-2115 (+2℃)
ECHAM6-3-LR	20	20	20
MIROC5	10	10	10
NorESM1-HAPPI	20	20	20
CAM4-2degree	20	20	20

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Table 2. Information on the ten catchments (hydrological stations) used for calibrated and validated parameters and the performance of the VIC model for monthly runoff simulation in each catchment.

Catchment	Basin	Area	Longitude	Latitude	Missing year	Calibration period		Validation period	
						NSE	*BIAS* (%)	*NSE*	*BIAS* (%)
Nianzishan	SHR	13567	122°53′	47°29′		0.66	-12.3	0.72	1.7
Liaoyang	LR	8082	123°12′	41°16′		0.82	-9.5	0.61	4.9
Yingluoxia	NWR	10009	100°11′	38°48′		0.88	-1.4	0.87	4.7
Xiahui	HR	5340	117°10′	40°37′		0.75	14.5	0.61	-22.7
Qinan	YR	9805	105°40′	34°54′		0.66	5.7	0.60	-5.9
Sanjiangkou	YTR	15242	111°18′	29°35′		0.84	-9.9	0.91	4.1
Xixian	HuR	10190	114°44′	32°20′		0.82	-6.2	0.83	5.7
Yangkou	SER	12669	117°55′	26°48′	1962, 1966	0.91	2.5	0.90	-3.1
Zhongaiqiao	SWR	3562	101°30′	23°21′	1964	0.78	-5.3	0.80	5.0
Changle	PR	6645	109°25′	21°50′		0.88	-3.6	0.82	7.1

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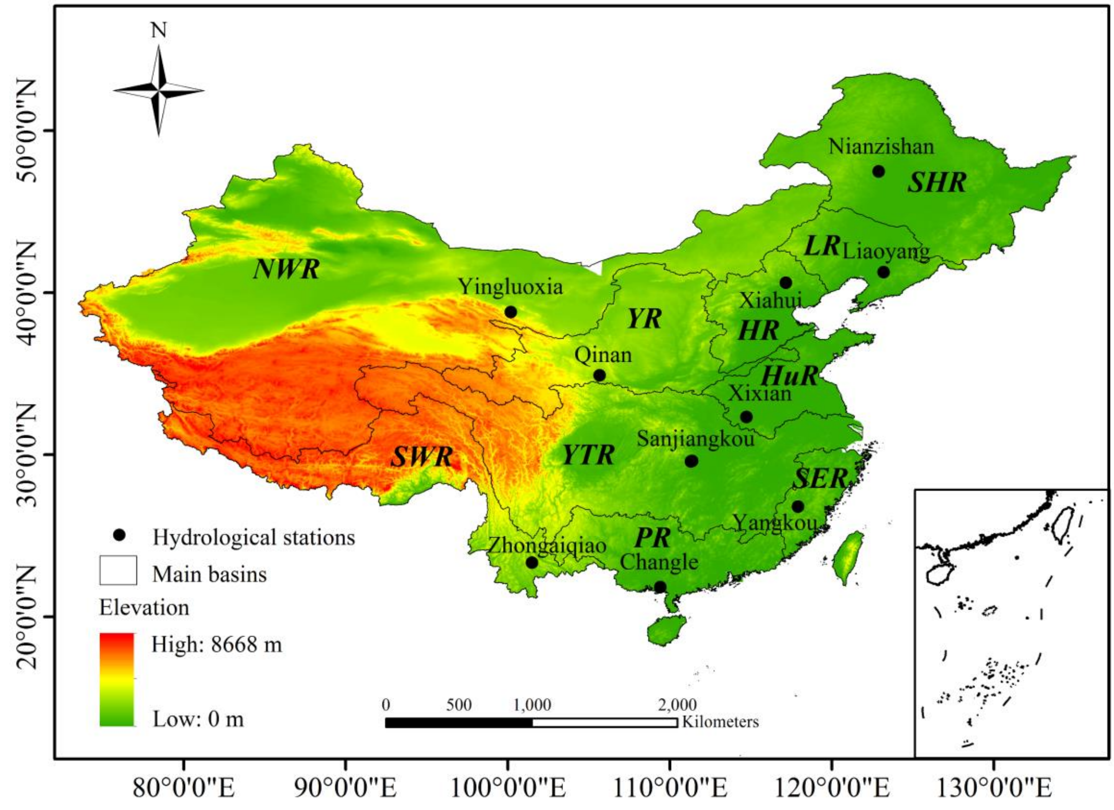

Figure 1: The ten main basins in China, as well as the ten catchments (hydrological stations) used for calibrated and validated the VIC hydrological model.

