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Water resources change in response to climate change in Changjiang River basin

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Abstract

Doubtlessly, global climate change and its impacts have caught increasing attention from all sectors of the society world-widely. Among all those affected aspects, hydrological circle has been found rather sensitive to climate change. Climate change, either as the result or as the driving-force, has intensified the uneven distribution of water resources in the Changjiang (Yangtze) River basin, China. In turn, drought and flooding problems have been aggravated which has brought new challenges to current hydraulic works such as dike or reservoirs which were designed and constructed based on the historical hydrological characteristics, yet has been significantly changed due to climate change impact. Thus, it is necessary to consider the climate change impacts in basin planning and water resources management, currently and in the future. To serve such purpose, research has been carried out on climate change impact on water resources (and hydrological circle) in Changjiang River. The paper presents the main findings of the research, including main findings from analysis of historical hydro-meteorological data in Changjiang River, and runoff change trends in the future using temperature and precipitation predictions calculated based on different emission scenarios of the 24 Global Climate Modes (GCMs) which has been used in the 4th IPCC assessment report. In this research, two types of macro-scope statistical and hydrological models were developed to simulate runoff prediction. Concerning the change trends obtained from the historical data and the projection from GCMs results, the trend of changes in water resources impacted by climate change was analyzed for Changjiang River. Uncertainty of using the models and data were as well analyzed.

1 Introduction

1.1 Changjiang River and the water resources management focus

Changjiang (Yangtze) River basin has total catchment area of 18 million km^2, and of 6300 km length. The river origins from the Qinghai-Tibet plateau, and then flows through 11 provinces, across China from west to east. The river reaches South China Sea at Shanghai, and there is 1/3 of China population living in the basin (Fig. 1). With annual rainfall of 1100 mm that gives an annual runoff of 996 billion m^3, Changjiang River basin used to be believed rich in water. However, with the rapid social-economic development, difficulty of Water Resources Management (WRM) is recently becoming more appealing. The pressures have been identified as: increasing conflicts between water supply and demands due to the rapidly growing population and industries, which also results in increasing of water pollution along the river; more frequent hydrological extreme events such as drought (e.g. in 2006 serve water shortage occurred in upper Changjiang river; spring 2010, a 100-year return period drought is now occurring in south west of Chin, partially in the basin of Changjiang Rive) and flood disasters (e.g. 1998 basin-wide flood, and every year some regional floods occur here and there) as a result of the variability of monsoon weather pattern which brings about 80% rain during the summer months; evidently modified hydrological characteristics of the river caused by climate change which may result in more extreme hydrological events, etc. In addition to the basin-wide pressure, inter-basin water transfers projects that are planned and under construction to supply water to the drought affected coastal plains of Northern China, also increased the difficulties of WRM in Changjiang River basin. Thus, promote effective and efficient water resources management in Changjiang River considering the sensitive impacts is essential for the economic development in China.

Under the administration of the ministry of Water Resources, Changjiang River basin is managed by the basin-wide authority – Changjiang Water Resources Commission (CWRC). For sustainable social-economic development, the basin planning is conducted by CWRC every 10 years, in which predictions on various aspects in the basin and corresponding water conservancy projects, landuse planning and WRM measures that shall be done in the future are provided. In particular, integrated WRM measures including engineering and strategic measures for flood management, drought relief and environment/ecology protection etc., are provided for the next 10 years. To have a comprehensive plan for the river basin, it is important to understand what has been changed in the past and what may happen in the future in terms of water resources and hydrologic circles, in particularly under the impact of climate change, which has been approved sensitive among all factors.

1.2 Climate change and water resources

Considerable amount of researches have been carried out to study climate change impacts on water resources in particular the technical paper collection of *Climate Change and Water* (IPCC, 2008) has summarized major findings, in which most conclusions have been found true for Changjiang River, for example "*Climate change affects the function and operation of existing water infrastructure – including hydropower, structural flood defences, drainage and irrigation systems – as well as water management practices*" etc. WRM is becoming increasingly difficult no matter due to climate change or the increasing demands. However, there are some questions shall be looked in-depth, at least for Changjiang River if not anywhere else. For example, is it true, that as stated in the 4th IPCC assessment report (IPCC, 2007), that there is a significant change in global climate, which is characterized by *warming-up*, concluded from instrument measurements of air temperature in the ground. It is true for many studied areas, however, due to lack of comprehensive study to the field measurements, it is not sure how Changjiang River basin behaves in terms of temperature change in the past and in the future.

