Application of a distributed catchment model to investigate hydrological impacts of climate change within Poyang Lake catchment (China)

Y. L. Li, H. Tao, J. Yao and Q. Zhang

ABSTRACT

The extreme cycles of flood and drought in the Poyang Lake catchment (China) place immense pressure on the region's water users and ecosystems. This study examines potential impacts of future climate change in the Poyang Lake catchment using the popular regional climate model, COSMO-CLM, and a distributed hydrological model, WATLAC. Near-future projections (2016–2035) indicate that the mean annual precipitation and temperature are expected to increase over the catchment, with the exception of some northern regions. Relative to the baseline period (1986–2005), the monthly mean precipitation is projected to increase in spring, summer and autumn (March-October), and to decrease in winter (November-February), with the most significant changes in September (62%) and January (−39%). Projected increases in monthly mean temperatures range from 0.3 to 1.4 °C, 0.2 to 0.7 °C, and 0.2 to 1.2 °C for Representative Concentration Pathways (RCP) climate scenarios RCP2.6, 4.5 and 8.5, respectively. Winter temperatures are expected to increase significantly regardless of the climate scenarios. WATLAC simulations indicate that future climate changes will lead to increased high flows in summer and reduced low flows in winter, in terms of both frequency and magnitude, suggesting a high likelihood of an increase in frequency and severity of flooding and droughts in the Poyang Lake catchment.

Key words | climate change scenarios, hydrological model, Poyang Lake catchment, regional climate model, river discharge

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INTRODUCTION

The increasing atmospheric concentrations of greenhouse gases, especially carbon dioxide, that have led to warming of the earth's surface (Feng *et al.* 2014) and associated climate change, are predicted to modify the world's terrestrial hydrological systems, with a strong impact on freshwater resources (Intergovernmental Panel on Climate Change (IPCC) 2013). Climate change is expected to vary spatiotemporal distributions of rainfall and snowfall in many regions, including increased frequency and severity of extreme climate events (Liuzzo *et al.* 2010; Jung *et al.* 2012; IPCC 2013; Emam *et al.* 2015). Actually, there is evidence that hydrological systems have already begun to respond to global warming in recent decades (e.g., Christensen *et al.* 2007; Bates *et al.* 2008; Murphy & Ellis 2014).

The availability of catchment water resources is closely linked to variations in climate. Climate change affects catchments through the direct influence of atmosphere drivers (e.g., temperature, precipitation and wind speed) and associated changes in catchment hydrological processes (Kienzle *et al.* 2012). While several climate variables are influenced

by climate change, precipitation and temperature are the two dominant factors affecting the variations of river discharge on the catchment scale (Liu *et al.* 2011). Catchment discharge behavior may be considered as a sentinel for regional water cycles, by exhibiting a particularly robust signal that integrates climate and landscape stresses and that reflects significant changes in these (e.g., Cornelissen *et al.* 2013; Xu *et al.* 2013; Fan & Shibata 2015). However, quantifying the catchment hydrological response to climate variations is challenging, given the inherent complexity of water flow pathways within watersheds (e.g., Teutschbein & Seibert 2012; Musau *et al.* 2015; Vezzoli *et al.* 2015).

The catchment hydrological response to climate change has been studied through the application of hydrological models using atmospheric inputs from various climate models (e.g., Xu *et al.* 2005; Chen *et al.* 2012; Kienzle *et al.* 2012; Awan *et al.* 2016). From a theoretical viewpoint, a physically based catchment model represents the underlying hydrological and land surface processes in greater detail than conceptual and statistical models (Beven 2001). Spatially distributed catchment models are ideally suited to assessing the impacts of climate change on both surface and subsurface hydrological responses, given the critical interdependencies between surface water and groundwater systems (Goderniaux *et al.* 2009). For example, Graham *et al.* (2011) and Kienzle *et al.* (2012) used the distributed ACRU (Agricultural Catchments Research Unit) agro-hydrological model to simulate the impacts of climate change in the Thukela River basin (South Africa) and the Cline River catchment (Canada), respectively. Cornelissen *et al.* (2013) and Fan & Shibata (2015) employed the semi-distributed SWAT (Soil and Water Assessment Tool) model to assess the impact of climate and land-use changes on river discharge in a tropical catchment (West Africa) and the Teshio River catchment (Japan), respectively. Hydrological projections and their associated applications to river discharge remain an important topic given increased confidence in changing climatic patterns around the globe.

During the past two decades, numerous large-scale climate models have been developed for global and/or regional hydrological assessment and modeling (Li *et al.* 2015a). Many previous studies have attempted to develop methods to downscale global climate model predictions to finer resolutions that better account for important spatial variability within catchments. Such methods can be classified into four types: (1) simple interpolation of the climate model data to a finer spatial scale, (2) statistical downscaling using empirical relationship between coarse-scale model output and local climate, (3) regional climate models (RCMs), and (4) global atmospheric general circulation models with high or variable resolution (Mearns *et al.* 2001; Arnell *et al.* 2003). Among these, RCMs have become one of the most popular methods to impart higher-resolution catchment characteristics, e.g., geographical features, vegetation variability, topography, etc., in simulations of both current and future climate patterns (Li *et al.* 2015a). Thus, RCMs are widely used to generate atmospheric input to hydrology models of a wide range of catchment scales (e.g., Bergstrom *et al.* 2001; Graham *et al.* 2011; Chen *et al.* 2012).

Poyang Lake, the largest freshwater lake in China, is located in the middle reach of the Yangtze River, and has a catchment area of $1.62 \times 10^5 \, \text{km}^2$ (Shankman *et al.* 2006). The lake and its surrounding catchment are in a wet, subtropical climate zone, which has experienced more frequent and intensive floods and droughts in recent decades (e.g., Shankman *et al.* 2006; Zhang *et al.* 2011). Poyang Lake's water balance is controlled primarily by catchment inflows and discharge to/from the Yangtze River. Inflows from Poyang Lake's catchment are the primary drivers of seasonal variations in the lake's water level (Shankman *et al.* 2006; Hu *et al.* 2007).

Changes to the hydrology of the region, and the subsequent societal, economic and environmental impacts, have attracted considerable research attention (e.g., Yin & Li 2001; Zhang *et al.* 2015). Previous studies of Poyang Lake's catchment have drawn a number of consistent conclusions regarding its historical and projected future response to climate change. For example, Ye *et al.* (2013) considered coupled water and energy budgets in differentiating the relative impacts of climate change and human activities on historical variations in river discharge from the Poyang Lake catchment during 1960–2007. Their empirical analysis found the annual river discharge has been modified primarily by climate change, while human activities within the catchment play a secondary role. Guo *et al.* (2008) used the SWAT model to examine climate (1953–2002) and land-use (2000) effects on river discharge in the Xinjiang River basin of Poyang Lake, and found that climate variability is the main driver of annual river discharge trends, while land-use

change may have a moderate impact. Zhao *et al.* (2010) used statistical analysis (for 1951–2003) to arrive at similar conclusions to those reported by Guo *et al.* (2008). These previous studies indicate that the variations of river discharge in Poyang Lake catchment are strongly related to regional climate variability and change, while human activities such as land-use change also have significant impact.