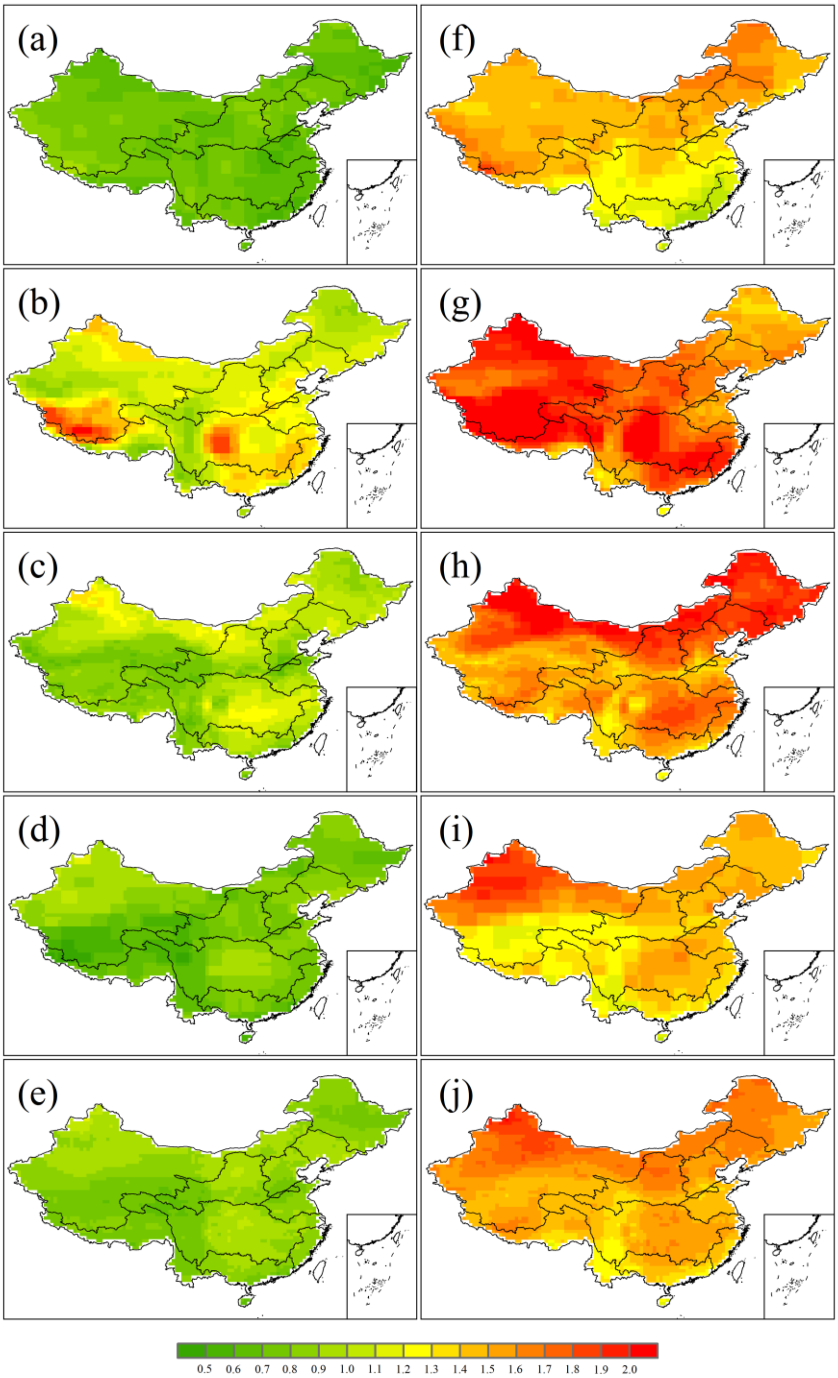

Figure 2: Median values of the projected changes in annual mean temperature (°C) under the 1.5°C warming scenario in China from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

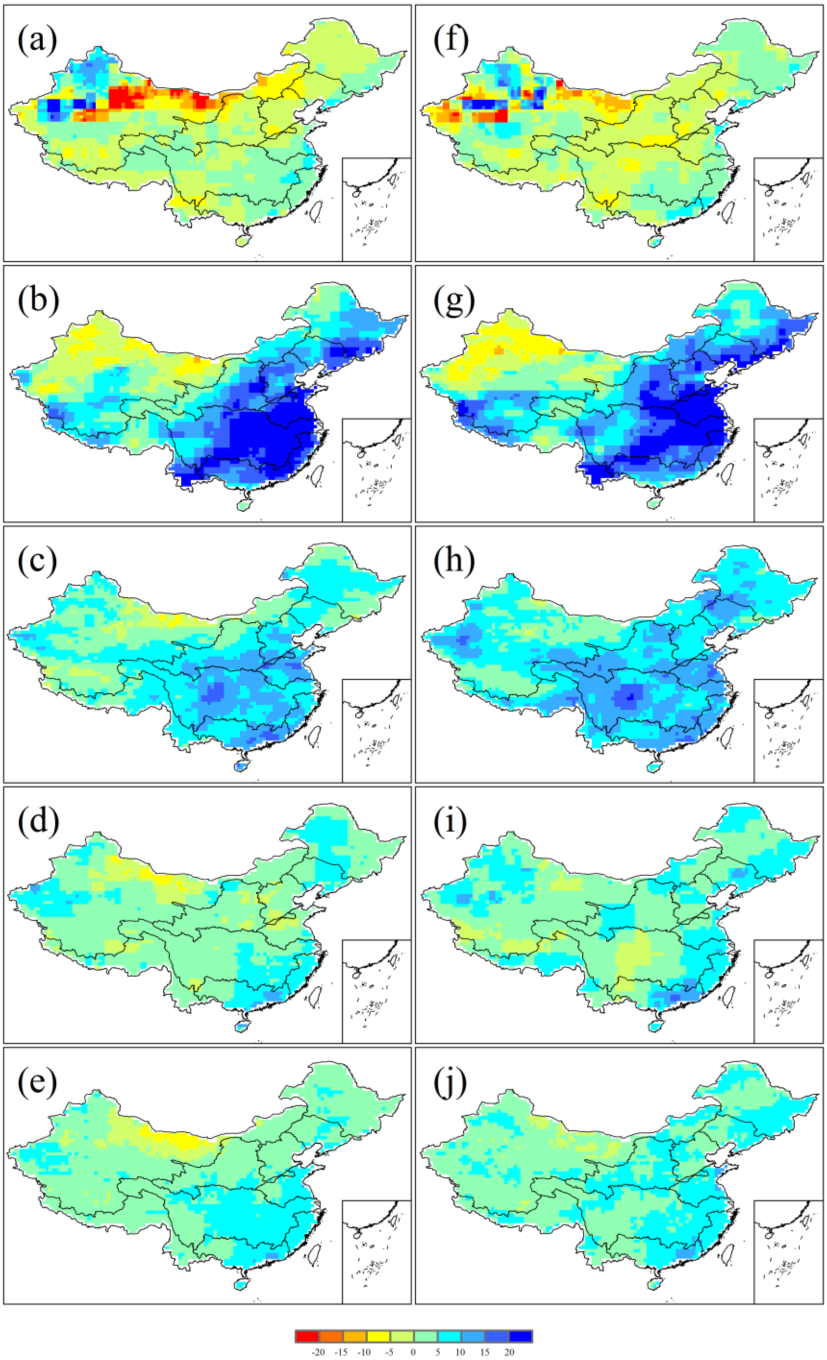

Figure 3: Median values of the projected changes in annual precipitation (%) under the 1.5°C warming scenario in China from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