In addition to the historical change that may indicate future trend of change, it is as well important to know how it changed and what will happen on water resources due to climate change impact. However, although the impacts of global climate change on hydrology and water resources have caught increasing attentions from various specialists world-widely (e.g. Kundzewicz and Kaczmarek, 2000; Milly et al., 2002; Palmer and Räisänen, 2002; Jonathan et al., 2004), few have been made in China (e.g. Feng et al., 2003; Zhu and Zhang, 2005; Ren, 2007 etc.), hardly any has been found on Changjiang River basin. Recently, few researches have carried out studies on the response of hydrology and water resources to global climate change impact in some part of the Changjiang River basin. For example, Zhu Li and Zhang Wanchang (2005) have studied the impacts of climate change impacts on water resources in Han River basin (the largest tributary of Changjiang River), researches have been carried out in Hubei Province (Feng, et al., 2003) and in Changjiang River basin (Ren, 2007). In these studies, the climate scenarios were constructed by arbitrary combinations and climate model outputs applied in the 3rd (or earlier) IPCC assessment reports. Currently, the climate models used for the 4th IPCC assessment report have been obviously improved in terms of model scheme and prediction accuracy compared to earlier models, which might better represent the change and impact of climate in water resources on Changjiang River.

As it is widely accepted, the climate change scenarios in the future are generally constructed by arbitrary combination of scenarios, by statistical correlation method based on long series of hydro-meteorological data, and by the basic outputs from GCMs. At present, with better understanding of climate mechanism, the continuous improvement of climate modes and the growing reasonability of GCM parameter process, the predicted climate products derived from GCMs based on different CO_2 and aerosol emissions are widely used. The GCMs method has now become one of the most common approaches to construct future climate change scenarios, which has been adapted in this work addressed below.

To study climate change impact, models are needed. Present studies on impacts of climate change on hydrology and water resources are normally based on hydrological models and water resources assessment models, combined with constructing the "what-if" scenarios, i.e., assuming IF certain changes appear then WHAT kind of changes in each component of hydrological cycle would occur correspondingly.

The most common hydrological models are statistically-based models which generate runoff based on the relationship of air temperature, rainfall and runoff; conceptual hydrological models developed based on the mass-balance concept; and distributed hydrological models such as TOPMODEL, SWAT and VIC etc.

In this paper, based on time series of precipitation and runoff in the period of 1953–2005, a statistical-based runoff model and a simplified water-balance hydrological model for the major hydrological stations in the outlet of the different sub-basin of Changjiang River basin are developed. The GCMs-based prediction of temperature and precipitation covering the entire Changjiang River Basin in the years of 2001–2100 have been derived from the outputs of the 24 global climate models (PCMDI, 2007) under three typical SRES scenarios of A1B, A2 and B1 (IPCC, 2001) used in the fourth IPCC assessment report. Scenario of A1B, A2 and B1 represent approximately the medium greenhouse gas emission, the high emission and the low emission, respectively. Based on the developed model and GCMs-based meteorological data, runoff in the next 100 years in the outlets of Changjiang River basin and its sub-basins are predicted. Analysis has been made on the trend of runoff changes in the next 100 years based on the model results.

2 Historical changes on hydro-meteorology in Changjiang River

2.1 Data

Data used are historical meteorological record from the National Meteorological Center including 174 precipitation stations and 37 temperature stations during the period of 1951–2005, and discharge time series (1950–2006) at gauge stations along the main stream of Changjiang River. To better understand the historical change characters, in addition to analyzing the entire basin as a whole, analysis has been as well carried out on 4 sub-basins including the upper area which is gauged at Yichang, the middle area gauged between Yichang and Wuhan, the mid-downstream area (from Yichang to

Datong), and the downstream area (gauged between Wuhan and Datong), as shown in Fig. 1.

2.2 Analysis methods

To analyze the change trends of precipitation and air temperature, the tendency of coefficient is adopted to indicate the precipitation change trend, expressed as:

$$r_{xt} = \sum_{i=1}^{n}[(X_i - \overline{X})(i - \bar{t})] / \sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(i - \bar{t})^2} \tag{1}$$

Where, n is the number of data, X is the rainfall data, $\overline{X}$ is the average rainfall, $\bar{t} = (n+1)/2$. The value sign of r_{xt} indicates the linear change trends within the period of computation.

The change tendency of climate is indicated using the slope of linear regression equation of (Zhu et al., 2005):

$$\hat{x}_t = \alpha_0 + \alpha_1 t \tag{2}$$

Where, $\alpha_1 = r_{xt}\frac{\delta_x}{\delta_t}$, δ_x is the standard deviation of the time series. δ_t is the standard deviation of i, i=1, 2, ...,n.