Limited attempts to predict the hydrological impact of future climate change on Poyang Lake's river discharge have been made. Ye *et al.* (2011) developed a regression model based on the relationship between Poyang Lake water levels and the catchment inflows and temperature to predict lake water level changes under the future time period of 2011–2050 by adopting the global climate model ECHAM5. For the lake's catchment, their investigation mainly focused on the changes of the total inflows by using the catchment model WATLAC (Zhang & Werner 2009; Ye *et al.* 2011), which may not be adequate to provide critical insights into the discharge behavior at sub-catchment scale regarding the spatial flow variability (Guo *et al.* 2007). Sun *et al.* (2012) employed a water balance model to evaluate the future change (2061–2100) of annual river discharge in the Ganjiang River and Xinjiang River basins of Poyang Lake. Their investigation mainly focused on the upstream mountainous regions and concluded that the annual river discharge shows an uptrend due to projected increases in both precipitation and evapotranspiration. More recently, Yan *et al.* (2015) combined a raster-based Xin'anjiang model and the Coupled Model Inter-comparison Project Phase 5 (CMIP 5) multi-model ensemble to simulate future river discharge under three climate change scenarios and two land-use change conditions in the Xinjiang River basin of Poyang Lake. They found that future climate and land-use changes affect not only the seasonal distributions of river discharge, but also the annual amounts of discharge. There is an urgent need to provide water resource managers and policy makers with detailed information on the potential impacts of future climate change on river discharge across the Poyang Lake catchment.

The purpose of this study is to quantify potential impacts of future climate change, estimated from an RCM, on the hydrology of the extensive Poyang Lake catchment. Our specific objectives are to: (1) calibrate and evaluate the reliability of a coupled catchment model for the baseline period (1986–2005); (2) analyze spatiotemporal changes in projected precipitation and temperature for the near future (2016–2035) under three IPCC scenarios; and (3) investigate the hydrological responses of river discharge in the different sub-catchments of Poyang Lake under future climate scenarios. We extend on previous studies of climate change impacts on Poyang Lake catchment by using a distributed hydrological model with automatic calibration scheme and a high-resolution RCM.

STUDY AREA

Poyang Lake lies on the northern border of Jiangxi Province, China (Figure 1). The lake receives inflows predominantly from five major rivers (i.e., the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers) within its drainage catchment (Figure 1). Poyang Lake is connected to the Yangtze River through a narrow channel at its northern end (Figure 1). The Yangtze River plays a complementary role in controlling the lake's outflows (Hu *et al.* 2007; Guo *et al.* 2012). The five rivers contribute approximately 89% of the lake's inflow, while backflow (i.e., the temporal reversal of flow from the Yangtze River to the lake at the lake's outlet) contributes around 3% of the lake's inflow. The remaining 8% is made up of other sources such as minor streams, rainfall to the lake's surface, and groundwater discharge (Li *et al.* 2015b). The hydrological regime of Poyang Lake is controlled both by the catchment rivers and the Yangtze River, resulting in dramatic seasonal water level fluctuations of 8 to 22 m, and associated changes in the water surface area, which varies from less than 1,000 to over 3,000 km^2 (Feng *et al.* 2012).

The Poyang Lake catchment has a mean annual precipitation and potential evapotranspiration of 1,666 mm/yr and 1,034 mm/yr, respectively (Li *et al.* 2014). Precipitation records show distinct wet and dry seasons, with 45% of annual precipitation concentrated in the wet season from April to June, and only 16% of rainfall occurring during September to December, on average. Temperatures are also highly seasonal, with a June-August average of 27.3 °C, a December-February average of 7.1 °C, and an annual average of 17.6 °C (Zhang *et al.* 2015). A digital elevation model of the catchment, derived from the National Geomatics Center of China, shows that the topography
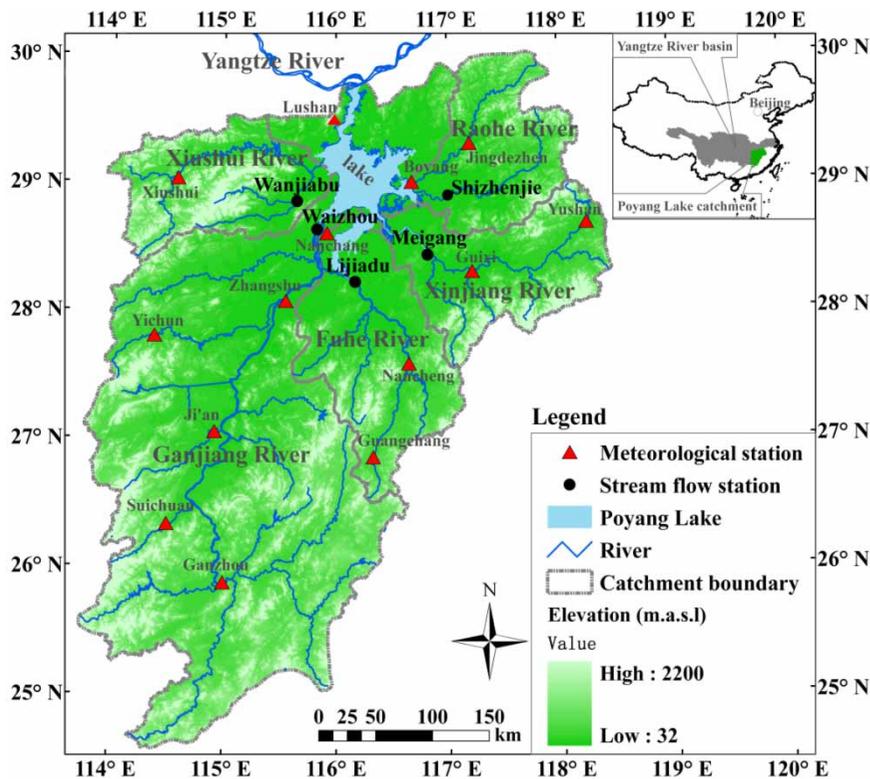
Figure 1 | Location of Poyang Lake catchment, its sub-catchments and hydrometeorological gauging stations.

varies from upstream mountainous areas at elevations of 2,100 m (above sea level) to downstream plain areas around the lake at elevations of about 32 m (Figure 1). The land-use data (for 2005), obtained from the Department of Soil Survey of Jiangxi Province, can be categorized into forest (61%), farmland (28%), water bodies (5%), pasture (4%) and urbanization (2%) (Li *et al.* 2014). The soils in the whole catchment are classified according to the Genetic Soil Classification of China (Shi *et al.* 2004), and have the following catchment-aggregated proportions: red soil (43%), latosol (23%), paddy soil (21%), yellow soil (7%), alluvial soil (3%) and others (3%) (Ye *et al.* 2011).

MATERIALS AND METHODS

Data availability

Measured daily precipitation and temperature from 14 weather stations inside Poyang Lake catchment (Figure 1),

all of which are standard national weather stations, were obtained from the National Climate Center of China Meteorological Administration. Observations of daily river discharge at the most downstream gauging stations of the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers (Figure 1) were used to represent runoff from the five sub-catchments of Poyang Lake. These data were obtained from the Hydrological Bureau of Jiangxi Province and the Hydrological Bureau of the Yangtze River Water Resources Commission of the Ministry of Water Resources of China. Hydro-climatic data are available at daily time steps for the period 1986–2005. The basic features of hydro-climatic records are listed in Table 1.