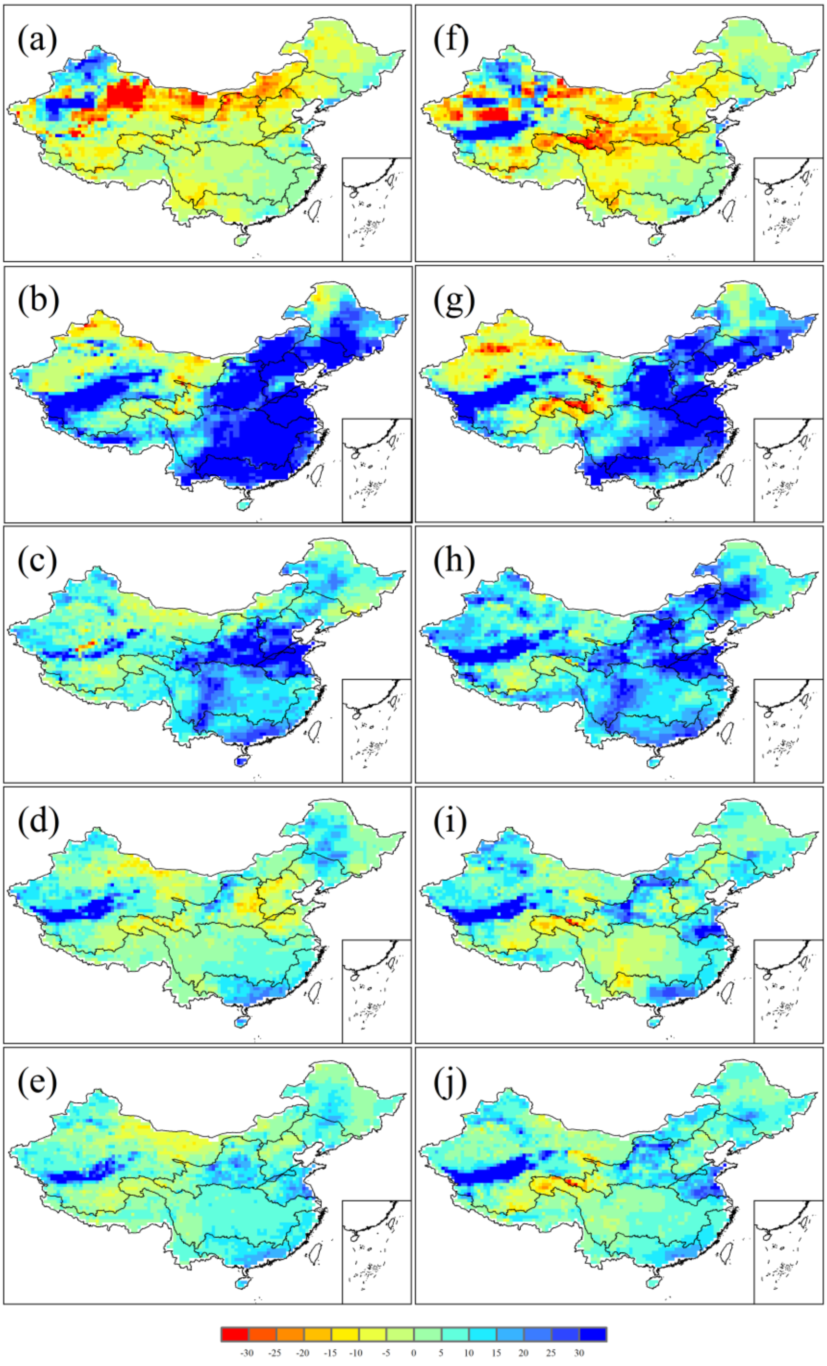

Figure 4: Median values of the projected changes in annual river runoff (%) across China under 1.5°C warming scenario from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (j), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

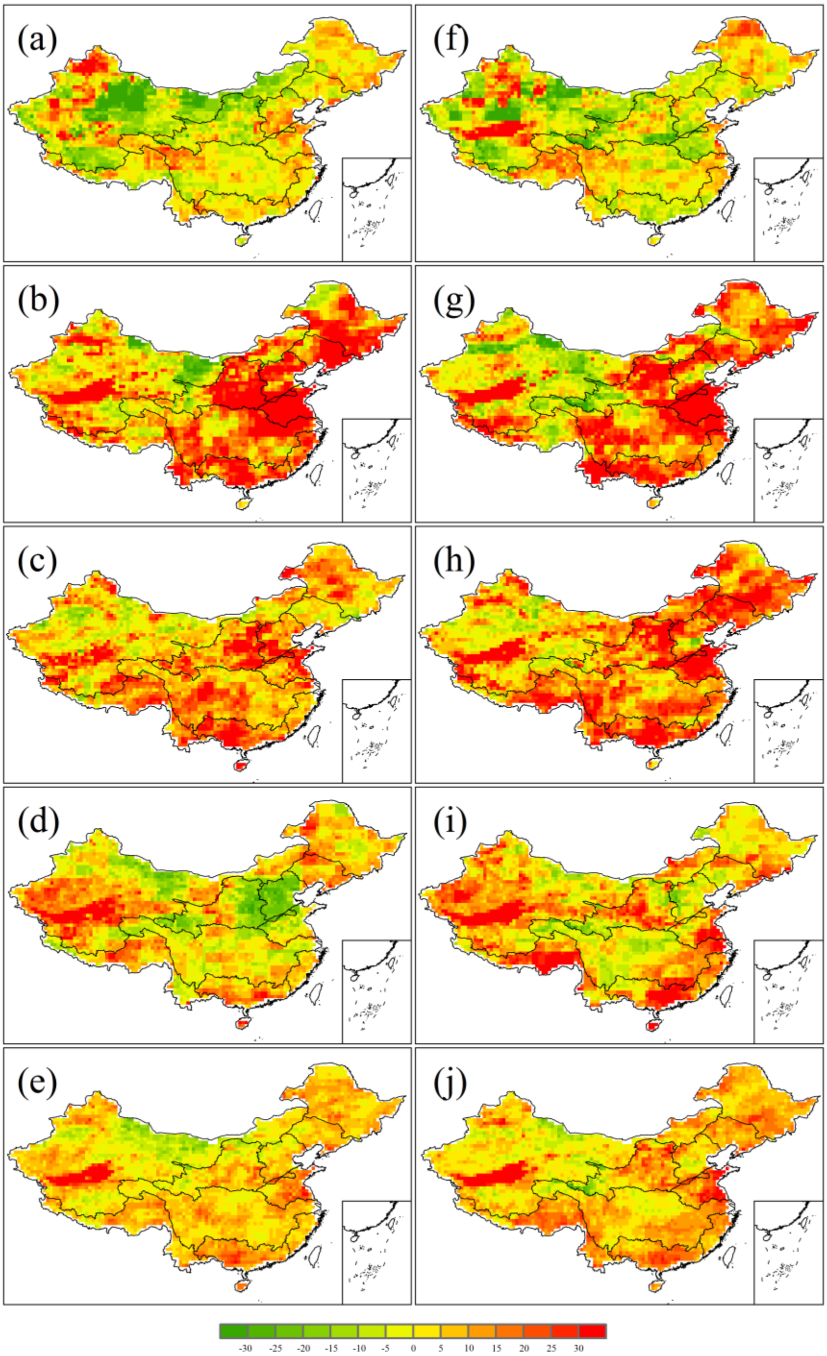

Figure 5: Median values of the changes in SD of the simulated annual river runoff (%) in China under 1.5°C warming scenario from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

