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ORIGINAL PAPER

Simulation of extreme precipitation over the Yangtze River Basin using Wakeby distribution

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Abstract Based on the daily observational precipitation data at 147 stations in the Yangtze River Basin during 1960–2005 and projected daily data of 79 grid cells from the ECHAM5/ MPI-OM model in the 20th and 21st century, time series of precipitation extremes which contain AM (Annual Maximum) and MI (Munger Index) are constructed. The distribution feature of precipitation extremes is analyzed based on the two index series. Three principal results were obtained, as stated in the sequel. (i) In the past half century, the intensity of extreme heavy precipitation and drought events was higher in the mid-lower Yangtze than in the upper Yangtze reaches. Although the ECHAM5 model still can't capture the precipitation extremes over the Yangtze River Basin satisfactorily, spatial pattern of the observed and the simulated precipitation extremes are much similar to each other. (ii) For quantifying the characteristics of extremely high and extremely low precipitation over the Yangtze River Basin, four probability distributions are used, namely: General Extreme Value (GEV), General Pareto (GPA), General Logistic (GLO), and Wakeby (WAK). It was found that WAK can adequately describe the probability distribution of precipitation extremes calculated from both observational and projected data. (iii) Return period of precipitation extremes show spatially different changes under three greenhouse gas emission scenarios. The 50-year heavy precipitation and drought events from simulated data during 1951–2000 will become more frequent, with return period below 25 years, for the most mid-lower Yangtze region in 2001–2050. The changing character of return periods of precipitation extremes should be taken into account for the hydrological design and future water resources management.

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1 Introduction

In recent decades, a change in mean precipitation has been documented in many regions throughout the world (IPCC 2007). A kind of amplification effect has been noted in the sense that small changes in mean values of precipitation may result in a relatively high increase in the probability of extreme precipitation (Groisman et al. 1999). Amplification effect between precipitation and runoff was noted by Chiew (2006). Besides for significant increasing trend in extreme precipitation observed in last decades in the North America, Europe, Australia, Japan, and other areas (cf. Karl and Knight 1998; Suppiah and Hennessy 1998; Iwashima et al. 2002), experiments with coupled UKHI and CSIRO model result in detection of increasing frequency of occurrence of extreme precipitation under global warming condition as well (Yonetani and Gordon 2001). Simulations by General Circulation Models of the coupled atmosphere–ocean system also indicate that the return periods of heavy precipitation events are expected to be shortened in a warmer climate (Burger 2005; Palmer and Räisänen 2002). As stated in the Fourth IPCC Assessment Report (IPCC 2007), it is very likely that frequency of heavy precipitation events will increase over most areas.

Changes in intensity and frequency of extreme precipitation are very likely to have serious social and economic implications. The modelling of extreme rainfall is essential in design of flood preparedness systems, therein flood protection measures, and in design of system for monitoring climate change (Huff and Angel 1992). Examination of droughts is of concern for water supply systems, agriculture, weather modification, etc. The statistics of extremes refer to the largest (or smallest) values of random variables. It has typically dealt with maximum (or minimum) values from sets of independent observations (Lambert et al. 1994). Usually, hydro-meteorologists fit General Extreme Value distribution (GEV) to historical discharge and rainfall data to estimate the magnitude of maximum value at the various return intervals (Katz et al. 2002; Nguyen et al. 2002; Fowler and Kilsby 2003). Some other frequency distributions, such as Log-normal, Pearson III, Log-Pearson III, etc, are also widely used in several countries (cf. Yue and Hashino 2007) as standard distributions in flood analyses (Sevruk and Geiger 1981). One of the recent developments in statistical modelling of extreme precipitation is in the use of multi-parameter distribution, such as four-parameter Kappa distribution or five-parameter Wakeby distribution (Parida 1999; Park et al. 2001). By suitable choice of parameter values, they can take the form of most underlying two-or three-parameter distributions, hence proving to be more flexible in practical applications.

Statistical distributions have been frequently used to model the series of annual maxima to define extremes with a given return period, but only a few studies have examined the statistical distribution of droughts in a view of dry spell extremes (Lana et al. 2006; Beverly and Martell 2005). The specific objective of this study is to select the best flood-drought frequency model to better estimate the extreme precipitation events over the Yangtze River Basin by using L-moments based on the observation, simulation, and scenario data.