Climate change scenarios and bias correction

The commonly used scenarios, called Representative Concentration Pathways (RCP), are designed to accommodate a wide range of possibilities in social and economic development consistent with specific radiative forcing paths (Kharin *et al.* 2013). We consider future climate

Table 1 | Main characteristics of the hydro-climatic records (1986–2005) of gauging stations in Poyang Lake catchment

Sub-catchment	Gauging station	Drainage area (km^2)	Mean annual discharge (10^9 m^3/yr)	Specific discharge (mm/yr)	Mean annual precipitation (mm/yr)
Ganjiang River	Waizhou	80,948	70	861	1,673
Fuhe River	Lijiadu	15,811	12	774	1,865
Xinjiang River	Meigang	15,535	19	1,233	2,001
Raohe River	Shizhenjie	8,400	10	1,212	1,838
Xiushui River	Wanjiabu	3,548	4	1,097	1,737

conditions predicted for the scenarios RCP2.6 (low emission), RCP4.5 (intermediate emission) and RCP8.5 (moderately high emission), in terms of precipitation and temperature outputs from the RCM COSMO-CLM (Steppeler *et al.* 2003). COSMO-CLM, developed by the Potsdam Institute for Climate Impact Research, has been successfully validated for the East Asian monsoon region (Fischer *et al.* 2013; Wang *et al.* 2013). COSMO-CLM uses a grid with a resolution of 0.5° over the East Asian domain. Details of COSMO-CLM are described in the above references and are omitted here for brevity.

When using the precipitation and temperature outputs of RCMs, it is necessary to implement a bias correction. Bias in RCM simulation results can arise from shortcomings of the RCMs themselves, but also from erroneous forcing data (Schoetter *et al.* 2012; Teutschbein & Seibert 2012). The simulations and projections of COSMO-CLM are decomposed for the baseline period 1986–2005, which is used to evaluate and bias-correct the model. The corrections are then applied to the emission scenarios (RCP2.6, 4.5 and 8.5) for the projection period 2016–2035 (Rockel *et al.* 2008; Huang *et al.* 2015).

In this study, the systematic biases in the climate variables are corrected for the COSMO-CLM projections by using the equidistant cumulative distribution function (EDCDF) matching method proposed by Li *et al.* (2010). The EDCDF method is based on transfer functions that are generated to map the distribution of the simulated historical data to that of the observations. For a given percentile, this method assumes that the differences between the modeled and observed values of the baseline period also apply to the projected future period, which means that the adjustment function remains the same. The method can be used to produce auxiliary ensemble

scenarios for various climate impact-oriented applications. Details of the mathematics and the associated parameters are described by Li *et al.* (2010) and Huang *et al.* (2015).

Catchment hydrological model

The catchment model WATLAC (Zhang & Li 2009; Zhang & Werner 2009) is a spatially distributed hydrological model that was developed for large-scale, physically based, continuous rainfall-runoff simulation. The model includes such processes as canopy interception, overland flow, stream flow routing, soil lateral flow, evapotranspiration, groundwater recharge and groundwater flow. Precipitation and potential evapotranspiration are the main driving forces for WATLAC. The model represents landscape and stream flow hydrology at a daily time step. WATLAC has already been successfully applied to a number of case studies, including the Fuxianhu Lake catchment (Zhang & Werner 2009), the Xitiaoxi catchment of Taihu Lake (Zhang & Li 2009), and the Poyang Lake catchment (Ye *et al.* 2011; Li *et al.* 2014). WATLAC is described in detail in the above references, and therefore only a brief description is given here.

The WATLAC model used in the present study is the same as the model used in a previous Poyang Lake catchment investigation by Li *et al.* (2014). Li *et al.* (2014) improved the Poyang Lake catchment model of Ye *et al.* (2011) by adopting a finer 1 km × 1 km grid and an automatic calibration software, PEST (Parameter ESTimation) (Doherty 2005), to better capture the heterogeneity of the land surface and reduce the calibration error. They used PEST to modify key model parameters: overland runoff (α), soil infiltration coefficient (β_1), groundwater recharge coefficient (β_2), flood travel time (k) in the Muskingum flood routing

method, and specified yield (S_y) of the shallow unconfined aquifer. Li *et al.* (2014) calibrated and validated the Poyang Lake catchment model for the time sequence of 2000–2008, and produced a satisfactory accuracy for the river discharges at the Waizhou, Xiajiang, Lijiadu, Meigang, Shizhenjie and Wanjiabu gauging stations. These results demonstrated that the model was able to simulate the catchment's rainfall-runoff behavior.

A temperature-based approach (i.e., Hamon 1961) was employed to convert RCM output to potential evapotranspiration for input to WATLAC, rather than pan evaporation (as used by Li *et al.* (2014)). This allowed for analyses of the influence of temperature changes on catchment hydrology, pertaining to past and future time periods. Other WATLAC model aspects are essentially the same as the approach of Li *et al.* (2014), and are described in detail therein. The effects of climate change on river discharge are often assessed by calibrating and validating hydrological models for current climate conditions, and hence the differences between the past and future climate change scenarios of model simulations are quantified. In the current study, the previous WATLAC model was recalibrated using time series of precipitation and temperature derived from 14 national meteorological stations (Figure 1). These data cover the baseline period for both the model calibration (1986–1995) and validation (1996–2005). The river discharge at Waizhou, Lijiadu, Meigang, Shizhenjie and Wanjiabu gauging stations (Figure 1), representing the Ganjiang, Fuhe, Xinjiang, Raohe and Xiushui Rivers, respectively, provided the observation dataset for WATLAC model calibration and validation. Calibration involved modifying the five parameters (i.e., α, β_1, β_2, k and S_y) within expected ranges using PEST until a reasonable match to river discharge was obtained.

Evaluation criteria of model performance

The bias correction of COSMO-CLM and the calibration of WATLAC were evaluated by comparing simulation results to measurements of precipitation, temperature and river discharge during 1986–2005. Commonly used statistics, including Nash-Sutcliffe efficiency coefficient (E_{ns}), determination coefficient (R^2), relative error (R_e) and Pearson correlation coefficient (r) were adopted to evaluate the

model-observation match. The formulations are given below:

$$E_{ns} = 1 - \frac{\sum_{t=1}^{n} (x_{obs} - x_{sim})^2}{\sum_{t=1}^{n} (x_{obs} - \overline{x}_{obs})^2} \tag{1}$$

$$R^2 = \frac{\left[\sum_{t=1}^{n} (x_{obs} - \overline{x}_{obs})(x_{sim} - \overline{x}_{sim})\right]^2}{\left[\sum_{t=1}^{n} (x_{obs} - \overline{x}_{obs})^2 \sum_{t=1}^{n} (x_{sim} - \overline{x}_{sim})^2\right]} \tag{2}$$

$$R_e = \frac{\sum_{t=1}^{n} (x_{sim} - x_{obs})}{\sum_{t=1}^{n} x_{obs}} \times 100\% \tag{3}$$

$$r = \frac{\sum_{t=1}^{n} (x_{obs} - \overline{x}_{obs})(x_{sim} - \overline{x}_{sim})}{\sqrt{\sum_{t=1}^{n} (x_{obs} - \overline{x}_{obs})^2 \sum_{t=1}^{n} (x_{sim} - \overline{x}_{sim})^2}} \tag{4}$$

where x_{obs} is the observed climate variables or river discharge, x_{sim} is the predicted climate variables or river discharge, $\overline{x}_{obs}$ and $\overline{x}_{sim}$ represent the average values of observed and predicted climate variables or river discharge, respectively, t denotes the current time step, and n is the total number of time steps. The ideal value for E_{ns}, R^2 and r is 1, and the ideal value for R_e is 0.