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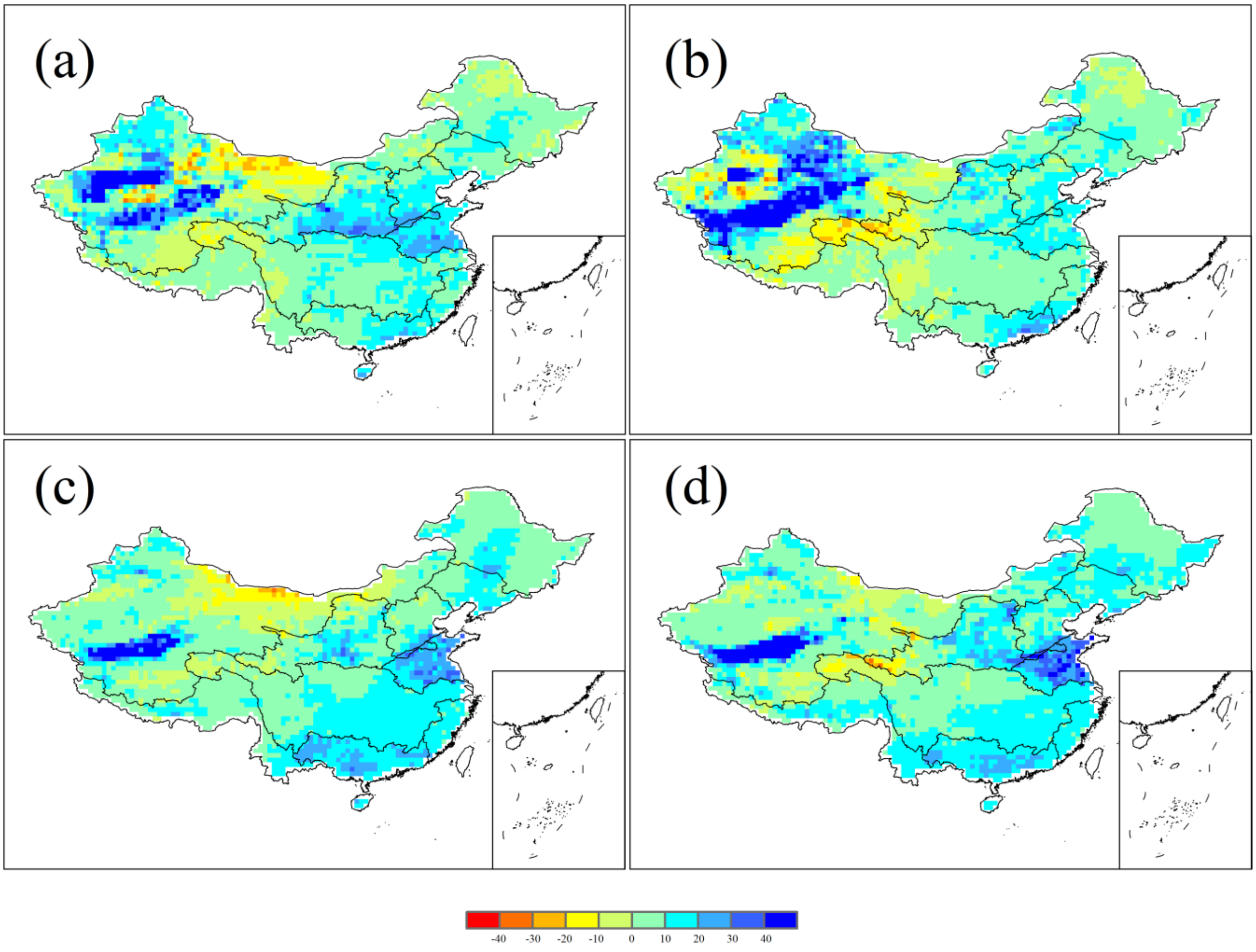

Figure 6: Changes in the low river runoff (Q_{10}) and high river runoff (Q_{90}) (%) in China under 1.5°C warming scenario in 2106-2115 (a, c) and 2.0°C warming scenario in 2106-2115 (b, d), respectively.

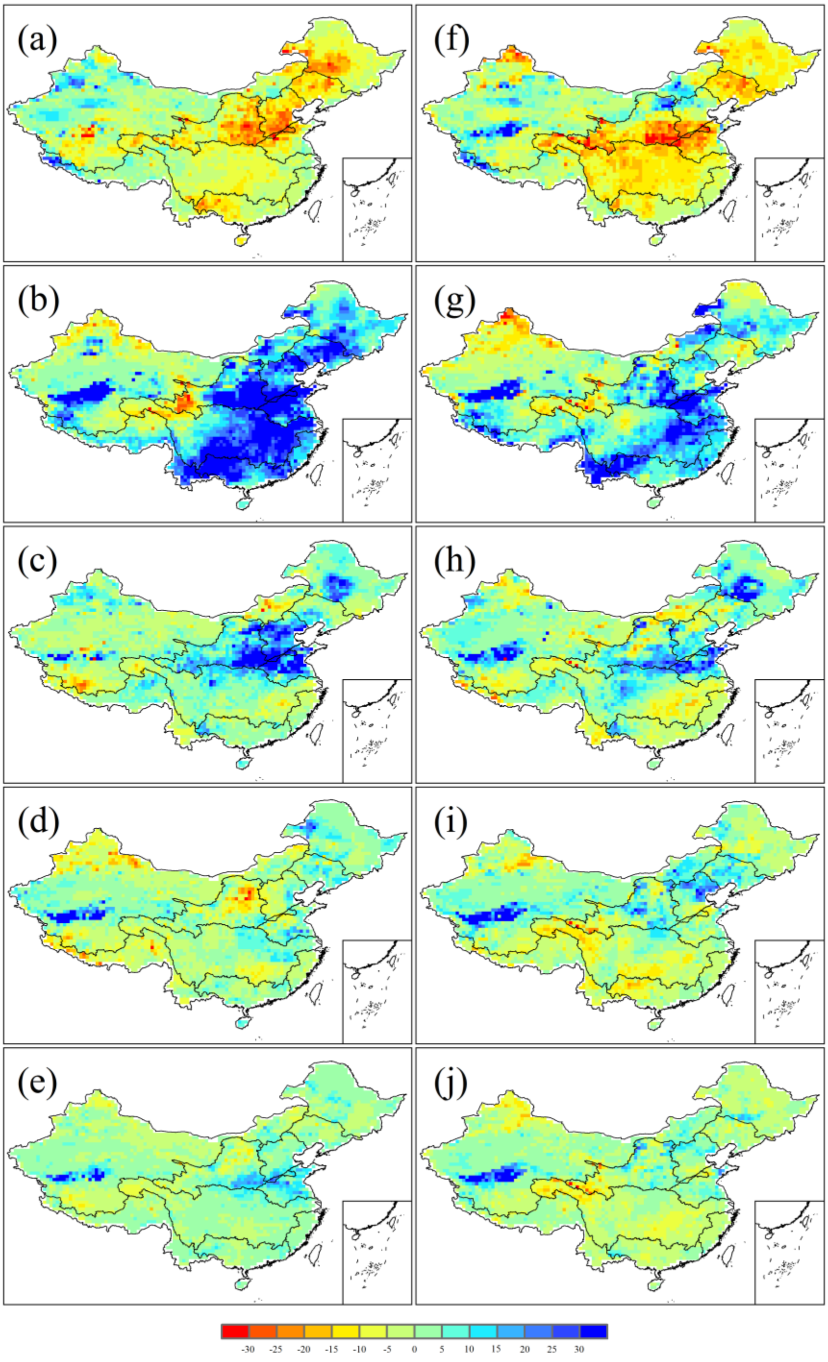

Figure 7: Median values of the changes in annual TEWR (%) in China under 1.5°C warming scenario from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