To assess the temperature tendency rate, the Mann-Kendall method is applied. In this method, assume x_i (i=1,2,3,...,n) is a random data set, p is the number of all data pair of (x_i, x_j, $i < j$) (i=1,2,..., $n-1$; $j=i+1$, $i+2\ldots n$) when $x_i < x_j$. The tendency is expressed as:

$$M = \tau / \sqrt{V_{\alpha,r}(\tau)} \tag{3}$$

Where, $\tau = 4p/(n(n+1))$-1,$V_{\alpha,r} = 2(2n+5)/(9n(n-1))$,$n$ is the number of data. If data length n is long enough, M follow the normal distribution. Thus, at the confidence of

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α, if $|M| < M_{\alpha/2}$, the change tendency is considered as not-obvious; otherwise, it is considered as obvious. Normally the confidence level α=0.05, and $M_{\alpha/2}$=1.96, which is used as the threshed valued for the analysis.

2.3 Results

2.3.1 Precipitation

Applying the above methods and using the time series of data, the precipitation change trends in 1951–2005 are analyzed for each sub-basins and the entire river basin. The results shows that there is a general tendency of decreasing happened in rainfall at the river basin (Fig. 2), but it is found not obvious, which shows a tendency rate of −10.0 mm/10 a and a M of −1.125.

Similar change has been found in the sub-basins except for the downstream area, which is between Wuhan and Datong, where a change of increasing precipitation has been found in 1970–2000, and a decline follows afterwards (Fig. 3), which shows a tendency rate of 5.9 mm/10 a and a M of 0.559.

Analysis has been made on precipitation intensity using the spatial distribution of maximum daily rainfall (Fig. 4) and the annual raining days (Fig. 5). As shown in Fig. 4, the spatial distribution of maximum daily rainfall (mm) shows tendency of decreasing at mainly north Changjiang River, and increasing of maximum daily rainfall is found in east part of Changjiang River. As shown in Fig. 5, the average annual raining days shows a tendency of decreasing, that at most places the annual raining days decreased up to 2.5 day per 10 years. Combining these two results, it can be found that in most areas of Changjiang river basin there is a tendency of increasing in precipitation intensity, which may suggest an increasing of flood frequency at those areas.

2.3.2 Temperature

As it is insufficient to use 37 meteorological data to represent the whole river basin, in addition to the data collected from the aforementioned 37 stations, temperature at representative cities, namely, Chongqing and Guiyang for upper area, Wuhan for middle area and Nanchang city for the downstream area, are collected and analyzed.

The results show a clear warming-up at Changjiang River basin during the past 60 years, in particularly after 1983, which can be explained by the economy bloom of China by that time (Fig. 6).

Analysis does show similar change tendency at representative cities except the city of Guiyang, which is located at Upper Changjiang River (Fig. 7). The temperature did not show much change before 1990s but there is an obvious declining of temperature after 1998.

2.3.3 Runoff

Datong is the gauge station before the river flows into the sea. Thus, it is used to represent the runoff change in the entire basin (Fig. 8). As it can be seen, there are years of more or less water before this century. After 2000, the runoff shows a slight declining (average tendency rater of –2.2 mm/10 a) but not obvious.

2.3.4 Summary

In summary, it has been found that the precipitation shows a declining tendency rate at Changjiang river as a whole but not necessary the same at local areas for example the downstream area between Wuhan and Datong area. In general, in agreeing with most studies, area-average temperature in Changjiang River basin shows an obvious change and tendency of warming-up, but at local area such as Guiyang city (Upper Changjiang River), there is declining of temperature. In corresponding to the change of precipitation, the annual runoff at Datong station (which gauges the entire basin at the downstream area) shows a declining after year of 2000.

3 Projection of runoff

In order to learn about the future change of water resources in corresponding to the change of climate, two types of models are developed to predict future runoff using the GCMs results.

3.1 Hydrological models

3.1.1 Statistical model

The multiple regression equation is used to establish the mathematical statistical relation model between the runoff (in depth), and the precipitation and area average temperature. Taking into consideration of the nonlinear relationship between the water resources system and climate changes, the nonlinear regression model are developed (Chen, et al., 2004). The model equation is derived as:

$$\log R = m \log P + nT + c \tag{4}$$

By rearranging Eq. (4), the following expression can be obtained:

$$\mathrm{Ln} R = m L\, nP + nT + c \tag{5}$$

Where R, P and T are the annual average runoff (mm), the annual average precipitation (mm) and the annual average temperature (°C), respectively; m, n and c are the regression coefficients.

Using historical time series (year 1953–2005) at main gauging hydrological stations in Changjiang River basin as calibration data, applying method of trial and error, the coefficients of m, n and c are determined.