RESULTS

Evaluation of bias correction

The outcomes of bias correction, given in Figure 2, show that prior to correction, the probability density of the COSMO-CLM simulated precipitation shows fewer occurrences of low and high precipitation but more occurrences of moderate precipitation than those observed. Both the COSMO-CLM simulated temperature and the observations show two peaks, of which the first represents the cold season and the second the warm season. The distribution pattern of the biases in the Poyang Lake catchment as derived from COSMO-CLM and from observations is consistent with a previous study by Huang *et al.* (2015), who found a similar pattern in the Tarim River basin of Northwest China. Generally, COSMO-CLM and observations show similar patterns with substantially differing densities
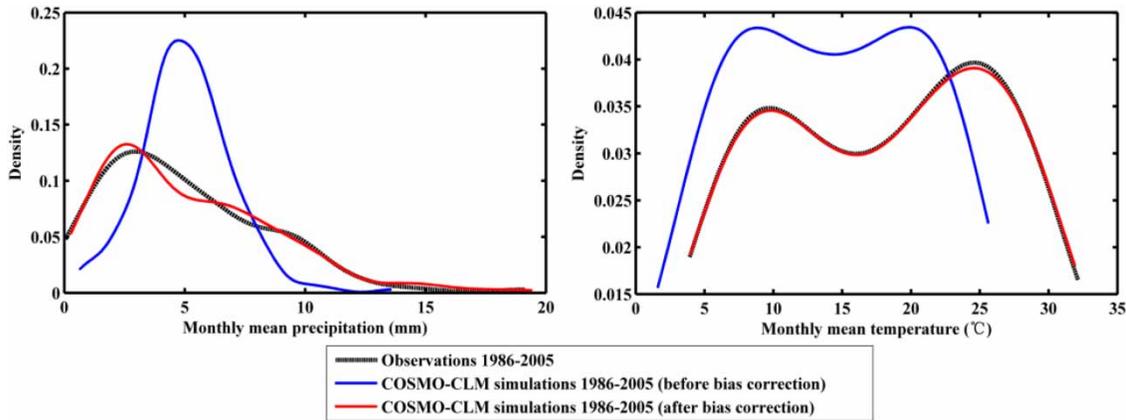
Figure 2 | Probability density functions of climate observations and COSMO-CLM outputs before and after bias correction for Poyang Lake catchment (averaged over the 14 weather gauging stations across the baseline period 1986–2005) for monthly average precipitation and temperature.

for both precipitation and temperature under 1986–2005 climate conditions. The outputs of COSMO-CLM, bias-corrected using EDCDF, are considerably better matched to monthly averages of precipitation and temperature measurements (Figure 2). Statistical performance measures quantify the improvements in the precipitation and temperature predictions following bias correction (Table 2). After the bias correction, the values of E_{ns} improve to 0.97, the R_e values are relatively low (<2.2%), and the r values show significant improvements (i.e., 99% confidence level), indicating a very effective method and greatly reduced RCM biases.

Calibration and validation for catchment hydrological model

The initial parameter values and parameter bounds were specified according to those adopted by Li *et al.* (2014),

who used literature values. The optimized WATLAC parameters are listed in Table 3. These optimized values are close to previous calibration results obtained by Li *et al.* (2014), indicating consistency in the approach and reliability of catchment runoff predictions.

The results of WATLAC calibration and validation are given as scatter plots and statistical measures in Figure 3 and Table 4, respectively. For all five gauging stations, scatter plots demonstrate that the WATLAC model is reasonably consistent in describing the catchment's rainfall-runoff behavior, although peak values proved somewhat difficult to accurately reproduce, as illustrated in Figure 3. The statistical results indicate a mostly better WATLAC model performance under calibration conditions relative to validation conditions (Table 4), as expected. Nonetheless, the model's ability to reproduce field observations during both calibration and validation time sequences suggests a reasonable model-measurement match.

Table 2 | Quantitative assessment of COSMO-CLM-simulated to observed monthly precipitation and temperature before and after the bias correction in the Poyang Lake catchment during 1986–2005

	Before bias correction			After bias correction		
Climate variables	E_{ns}	r	R_e (%)	E_{ns}	r	R_e (%)
Precipitation (mm)	0.46	0.71*	21.2	0.97	0.97**	2.2
Temperature (°C)	0.62	0.88*	−11.3	0.97	0.99**	0.1

**Significant at the 99% confidence level.
*Significant at the 95% confidence level.

Table 3 | Parameter constraints and calibration results for the WATLAC catchment model

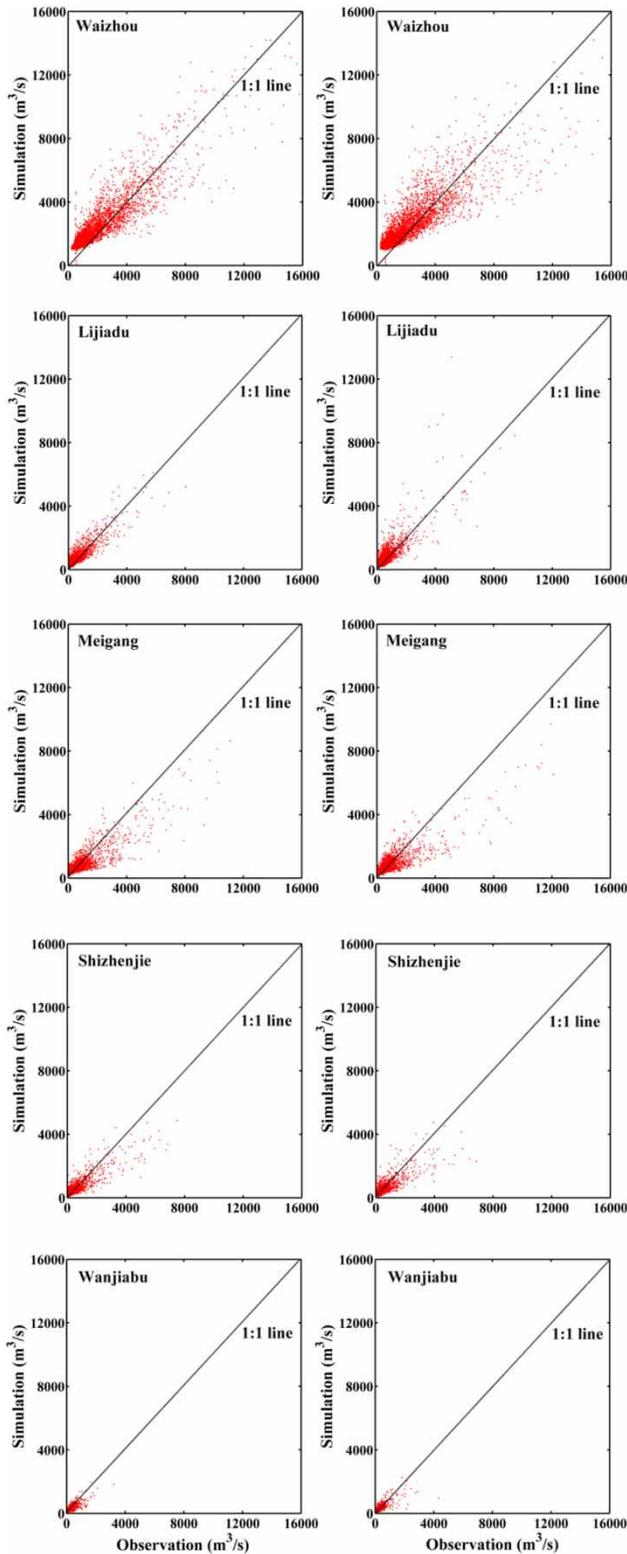| Parameter	Initial value	Lower bound	Upper bound	Optimal value
α (−)	0.997	0.01	2.0	0.913
β_1 (−)	0.162	0.01	2.0	0.233
β_2 (−)	0.035	0.01	2.0	0.044
k (days)	4.80	0.01	5.0	4.90
S_y (−)	0.054	0.001	0.3	0.138

Figure 3 | Scatter plots of WATLAC-simulated daily discharge against the observed daily discharge for the calibration period (left graphs) and validation period (right graphs) at five river gauging stations.