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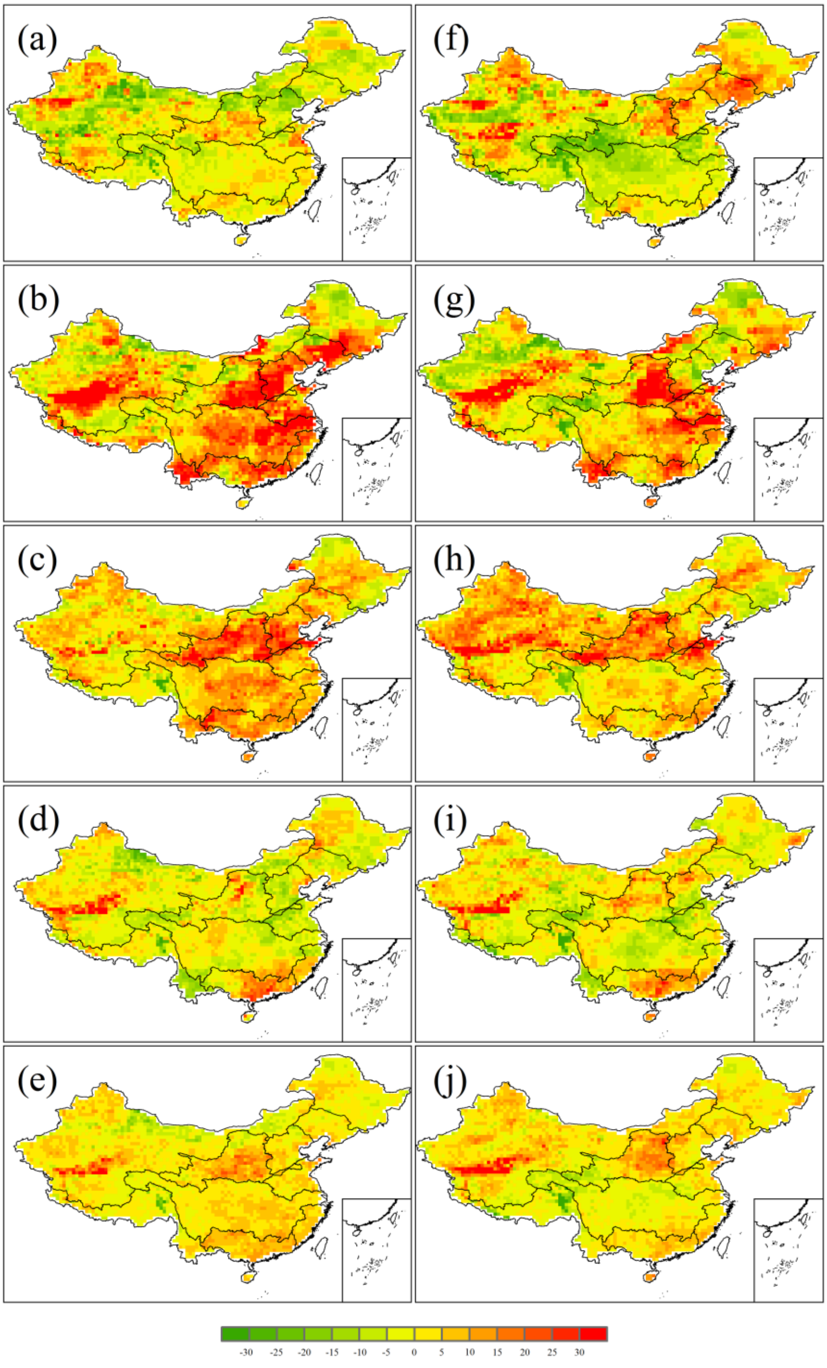

Figure 8: Median values of the changes in SD of TEWR (%) in China under 1.5°C warming scenario from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e), and under 2.0°C warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

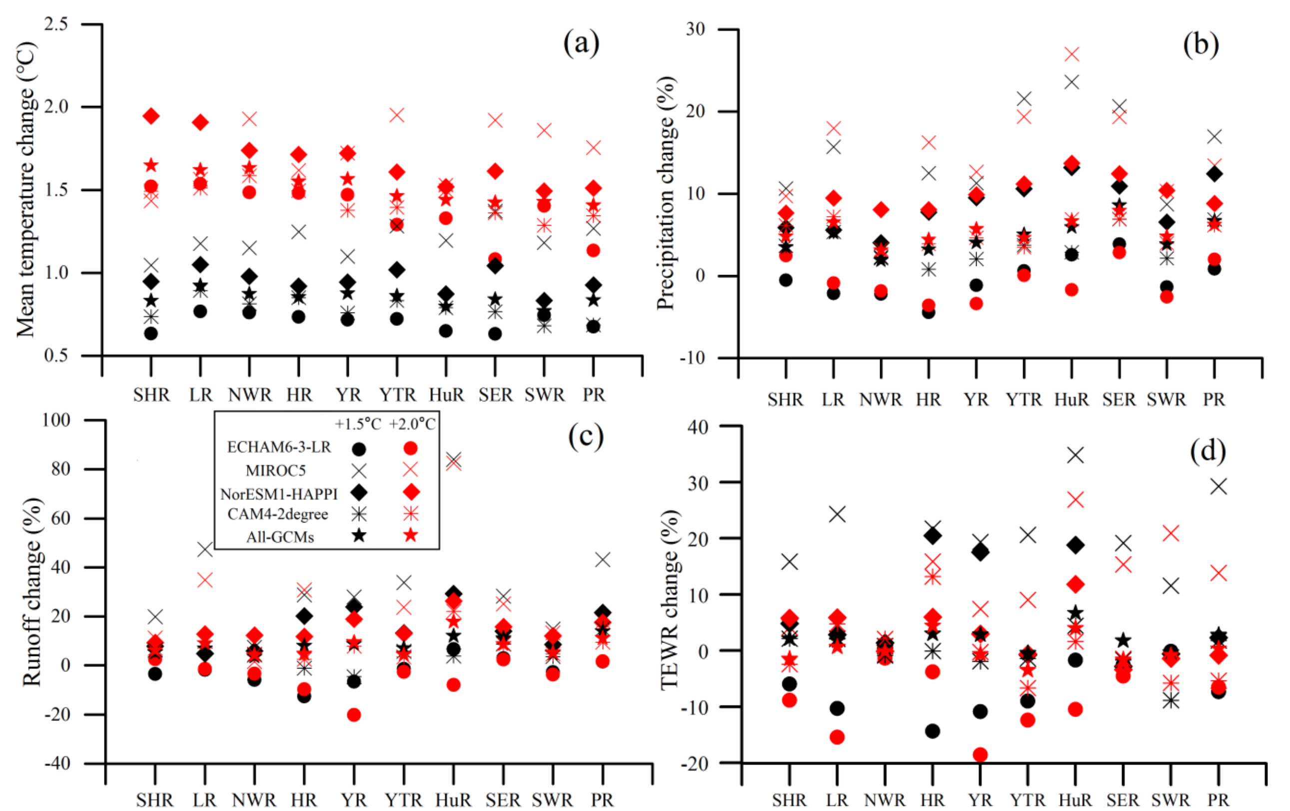

Figure 9: The median values of changes in annual mean temperature (℃), annual precipitation (%), annual river runoff (%) and annual TEWR (%) in all corresponding ensembles in the four GCMs over 2106-2115 under 1.5℃ and 2.0℃ warming scenarios relative to baseline period from 2006 to 2015, respectively, in the ten main basins across China.