The statistical models for subareas of Changjiang River basin are calibrated as follows:

The upstream area: $\mathrm{Ln}R = 1.0654\mathrm{Ln}P + 0.0214T - 1.4455$ (6)

The middle stream area: $\mathrm{Ln}R = 1.8001\mathrm{Ln}P + 0.0386T - 7.1057$ (7)

The entire river basin: $\mathrm{Ln}R = 1.5798\mathrm{Ln}P + 0.0391T - 5.3117$ (8)

In Eqs. (6), (7) and (8), R represents the annual average runoff depth (mm) at the outlet gauging stations, T and P are the average precipitation (mm) and the average temperature (°C) of the calculated areas.

3.1.2 Simplified water-balance model

Based on the hydrological time series of year 1953–2005, an assumption that the fluctuation in annual river basin storage volume ($\frac{\Delta S}{\Delta t} \approx 0$) is approximate to zero (Michael and Jorge, 2001) is made. Using the commonly used water balance equation, expression to calculate runoff depth at the river basin outlet is obtained as:

$$Q = P - \mathrm{ETa}_{-\mathrm{WB}} \tag{9}$$

Where, P is the annual average precipitation in the river basin, $\mathrm{ETa}_{-\mathrm{WB}}$ is the estimated annual average evaporation in the river basin. Due to the fact that the outputs from GCMs are mainly temperature and precipitation, the monthly potential evapotranspiration $\mathrm{ET}_\mathrm{p}(i)$ has been estimated by applying the Blaney-Criddle empirical evaporation estimation method (XU and Singh, 2002), where, i is referring to the month. The corresponding total annual potential evaporation amount $\left(\sum_{i=1}^{12} \mathrm{ET}_\mathrm{p}\right)$ is added up. Then, to estimate the actual evapotranspiration amount ($\mathrm{ET}_{\mathrm{a-B\&C}}$) in the river basin, Pike empirical formula (Dingman, 2002) is applied. Finally, statistics on the actual annual average evapotranspiration values in different regions are made and a relation between $\mathrm{ET}_{\mathrm{a-B\&C}}$ and $\mathrm{ET}_{\mathrm{a-WB}}$ is estimated using historical observations.

The Blaney-Criddle method is a method proposed by Blaney and Criddle in 1950 to calculate potential evapotranspiration in western United States. It was expressed as:

$$\mathrm{ET}_\mathrm{p}=k\cdot\mu\cdot(0.46\cdot T_\mathrm{a}+8.13) \tag{10}$$

Where, ET_p is the potential evapotranspiration based on surface plant condition (mm), T_a is the average temperature (°C), μ is the percentage of monthly total sunny days, $k$is the monthly consumption coefficient which is mainly depending on the type of plant, location, season and growing period (generally from May to October). In this study, the k values have been recalculated for Changjiang River basin, which is 0.8 during the growing period from May to August, 0.3 in non-growing period from October to March and 0.65 during the transition period in April and September, respectively.

Another adapted method, the Pike empirical formula, is an empirical equation, proposed by Pike in 1964, for calculating approximately the actual annul evapotranspiration values on the basis of annual precipitation and annual potential evapotranspiration information, expressed as:

$$\mathrm{ET}_\mathrm{a}=\frac{P}{[1+(^{P}/_{\mathrm{ET}_\mathrm{p}})^2]^{0.5}} \tag{11}$$

Where, ET_a is the actual annual evapotranspiration value (mm), ET_p is the annual potential evapotranspiration value (mm) and P is the total annual precipitation amount (mm).

3.2 Model verification

Criteria of the statistical correlation coefficient (r), the deterministic coefficient (R^2) and the Root Mean Square Error (RMSE) between the simulated values and the observed values by two different models are used to evaluate the performance of the developed hydrological models (as shown in Table 1). In the entire Changjiang River basin and in the middle and lower streams, the statistical model shows a fairly high accuracy, with

$R^2 > 0.8$, $\text{RMSE} < 60$ mm/year. But it shows rather bigger errors in the upstream, with R^2 only being 0.57. Such error might be caused by the fact that there are several different climate regions in the upper area of Changjiang River, where the spatial difference of temperature and precipitation distributions is large.

For the river basin, i.e., upstream of Datong station (near the estuary area) and the area between Yichang to Datong, the simplified water balance model shows a fairly good performance in simulating the runoff, with R^2 of 0.90, however with a relatively larger RMSE. It has been found that there exists systematic error due to the insufficient monitoring data of precipitation and temperature. In addition, due to large time interval, i.e., one year, the seasonal variations in parameters can not be reflected. For the upstream area, the R^2 is 0.61, which is smaller than that in the other two areas. The uncertainty courses could have been resulted from the errors in estimating evaporation. In the empirical Blaney-Criddle formula, only the area average temperature and some radiation information are considered, which cannot represent the actual evaporation characteristics in the transitional region from Qinghai-Tibet Plateau to the plain areas.

The hydrological models developed in this study show some uncertainty in the results. However it is considered reasonable to apply them to analysis the change trend of the runoff associated with the change of climate in the future based on the GCMs outputs.