Future changes in precipitation and temperature

Figure 4 shows the percent change in average annual precipitation and average annual temperature, under RCP2.6, 4.5 and 8.5 scenarios, at the 14 meteorological stations within the catchment. For all three climate scenarios, the mean annual precipitation is expected to increase during 2016–2035, relative to 1986–2005, in the majority of stations (Figure 4(a)). The precipitation changes across the catchment show a somewhat complex pattern, in which precipitation tends to increase in the southern high mountainous regions, whereas precipitation may decrease slightly in the northern downstream regions (Figure 4(a)).

The annual temperature is expected to be higher than the mean temperature of 1985–2005 in all stations and climate scenarios, except the six most northerly stations in scenario RCP4.5 (Figure 4(b)). This is consistent with the findings of Sun *et al.* (2012), who show that, in general, precipitation and evapotranspiration (as a surrogate for temperature) are projected to increase in Poyang Lake catchment under future climate conditions. For the case of the mean annual temperature, it does not manifest a systematic increasing trend in the future time 2016–2035 under RCP2.6, 4.5 and 8.5 scenarios. That is, the magnitude of projected increases in mean annual temperature under RCP2.6 ($>0.5\,^{\circ}$C) is higher than that of the RCP4.5 and 8.5 ($<0.5\,^{\circ}$C) at some stations (Figure 4(b)), which is consistent with previous studies that concluded that the RCP2.6 may have a warmer global mean surface temperature than RCP4.5 and/or RCP8.5 despite a lower greenhouse gas forcing during 2018–2037 (Chalmers *et al.* 2012; Miao *et al.* 2014).

The monthly mean changes (2016–2035 versus 1986–2005) in precipitation and temperature in the five sub-catchments and in the whole Poyang Lake catchment are shown in Figure 5. For all three climate scenarios, precipitation changes show complex patterns at the monthly scale. Although the general relationships between the three climate scenarios are fairly consistent between sub-catchments, substantial differences in the magnitude of precipitation changes are evident (Figure 5). Generally, increases in monthly mean precipitation tends to occur during spring to autumn (i.e., March-October), with the largest increases of 62% and 50% (RCP8.5) occurring in

Table 4 │ Quantitative assessment of WATLAC model calibration (1986–1995) and validation (1996–2005)

Sub-catchment	Gauging station	Calibration			Validation		
		E_{ns}	R^2	R_e (%)	E_{ns}	R^2	R_e (%)
Ganjiang River	Waizhou	0.83	0.81	12.0	0.73	0.76	9.0
Fuhe River	Lijiadu	0.82	0.74	14.0	0.70	0.71	10.6
Xinjiang River	Meigang	0.80	0.75	3.4	0.75	0.78	3.2
Raohe River	Shizhenjie	0.77	0.79	7.4	0.70	0.71	6.8
Xiushui River	Wanjiabu	0.75	0.70	11.0	0.71	0.71	13.6
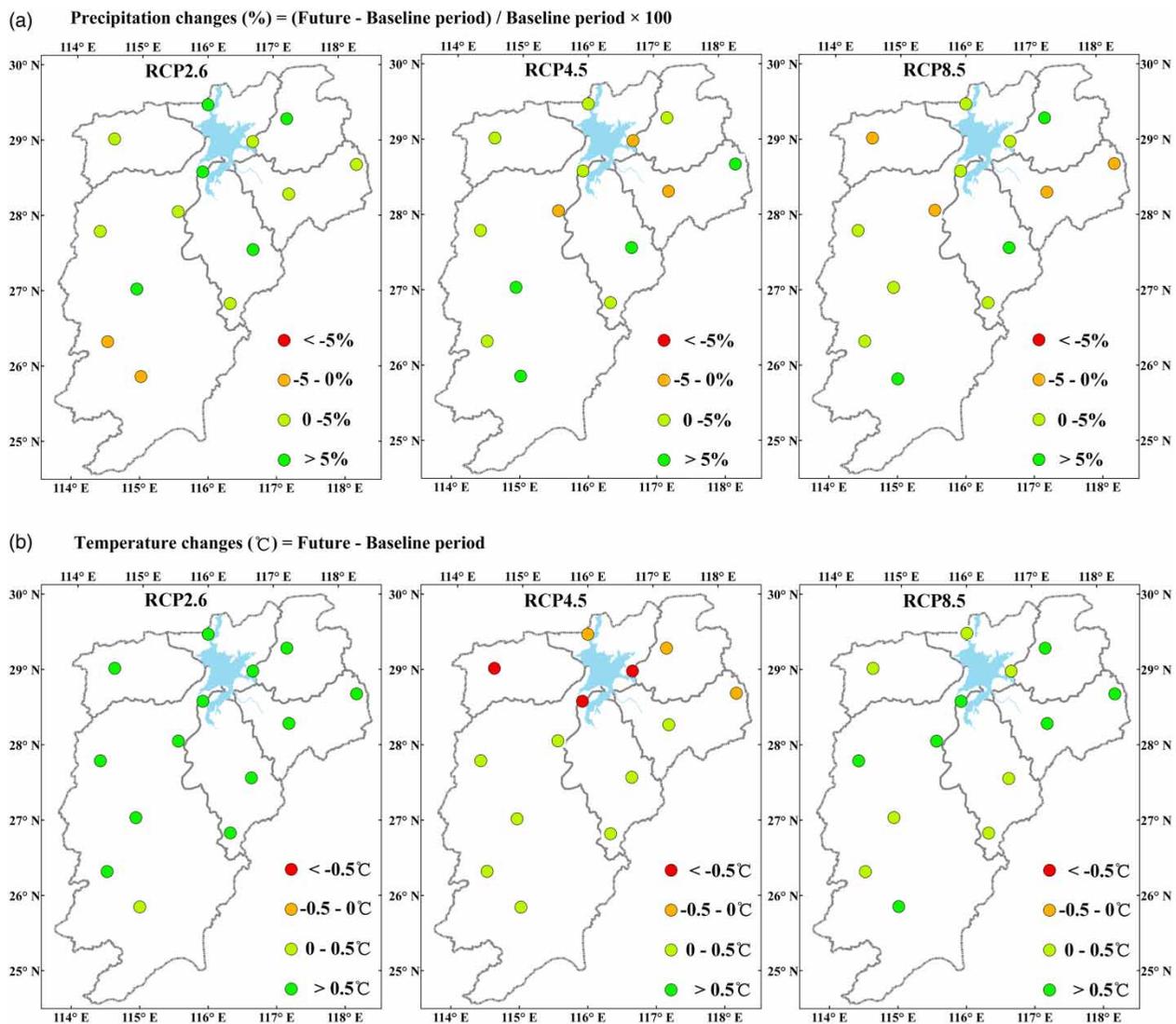
Figure 4 │ Changes in (a) mean annual precipitation and (b) mean annual temperature during 2016–2035 compared to the baseline period (1986–2005). Results from RCP2.6, 4.5, and 8.5 climate scenarios are shown at 14 meteorological stations within the catchment.
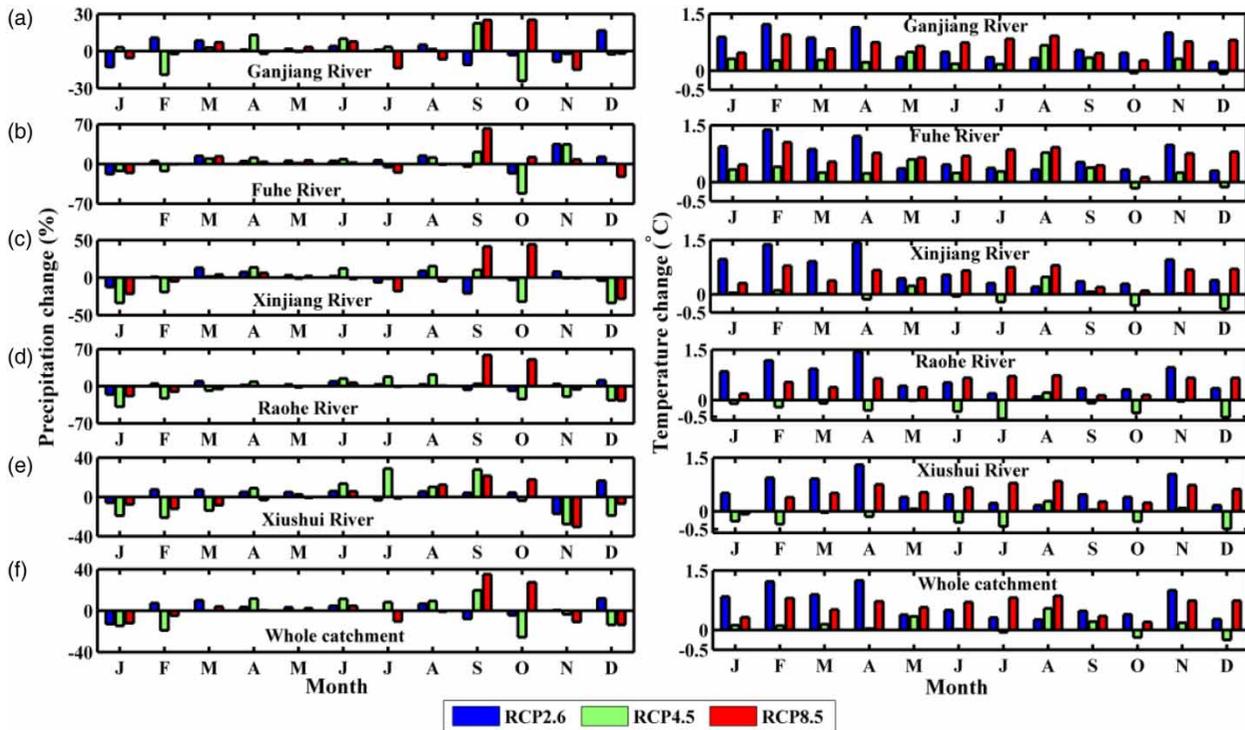
Figure 5 │ Change of future 2016–2035 monthly mean precipitation (left-hand graphs) and temperature (right-hand graphs) for each sub-catchment (a–f) compared to the baseline period 1986–2005.