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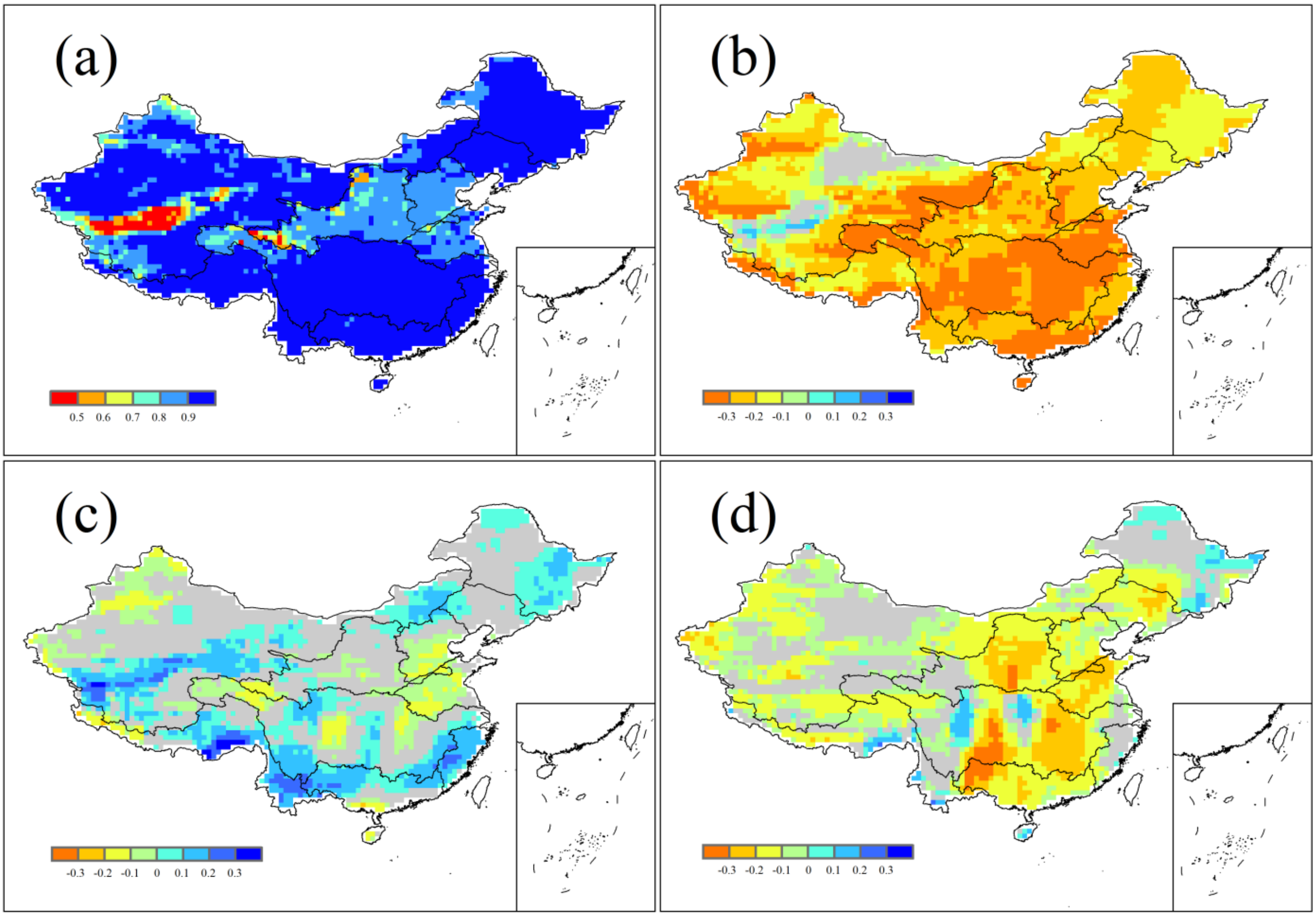

Figure 10: Spatial patterns of the Pearson Correlation Coefficient (*r*) between data series of river runoff changes and four key impact factors changes (a: river runoff and precipitation, b: river runoff and annual maximum temperature, c: river runoff and annual minimum temperature, d: river runoff and wind speed), only grids with significant correlation were shown (p<0.05).

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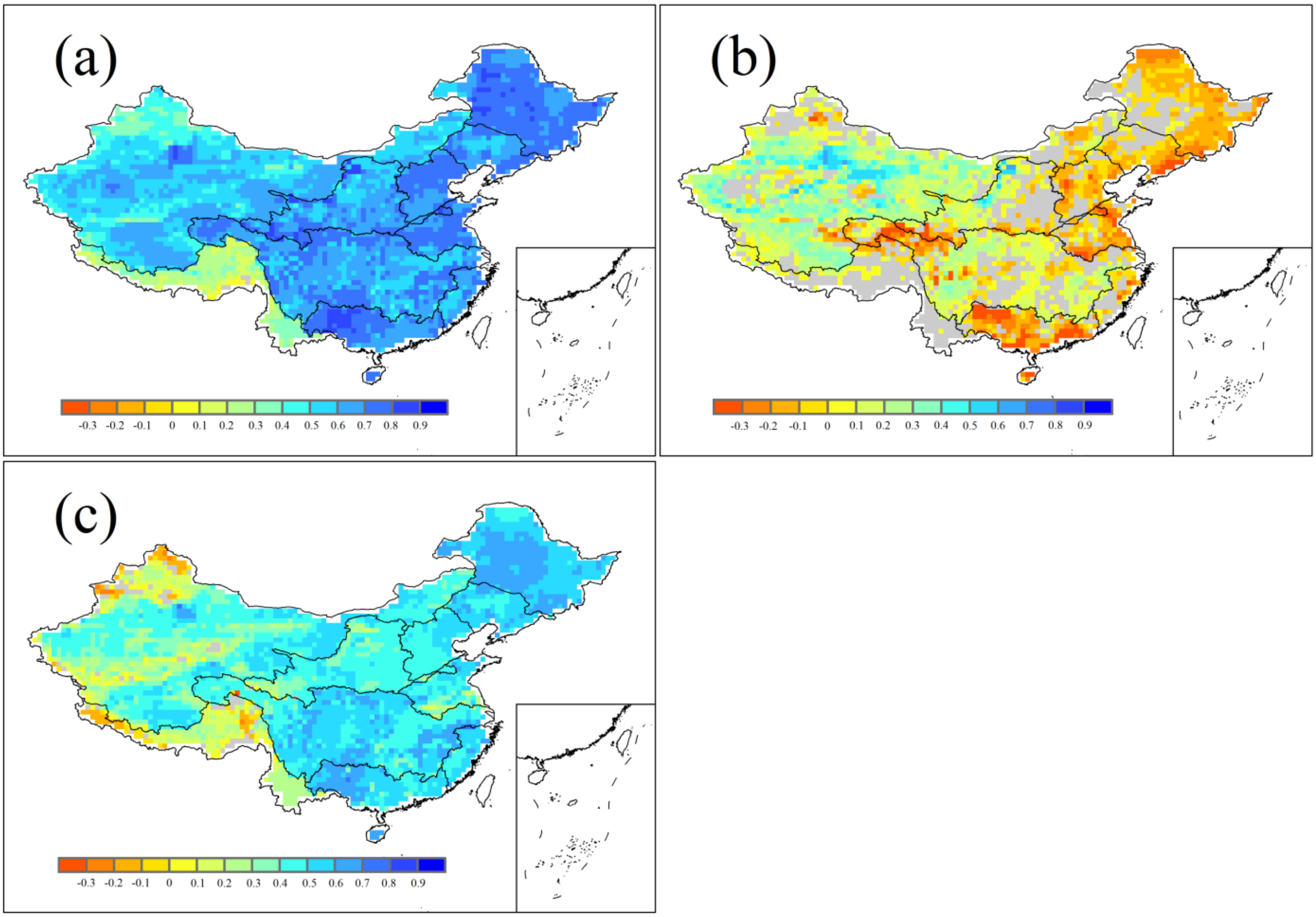