3.3 Model results

Based on the outputs of GCMs about the Changjiang River basin, the spatial resolution ranges form 1 to 5 degrees, and of monthly temporal resolution. The above two hydrological models are applied to estimate the runoff for different areas with the input of yearly average temperature and area-averaged precipitation considering different emissions scenarios. Analysis has been carried out to the estimated modeling results using the methods of linear regression and Mann-Kendall test (confidence level is 0.05).

3.3.1 Precipitation projection

With the three emissions scenario, the trend of projected precipitation have been found to decline in the following 10 years (that is from the year 2010 to 2020) for the entire river basin (Fig. 9a); in the next 30 years (before the year of 2040) the trend is estimated to increase however insignificantly. Significant increasing is found for all three different emissions scenarios after 50 years. The results also show that scenarios A2 and A1B affect the change of projected precipitation more significantly than B2. The average increase of projected precipitation for the different emission scenarios is around 8~13 mm (A2) and 12~14 mm (A1B) and 4~8 mm (B1), respectively, in the coming 10 years.

3.3.2 Temperature projection

During the period of the next 100 years, yearly average temperature is projected to increase rapidly (Fig. 9b) for the whole Changjiang River basin regardless whichever emission scenarios. The average increasing rate ranges from 0.1 to 0.5 °C over the period of 10 years.

3.3.3 Runoff projection

The two developed hydrological model are applied to estimate the runoff projection using the projected temperature and participation considering different emission scenarios, the results are presented in Fig. 10 and Table 2.

As shown in Table 2 and Fig. 10, results of the two hydrological models are different in quantity, but the change trends agree with each other in general, i.e. little change has been found during the first 20 years (2020–2040), and then increasing of runoff occurs, the increasing becomes more appealing after year 2060. It is also found that the runoff respond more evidently to the middle and high emission scenarios (A1B and A2), and less evidently to the lower scenario (B1).

The results also show that that statistic model (Fig. 10, right hand side) shows larger uncreatinty range comparing to the simplified mass-balanced model (Fig. 10, left hand side) model, especially at the high temperature part. This might be due to the difficult of extrapolation for statistical models, that when future projected temperature exceeds the historical data that was used for model calibration and validation, the model may not be able to simulate such data range.

4 Conclusions and recommendations

Analyses have been made on the historical data of temperature, participation and runoff at Changjiang River basin. The results show an increasing tendency of temperature at basin-scale, but at local level decreasing of temperature might be as well happening. The results also indicate an increasing in precipitation intensity, which may result in increasing of flood occurrence that shall be considered in flood management practices. However, It has been found that both precipitation and runoff show a slight declining in terms of quantity in the past 10 years, this may indicate an much serve in dry season when drought issues may happen, which was unfortunately true due to the fact that there occurred 100-year return period drought problem in upper Changjiang River in spring 2010.

The above findings might be limited due to lack of sufficient data (data is never sufficient!) but can be taken into consideration in the basin planning for future implementation as well as the present water resources management practices, especially for extreme issues such as flood and drought management. It is happening now that in current flood and water resources management, more monitoring system have been put into the basin to improve monitoring and management capability to flash flood that may be caused by the increasing of storm intensity. In addition, increasing attention has been put on drought management in practices, for example, proposals and plans have been made to improve the drought monitoring and management capacity in the 12th 5-year national plan.

Based on the outputs of the 24 GCMs, which are used by IPCC for the fourth climate assess report, the estimation for precipitation and temperature under the different SRES scenarios have been made and analyzed over 100 years in future over Changjiang River basin. It has been found that rainfall in Changjiang River basin will decrease firstly before 2020, then changes to increasing during the period of 2020 to 2040, and then continue to increase more significantly till 2100. The trend of temperature on Changjiang River basin is predicted to keep on increasing over the future 100 years.

Two types of hydrological models, namely the statistic model and the simplified mass-balanced model, were developed to simulate the future runoff using the projected precipitation and temperature data, considering different condition of the SRES scenarios (A1b, A2, B1). The results show a similar trend of projected runoff in the outlet of Changjiang River basin in comparing with the projected precipitation change tends, that is, runoff in the outlet (Datong) of Changjiang River basin is estimated to slightly decrease during the period of 2010 to 2040, and then change to increase significantly after the year of 2060.

However, the results showed a significant difference between the two hydrological modeling results, uncertainties are also found, in particularly the statistic model shows a larger uncertainty in comparing with the simplified mass-balanced model. This might be due to the extrapolation problem that generally exists in this type of data-driving approaches. In addition, due to the sparse spatial and temporal resolution of the hydrological models, the distribution of water resources in Changjiang River basin might not have been accurately represented. Similar uncertainty sources can be found for the estimation of evaporation. Thus, it is suggested to improve the study with more comprehensive models, i.e. distributed hydrological models, which can be calibrated and validated with much higher resolution and more optimized parameters. Method of estimating evaporation shall be studied as well.