September and October, respectively. Monthly precipitation may decrease in late autumn and winter (i.e., November-February), with the largest decrease in November for the RCP2.6 scenario (18%) and RCP8.5 (31%), and in January for RCP4.5 (39%). It is also noteworthy that the future monthly precipitation of Poyang Lake catchment has a range between 41 mm in winter and 350 mm in summer averaged over the three climate scenarios.

Relative to the precipitation changes, the monthly mean temperature tends to show a fairly consistent increasing trend throughout the year, except a slightly decreasing trend for the Xinjiang, Raohe and Xiushui Rivers with the RCP4.5 scenario (Figure 5). The RCP2.6 scenario appears to contribute most to the late winter (January-February), spring (March-May) and autumn (September-November) warming across the Poyang Lake catchment, while the RCP4.5 and 8.5 scenarios contribute the most to the summer (June-August) and early winter (December) warming. It is projected that the monthly mean temperature will vary from approximately 6.1 °C to 28.7 °C under future climate scenarios. The range of monthly temperature increase, averaged across the Poyang Lake catchment, is

0.3–1.4 °C for the RCP2.6 scenario, 0.2–0.7 °C for RCP4.5, and 0.2–1.2 °C for RCP8.5, indicating the strong likelihood of warmer temperatures in the near future. In all three emission scenarios, the increase in temperature is distinctly larger from November to April (up to 1.5 °C) compared to other months of the year (<1 °C), suggesting a warmer winter and spring in the future.

Climate change impacts on river discharges

Table 5 summarizes the changes in mean annual river discharge in the five sub-catchments and the whole Poyang Lake catchment. The annual discharge change with respect to the baseline period has the range between −1.0% and 5.0% under the three climate scenarios. Taking the average of the three climate scenarios, the mean annual river discharge is projected to increase in all of the rivers, with the exception of the Xinjiang River. For the whole catchment, the mean river discharge is projected to increase by 1.2%, averaged across the three scenarios.

Seasonal changes in future river discharge are indicated in Figure 6. The results show that all climate scenarios cause

Table 5 | Projected mean annual changes (%) in river discharge for each sub-catchment relative to the baseline period 1986–2005 (negative values are in bold)

	Sub-catchment					
Scenario	Ganjiang River	Fuhe River	Xinjiang River	Raohe River	Xiushui River	Whole catchment
RCP2.6	− **1.3**	5.0	0	0.1	3.1	0
RCP4.5	2.0	2.0	− **1.0**	0.2	2.0	1.5
RCP8.5	2.0	5.0	− **1.0**	0.4	− **1.0**	2.0
Average	1.0	4.0	− **0.7**	0.2	1.3	1.2
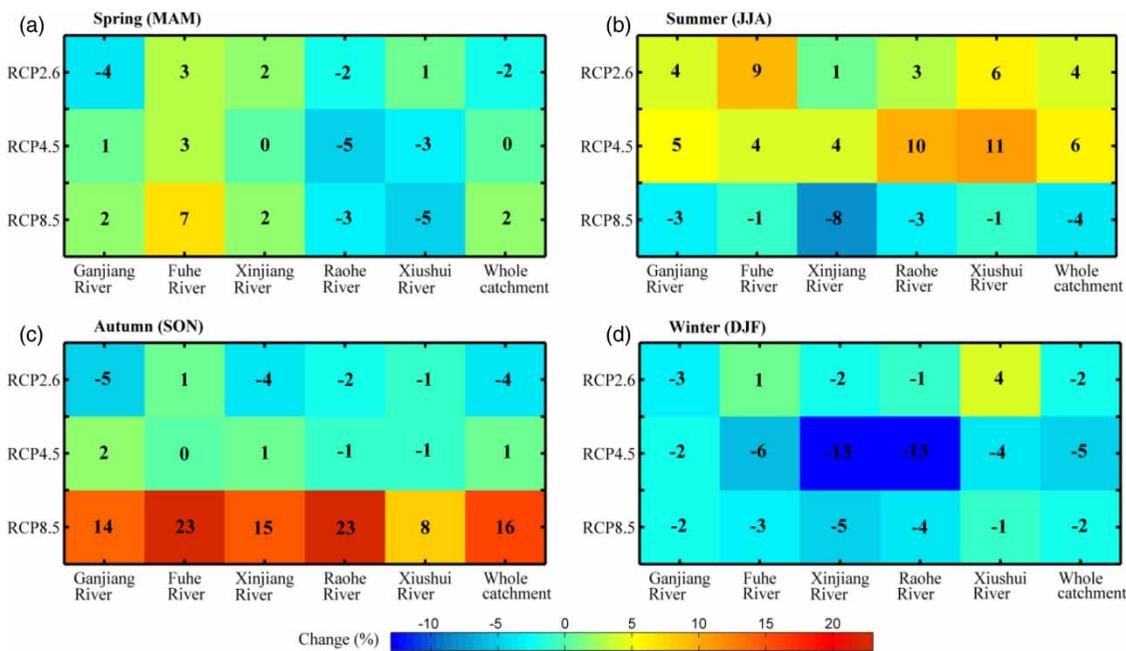
Figure 6 | Projected seasonal changes in river discharge for each sub-catchment relative to the baseline period 1986–2005. The values in figures represent percent change (%).