2 Data and methodology

Three sets of daily precipitation data during flood season (April to September) are used in the current study, including observation data for the period 1960–2005 originating from 147 stations provided by China Meteorological Administration, model data for 79 grid cells from ECHAM5/MPI-OM under the climate of the 20th century climate scenarios (1941–2000) and 21st century (2001–2050) SRES scenarios (B1, A1B and A2). Location of the observational stations and projected grid points is plotted in Fig. 1a. The Yangtze River Basin is divided into two main parts with the Yichang hydrological station taken as the boundary: the upper Yangtze reaches (containing five sub-catchments) with 69 stations and the mid-lower Yangtze reaches with 78 stations, as shown in Fig. 1b. This is usually divided further to the middle reaches and the lower reaches with Hukou station as the boundary. From the above-mentioned raw data, time series of annual maximum of daily precipitation (AM index) are constructed to analyze the heavy precipitation events. With reference to the Munger Index (Richard and Heim 2002), another time series of the longest period of consecutive days with daily precipitation below 1.27 mm/d are constructed. The MI index can be used to analyze the rainfall deficits and meteorological droughts.

For quantifying the characteristics of flood-drought events over the Yangtze River Basin, comparative frequency analyses have been carried out to assess the adequacy of frequency distribution models for describing extreme precipitation events. The distributions applied in the current study include: General Extreme Value (GEV), General Pareto (GPA), General Logistic (GLO) and Wakeby (WAK). Two parameter distributions are not considered. Cumulative functions of GEV, GPA, GLO, and quantile function of WAK are defined as Eq. (1–4). It is quite common to use GEV distribution for the analysis of extremes. While, in the case of the extremes exceeding a certain threshold, the alternative to the GEV distribution could be the GPA distribution. If and only if Y follows a generalized Pareto distribution with parameter p not less than 0, then the random variable X=-ln(Y/p–1) is a generalized logistic distribution variable. The WAK distribution is defined by five parameters, more than most of the common systems of distribution. This allows it to mimic the GEV or GPA distribution if parameter values are suitably adjusted. For example, when values of parameter α or γ are equal to 0, WAK exhibits shapes of GPA distribution.

$$F(x) = \begin{cases} \exp\left(-(1+kz)^{-\frac{1}{k}}\right) & k \neq 0 \\ \exp\left(-\exp(-z)\right) & k = 0 \end{cases}$$
$$(domain: 1+kz>0\, for\, k\neq 0; -\infty < x < \infty\, for\, k=0) \qquad (1)$$

$$F(x) = \begin{cases} 1-\left(1+K\left(\frac{X-\mu}{\sigma}\right)\right)^{-\frac{1}{k}} & k \neq 0 \\ 1-\exp\left(-\left(\frac{X-\mu}{\sigma}\right)\right) & k = 0 \end{cases}$$
$$(domain: \mu \leq x < \mu-\sigma/k\, for\, k<0; \mu \leq x < \infty\, for\, k\geq 0) \qquad (2)$$