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Table 1. Statistics of the simulated and observed runoff for the statistical model and simplified water-balance model in Changjiang River basin.

Regions	River basin above Datong		River basin above Yichang		Intervening area from Yichang to Datong	
Models	Statistical model	Simplified water balance model	Statistical model	Simplified water balance model	Statistical model	Simplified water balance model
r	0.91	0.90	0.75	0.78	0.91	0.90
R^2	0.84	0.81	0.57	0.61	0.83	0.81
RMSE	29	138	29	105	54	189

Note: the unit of RMSE is mm/year.

Table 2. Estimated runoff at Datong station during the year of 2001-2100 based on projected climate change by the statistic (S) and simplified water balance (WB) models (unit: mm/year).

Scenarios	Time period	2001–2020		2001–2040		2001–2060		2001–2080		2001–2100	
	Model	S	WB	S	WB	S	WB	S	WB	S	WB
A1B	Change rate	−6.4	3.1	−0.7	12.8	7.3	23.3	7.3	23.5	6.7	22.5
	MK value	−0.91	0.71	−0.42	4.52	4.48	8.14	6.87	10.45	8.49	12.34
A2	Change rate	−1.7	−7.5	7.2	−1.4	15.1	4	18.8	4.8	22.8	6.1
	MK value	−0.45	−1.75	2.54	−1.07	6.99	3.09	9.85	5.51	12.06	7.93
B1	Change rate	−6	−13.8	6	−1.7	9.6	1.2	11.5	3.1	11.6	3.7
	MK value	−1.04	−1.88	2.87	−0.35	6.77	1.81	9.32	4.3	11.22	6.62

Fig. 1. Changjiang River and its sub-catchments. The city of Wuhan is where the basin authority CWRC is located.

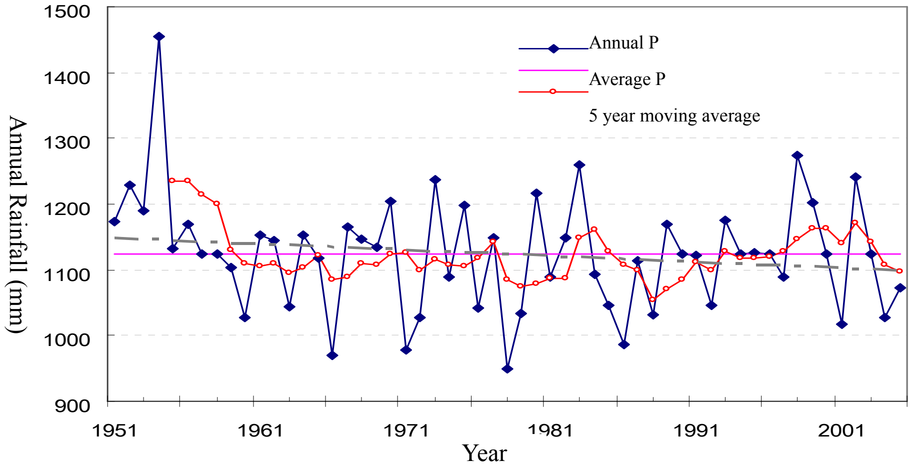

Fig. 2. Annual average and 5-year moving average precipitation in Changjiang River, 1951–2005.

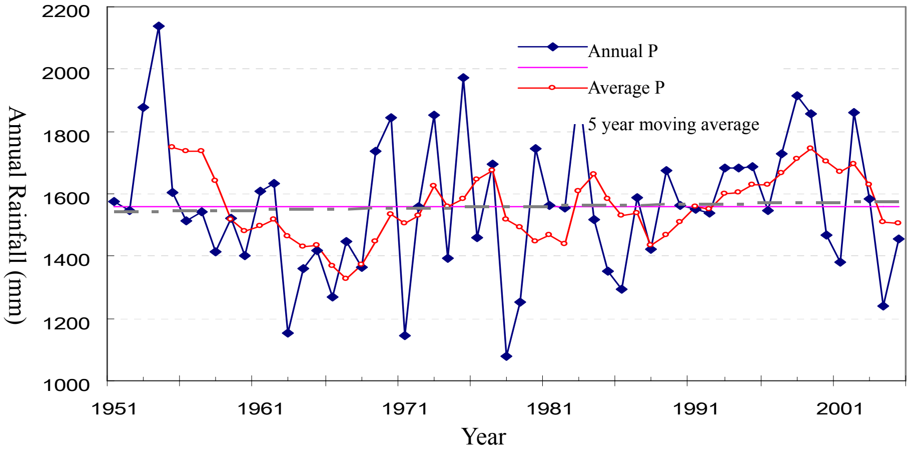

Fig. 3. Annual average and 5-year moving average precipitation in the downstream of Changjiang River, sub-basin of Wuhan-Datong, 1951–2005.