Figure 11: Spatial patterns of the Pearson Correlation Coefficient (*r*) between data series of TEWR changes and three key impact factors changes (a: TEWR and precipitation; b: TEWR and evapotranspiration; c: TEWR and river runoff), only grids with significant correlation were shown (p<0.05).

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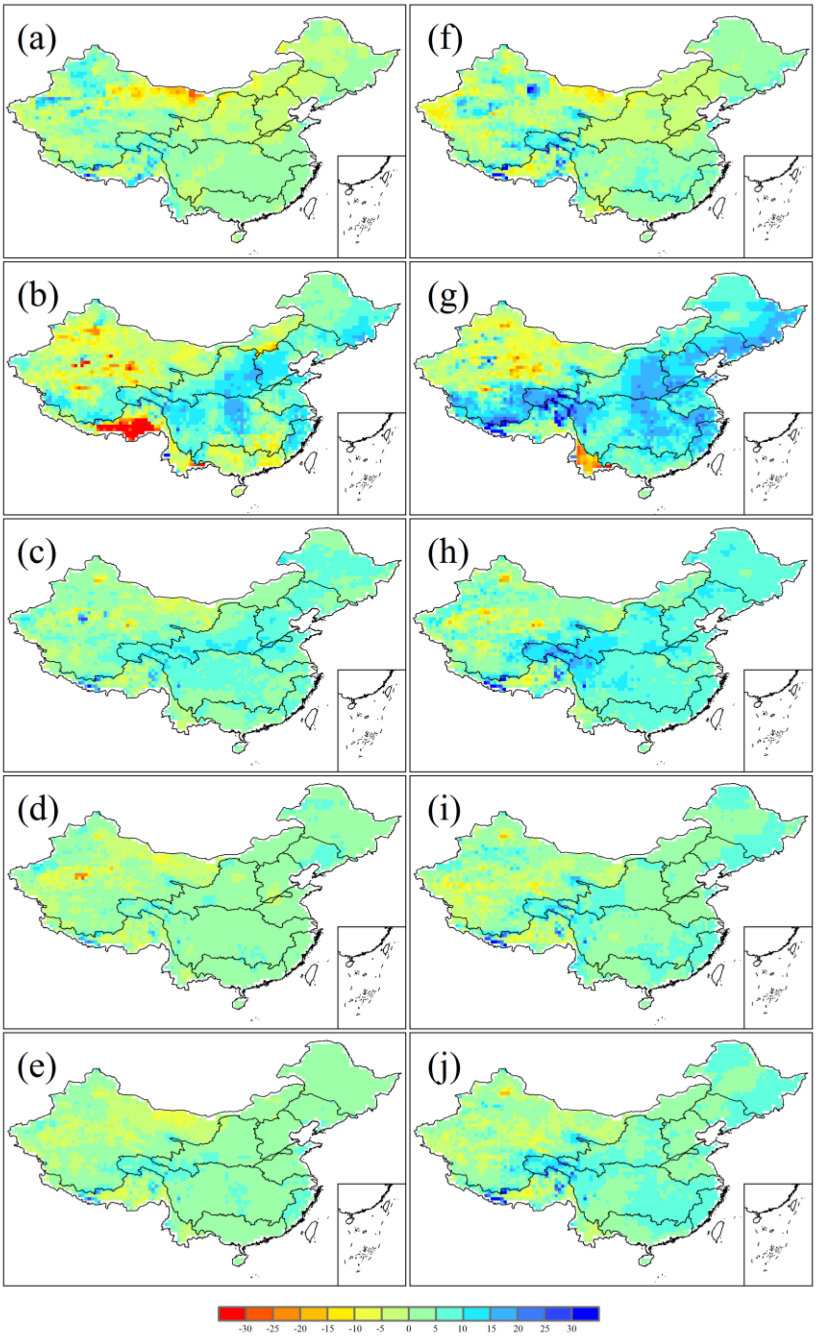

Figure A1: Median value of the changes in annual evapotranspiration (%) in China under 1.5℃ warming scenario from the ECHAM6-3-LR (a), MIROC5 (b), NorESM1-HAPPI (c), CAM4-2degree (d), all the four GCMs (e) and under 2.0℃ warming scenario from the ECHAM6-3-LR (f), MIROC5 (g), NorESM1-HAPPI (h), CAM4-2degree (i), all the four GCMs (j).