distinctly decreasing river discharge in all of the sub-catchments in winter, ranging from −1% to −13% (Figure 6(d)). This is attributable to the temperature increase and/or precipitation decrease during winter (see Figure 5), which is more likely contributing to projected decreased winter river discharges relative to the baseline period. Unlike climate scenario RCP8.5, both RCP2.6 and RCP4.5 result in an increase in simulated river discharges in summer (Figure 6(b)), with the largest increase of 11%. Unlike the river discharge response in winter and summer, there is variability in the climate change impact in spring and autumn (Figure 6(a) and 6(c)). That is, the three climate scenarios result in both increase and decrease in simulated river discharge, varying between the sub-catchments and

climate change scenarios. It is noteworthy that the magnitude of projected increase in river discharge in autumn (up to 23%; RCP8.5) is markedly larger than the decrease in river discharge in spring and autumn (Figure 6(a) and 6(c)). This leads to the increase in discharge for the catchment as a whole, as reported above.

For the whole Poyang Lake catchment, the monthly mean discharge has a range between 2,340 m^3/s and 9,100 m^3/s under future climate changes. Figure 7 further shows the future change in monthly mean discharge in the five sub-catchments and for the whole Poyang Lake catchment, compared to the baseline period. The differences between climate change scenarios are considerable, whereas the discharge trends show similar patterns across
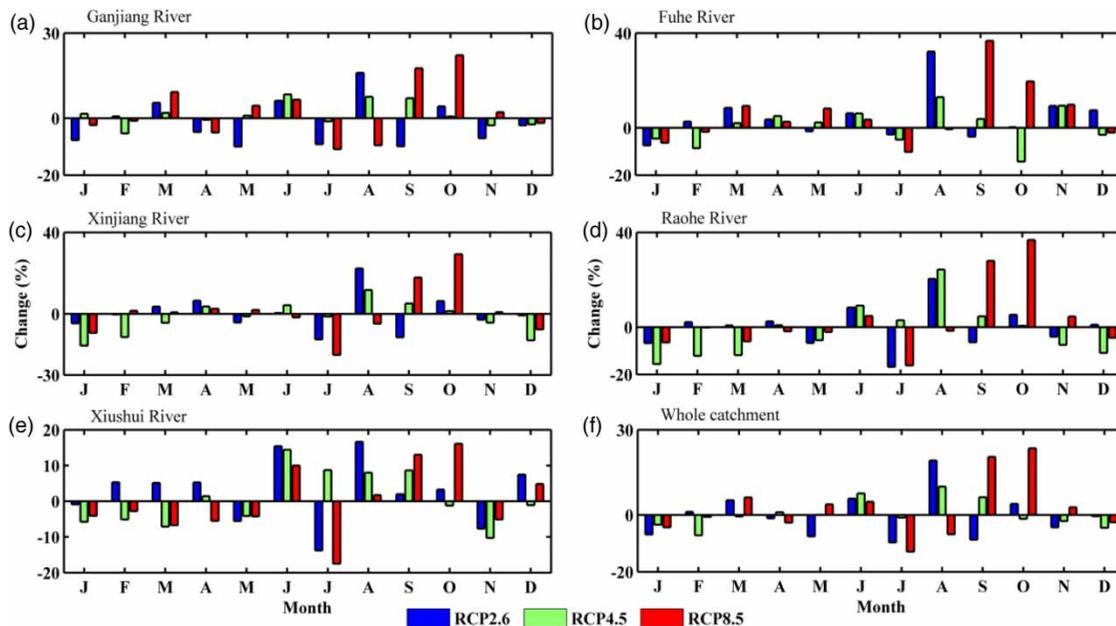
Figure 7 | Percent change in future (2016–2035) monthly mean discharge for each sub-catchment (a)–(f) compared to the baseline period (1986–2005).

all of the sub-catchments. Figure 7 shows that monthly mean discharge has a decreasing trend in January, February, July, and November, with the largest change of −20% in July (ranging from −1% to −20% for all the sub-catchments). The monthly mean discharge increases in June, in particular in the Xiushui River, which has the highest increase of 16%. Changes in monthly discharge in other months show both increasing and decreasing trends between the different sub-catchments and climate change scenarios. The monthly mean discharge is expected to change considerably in August-October (ranging from −14% to 37%; and averaging 10%). The Figure 7 results indicate that the projected increase in discharge from the Fuhe and Raohe Rivers is larger (up to 40%) than projected discharge changes in the other rivers (up to 20%).

Flow duration curves (FDCs) show the percentage of time that river discharge is likely to equal or exceed a given value. FDCs based on projected daily river discharge during 2016–2035 are presented in Figure 8, illustrating the projected range of changes compared to the baseline period. In general, results show that all climate scenarios tend to increase peak flows in terms of frequency and magnitude, although there is a clear difference in the projected changes of climate scenarios between the rivers (Figure 8). The projected changes of exceedance probability in extreme low flows and the lowest river discharge are not apparent for different rivers under the three climate scenarios (Figure 8).

For different rivers, the three climate scenarios tend to produce increases in high flows (Q10) and decreases in low flows (Q90) with only the exception of the RCP8.5 scenario (Figure 9). The projections suggest that high flows and low flows could be serious issues for flooding and drought management across the Poyang Lake catchment in the near future. This is primarily attributable to the increases in river discharge in summer and decreases in winter (Figures 6 and 7).