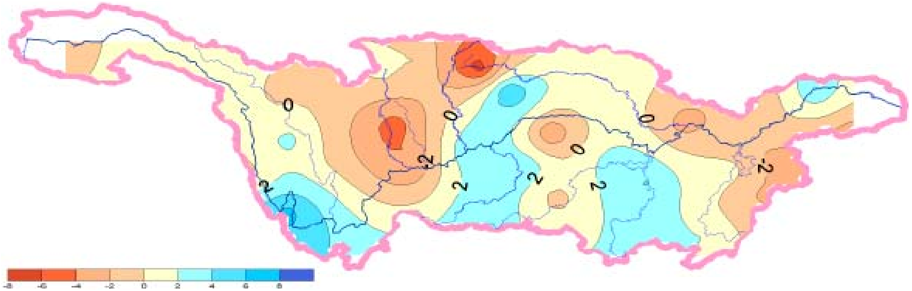

Fig. 4. Spatial distribution of daily maximum rainfall tendency rate in Changjiang River, mm/10 a, blue color indicates increasing and red color indicates decreasing.

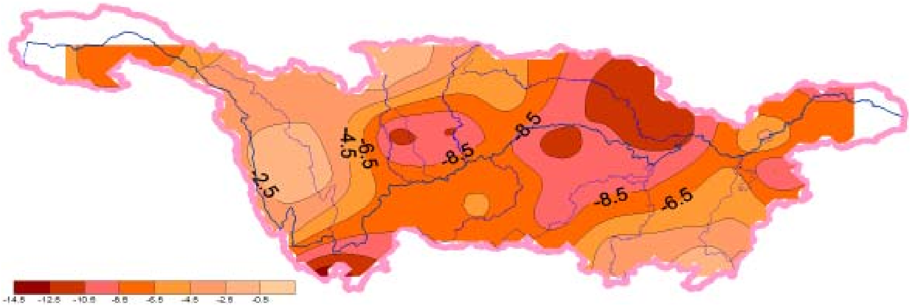

Fig. 5. Spatial distribution of annual raining days tendency rate in Changjiang River, day 10 a.

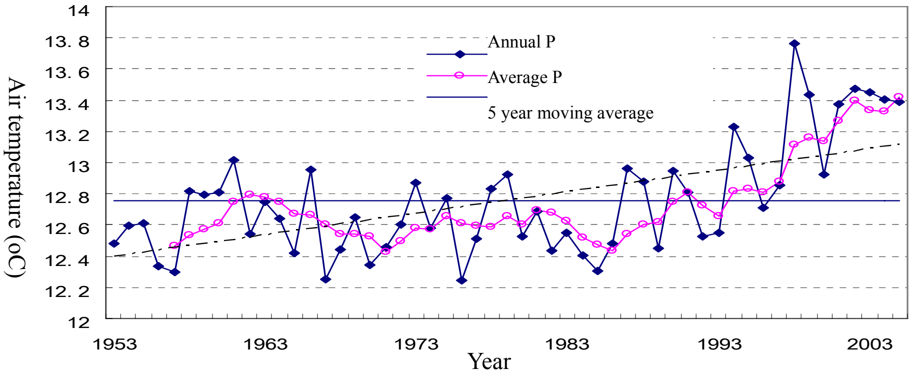

Fig. 6. Annual average and 5-year moving average air temperature in Changjiang River, 1953–2005.

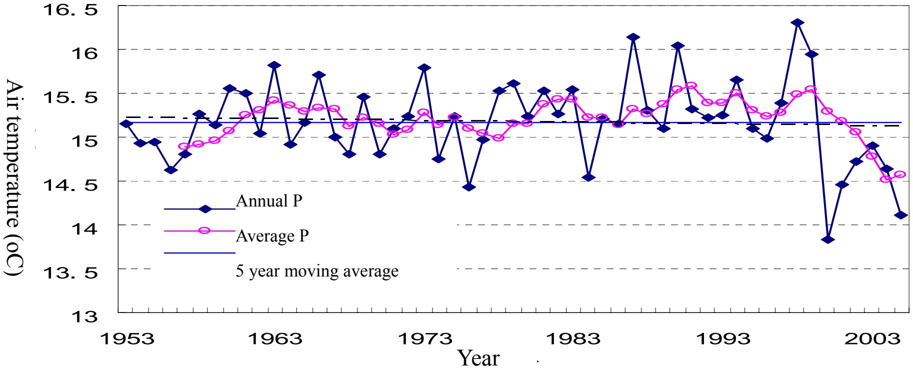

Fig. 7. Annual average and 5-year moving average air temperature in Guiyang city at Upper Changjiang River, 1953–2005.