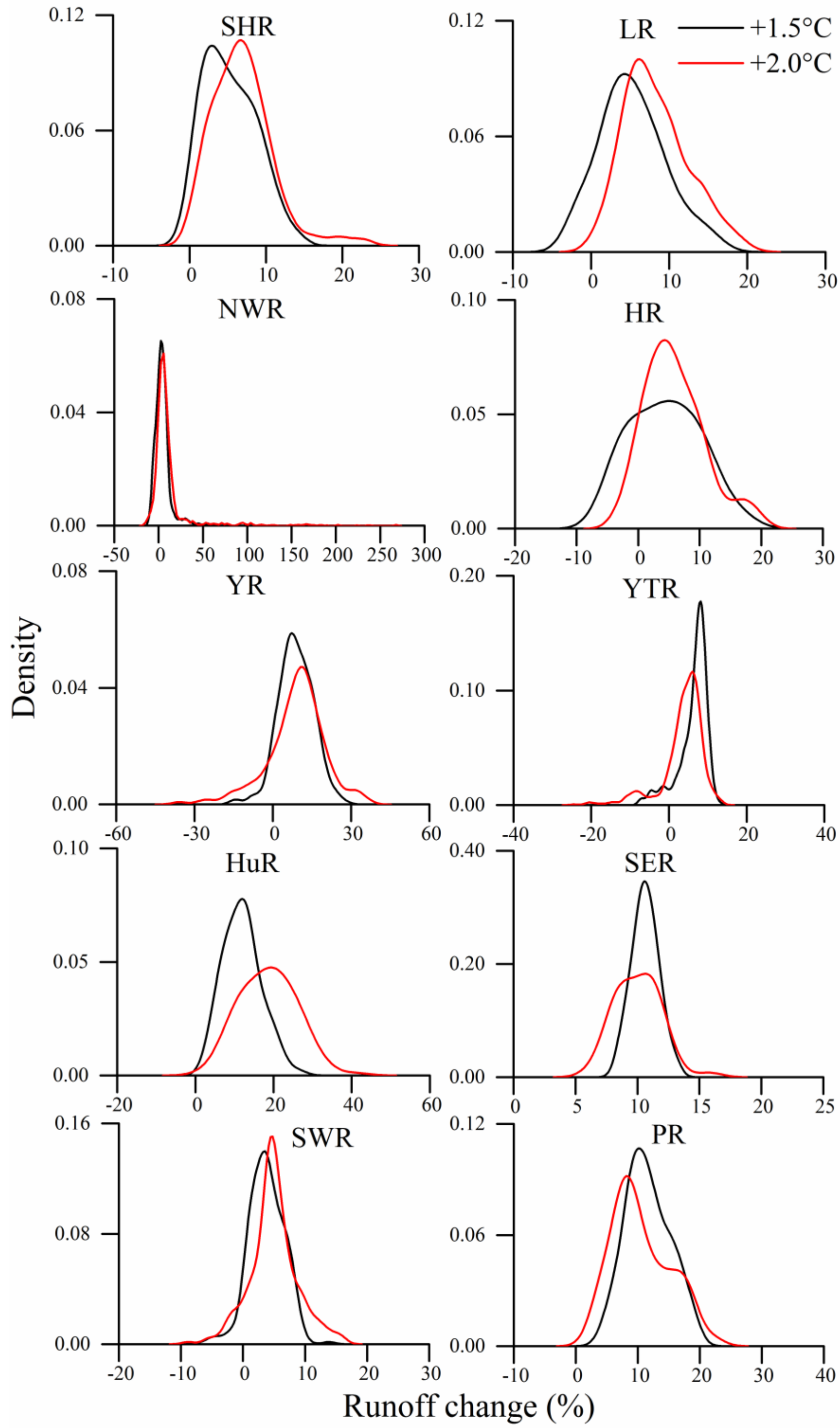

Figure A2: Probability density functions of river runoff change (%) under 1.5℃ warming scenario and 2.0℃ warming scenario in every basin.

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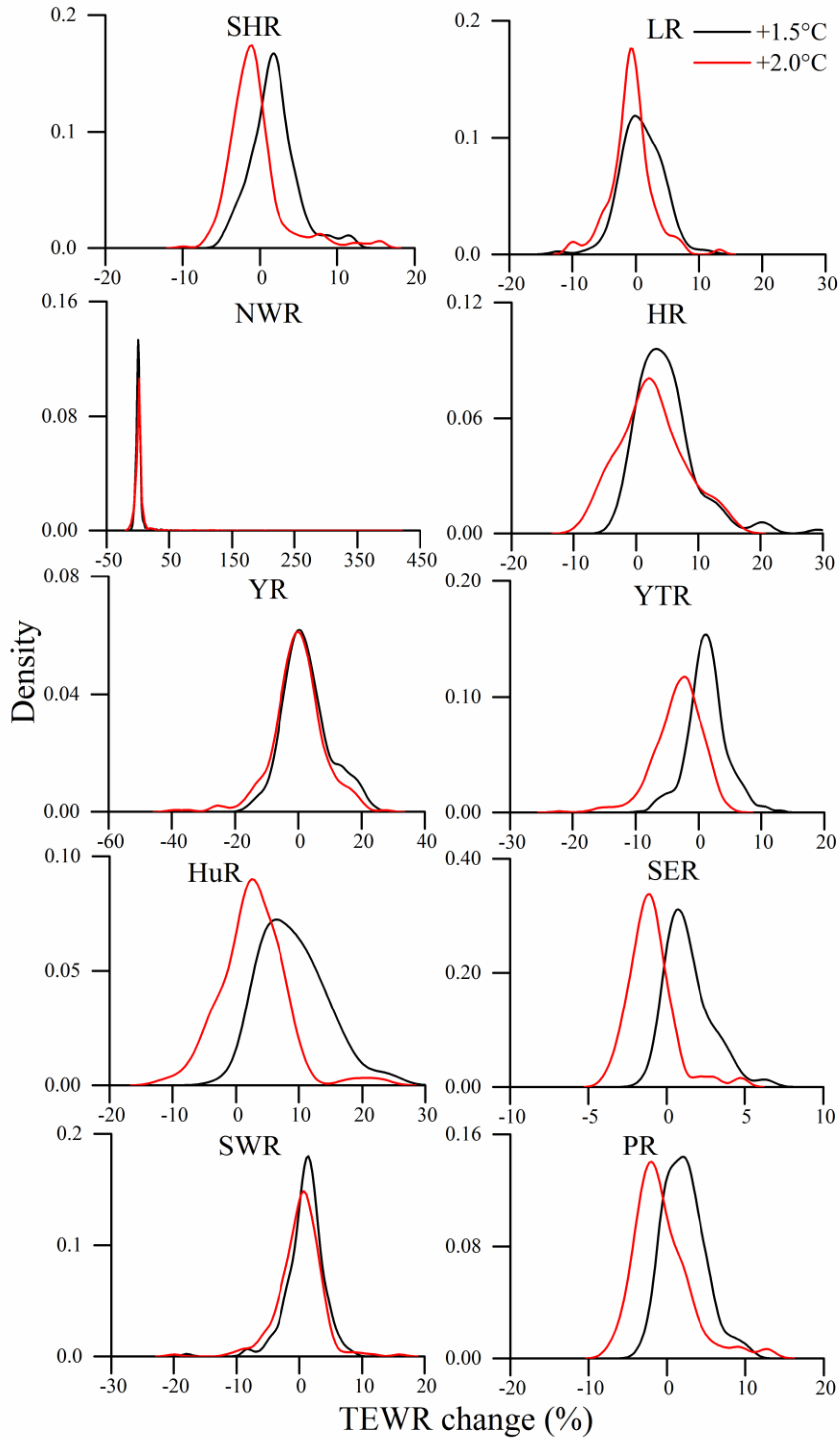

Figure A3: Probability density functions of TEWR change (%) under 1.5°C warming scenario and 2.0°C warming scenario in every basin.