DISCUSSION AND CONCLUSIONS

The potential implications of climate change on the hydrological system over the Poyang Lake catchment (China) have been assessed using the WATLAC model and the RCM COSMO-CLM. Previous studies have concluded that although the land-use change exerts some impacts on the river discharge, climate change is the primary factor causing the river discharge change of the Poyang Lake catchment (Guo *et al.* 2008; Zhao *et al.* 2010; Ye *et al.* 2013), and therefore, the effect of land-use/cover change on river discharge was not considered in this study. The major sources of
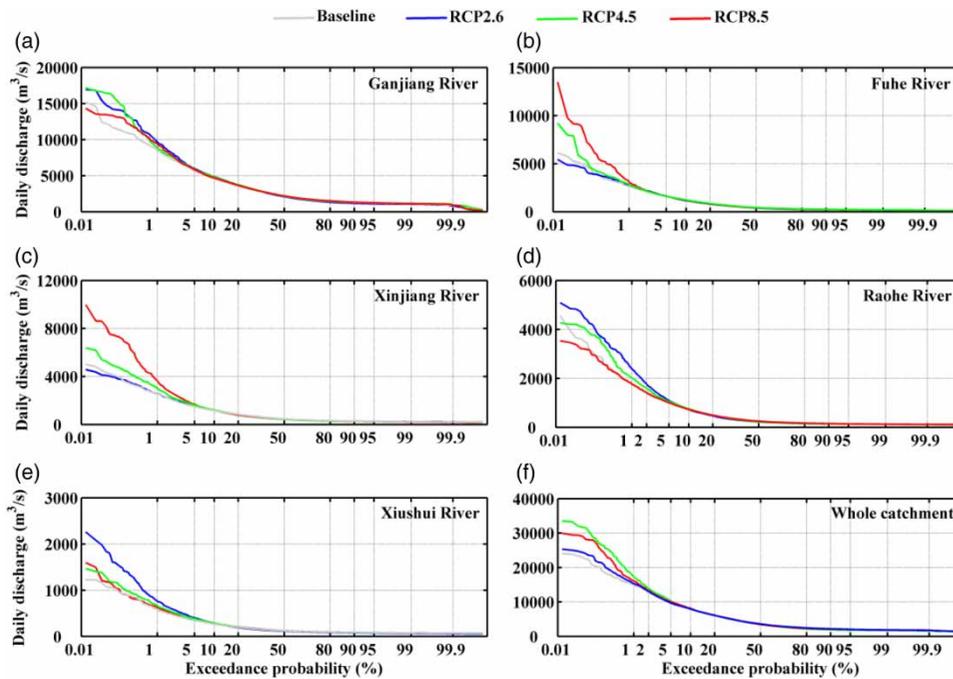
Figure 8 | Exceedance probability plots for projected (2016–2035) daily discharge for each sub-catchment (a)–(f) compared to the baseline period 1986–2005.
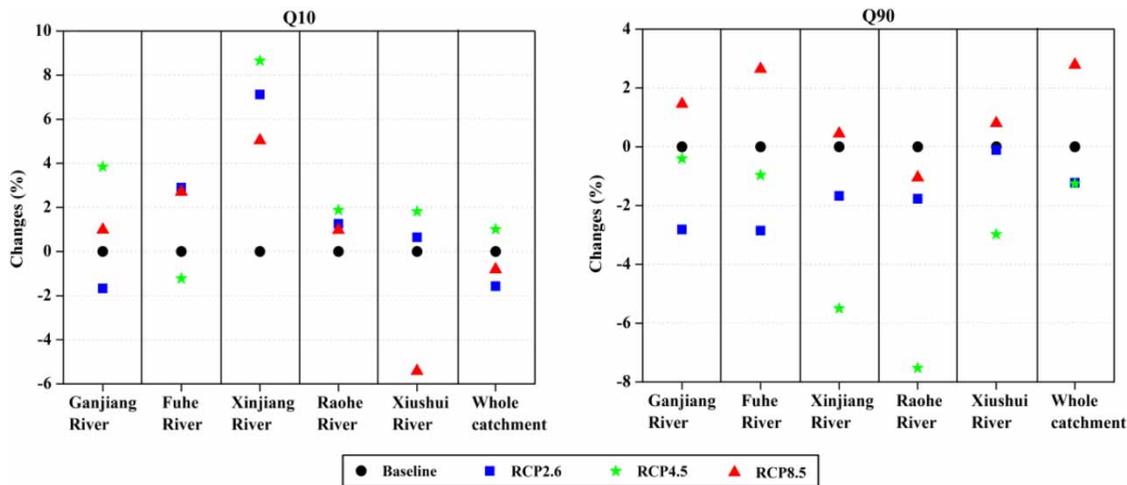

Figure 9 | Changes in high flows (Q10) and low flows (Q90) under RCP2.6, 4.5 and 8.5 compared to the baseline period 1986–2005 for different sub-catchments. Q10 and Q90 are the 10 and 90% values from the FDCs and are used as proxy indicators of changes in flood and drought conditions, respectively.

uncertainty are the path of future emissions used in this study. However, there is no universally accepted methodology for evaluating the relative quality of RCMs with regard to their ability to project the future climate (Bader *et al.* 2008; Kienzle *et al.* 2012). In the current study, a suite of climate change scenarios was applied to cover a wider range of climate change uncertainties, which predict

principally progressive future changes in the precipitation and temperature regime.

It is also acknowledged that obvious differences between climate observations and COSMO-CLM simulations were observed in this study. According to the bias-corrected scenarios, the projected climate variables and associated river discharges for different RCPs do not show

a distinctly overall increase or decrease across the Poyang Lake catchment. However, the mean monthly temperature shows a fairly consistent increasing trend for different sub-catchments regardless of climate scenarios. The future climate in the catchment is projected to have an increased mean monthly temperature ranging from 0.3–1.4 °C, 0.2–0.7 °C, and 0.2–1.2 °C for RCP2.6, 4.5 and 8.5 scenarios, respectively. Although the variation pattern of monthly precipitation has slight differences between the RCPs, the results tend to show a general increase in precipitation in all seasons, with the exception of winter. Changes in the annual cycle of precipitation are mostly projected to increase in March-October, with the largest increase of up to 62% in September, while precipitation is predicted to decrease in November-February, with the largest decrease of up to 39% in January.

Hydrological simulations indicate that the projected increases in mean annual river discharge are expected to vary between 0.2% and 4% in the future time period, except for the decreasing trend for the Xinjiang River sub-catchment. The projected changes in precipitation and temperature are likely contributing to the decreased winter river discharges and increased summer river discharges. The projections also show a great likelihood of increases in high flows and decreases in low flows in terms of both frequency and magnitude, suggesting an increasing frequency and severity of flooding and droughts in the Poyang Lake catchment in the future climate. The broad range of projected river discharges is primarily the result of uncertainty in projections of future precipitation, and the variability of precipitation across the projections can be attributed to the effect of emissions pathways. Based on a wide range of RCMs, Bucchignani *et al.* (2014) concluded that all previous RCMs performed over China have non-negligible precipitation and temperature biases, mainly due to shortcomings of the RCMs in reproducing atmospheric dynamics and partly due to low quality of the gridded datasets used for validation.

The severe water shortages of Poyang Lake have aroused wide concern recently and raised questions such as whether the lake water levels will increase in the dry period under future climate change, which is of high importance for policy makers as it may affect various aspects of the lake (Dai *et al.* 2008; Zhang *et al.* 2015). Model

simulations in Ye *et al.* (2011) indicate that the total inflows from the catchment will increase in the wet period and decrease in the dry period under future climate conditions, resulting in a possible change in water levels for the flood (0.1 to 1.34 m) and dry (−0.32 to −1.31 m) seasons in the lake. Considering the outcomes of this study, the significant decreases in winter river discharge for different rivers, resulting from changes in catchment climate, are more likely to further worsen the seasonal dryness of the lake. Thus, water resource managers and wildlife managers in Poyang Lake and its catchment may need to adapt to less water availability during the dry months, and as peak flows become more extreme, more works should be directed at quantifying their impact on existing infrastructure.

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