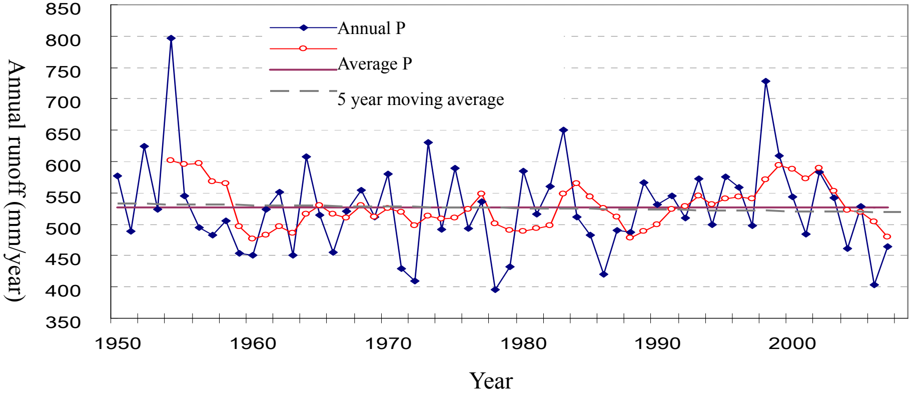

Fig. 8. Annual average and 5-year moving average runoff in Changjiang Rive (gauged at Datong station), 1950–2005.

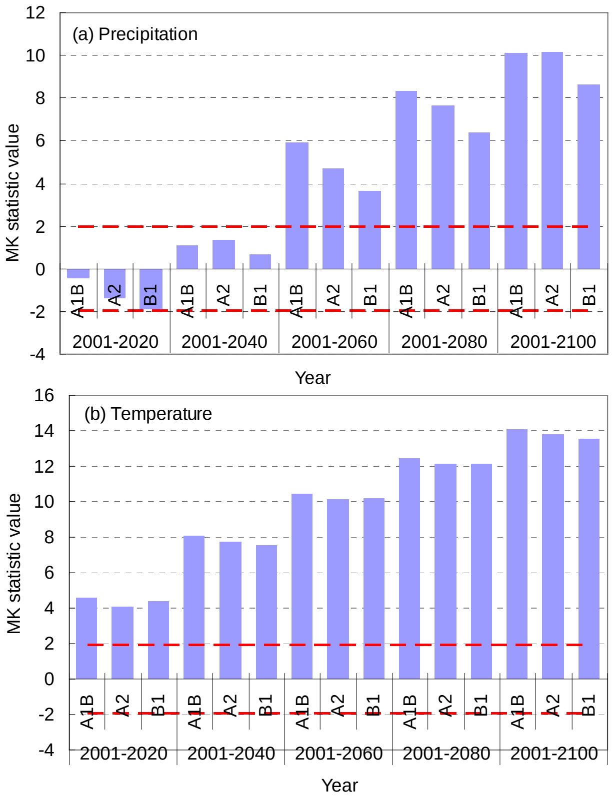

Fig. 9. MK values for **(a)** precipitation and **(b)** temperature for the period of 2001–2100. The MK values represent the change tendency of precipitation and temperature, the dash line indicates the 95% confidence level. The change tendency is considered as significant when the absolute value of MK is larger than 1.96; otherwise, it is insignificant.

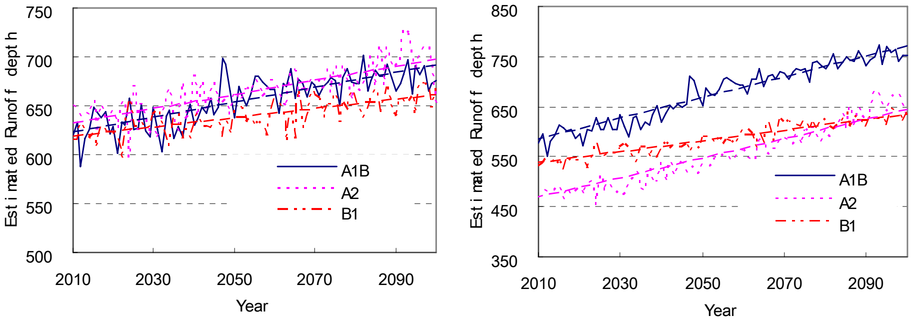

Fig. 10. Estimated yearly runoff at Datong station using statistic model (Right), and simplified water balance models (Left), respectively, over the future periods of 100 years, with three SRES scenarios A1B, A2 and B1 (unit: mm/year).