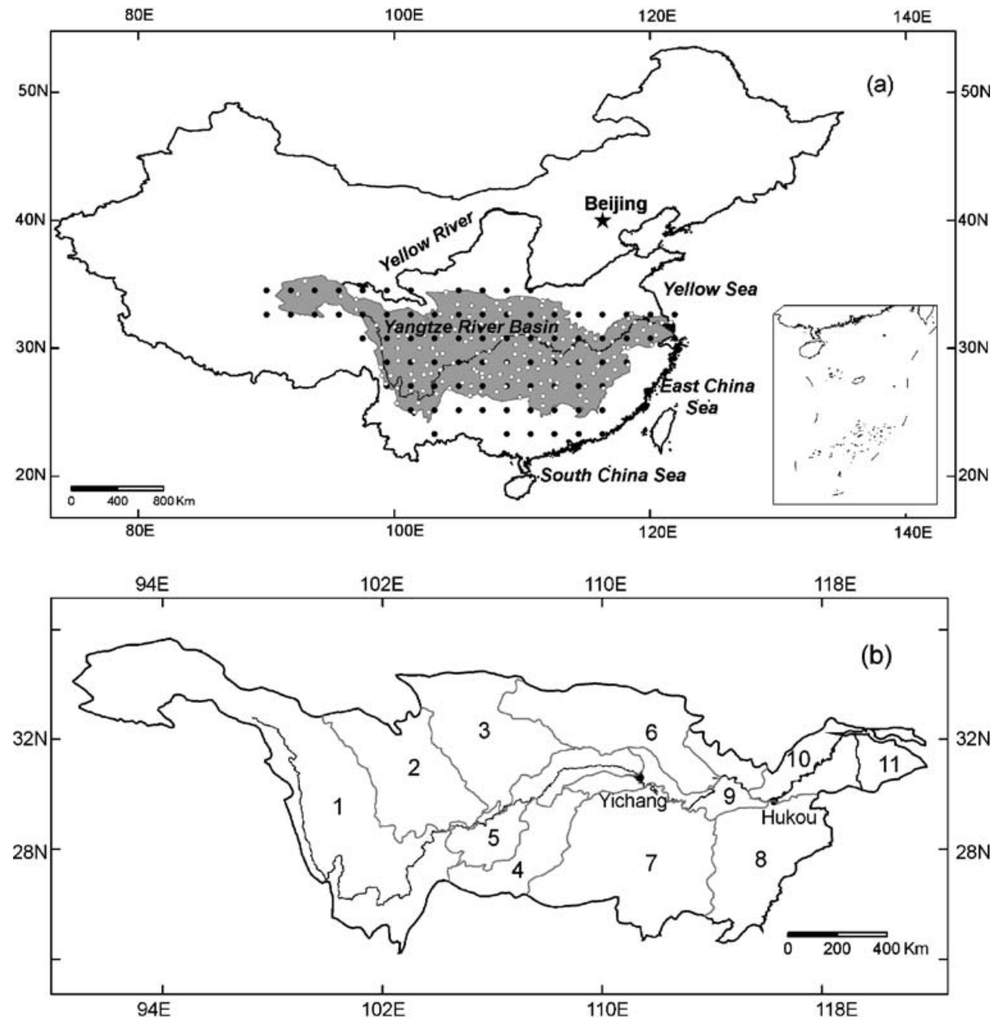


Fig. 1 a Location of observational stations and projected grid points and **b** location of hydrological sub-catchments: *1* Jinshajiang River; *2* Mintuojiang River; *3* Jialingjiang River; *4* Wujiang River; *5* Upper mainstream section; *6* Hanjiang River; *7* Dongting Lake; *8* Poyang Lake; *9* Middle mainstream section; *10* Lower mainstream section; *11* Taihu Lake

$$F(x) = \begin{cases} \frac{1}{1+(1+kz)^{-\frac{1}{k}}} & k \neq 0 \\ \frac{1}{1+\exp(-z)} & k = 0 \end{cases}$$
$$(domain: 1 + kz > 0\, for\, k \neq 0; -\infty < x < \infty\, for\, k = 0) \quad (3)$$

where, $z = \frac{x-\mu}{\sigma}$;k, δ, μ are shape, scale and location parameters, respectively); and

$$x(F) = \xi + \frac{\alpha}{\beta}\left(1 - (1-F)^{\beta}\right) - \frac{\gamma}{\sigma}\left(1 - (1-F)^{-\sigma}\right)$$
$$(domain: \xi \leq x < \infty\ if\ \sigma \geq 0\ and\ \gamma > 0; \xi \leq x < \xi + \alpha/\beta + \gamma/\sigma\ if\ \sigma < 0\ or\ \gamma = 0) \quad (4)$$

The distribution parameter can be conventionally estimated based on the available sample data by the method of moments (MOM), maximum likelihood estimator (MLE), probability weighted moments (PWM), or L-moment estimator (LME). Previous studies show that parameter estimates from small samples computed by using the PWM method are less complicated and yet sometimes more accurate than the MLE method. Also, with some distributions, explicit expressions for the parameters can be obtained by the PWM method, but not the MLE or the MOM method. In addition, procedures based on the PWM and the LME are equivalent, but the LME method (cf. Chen et al. 2006) is more convenient because it directly provides measures of the scale and of the shape of the probability distribution (Hosking 1990; Rao and Hamed 1994). Thus, we apply the LME approach to the case of the Yangtze River Basin, which is known as a river with very high precipitation variability. L-moments are calculated by equation:

$$L_{t+1} = \sum_{k=o}^{t} \beta k(-1)^{t-k} \binom{r}{k}\binom{r+k}{k} \tag{5}$$

$$where, \binom{r}{k} = \frac{r!}{k!(r-k)!} \quad r \geq k; \tag{6}$$

$$\beta k = \frac{1}{n}\sum_{i=1}^{n-k} \frac{\binom{n-i}{k}}{\binom{n-l}{k}} xi \tag{7}$$

For any distribution, the first four L-moments can be deduced from

$$\begin{cases} L_1 = \beta 0 \\ L_2 = 2\beta 1 - \beta 0 \\ L_3 = 6\beta 2 - 6\beta 1 + \beta 0 \\ L_4 = 20\beta 3 - 30\beta 2 + 12\beta 1 - \beta 0 \end{cases} \tag{8}$$

The λ mean, λ_1 is a measure of central tendency, λ standard deviation, λ_2 is a measure of dispersion. The L-moment ratios are defined to be

$$\begin{cases} t_2 = \frac{L_2}{L_1} \ (L - coefficient) \\ t_3 = \frac{L_3}{L_2} \ (L - skewness) \\ t_4 = \frac{L_4}{L_2} \ (L - kurtosis) \end{cases} \tag{9}$$

In order to select a robust distribution for extreme precipitation events over the Yangtze River Basin, a goodness-of-fit test can be applied, which examines whether a sample comes from a population with a specific distribution. The Kolmogorov-Smirnov (KS) test is used to measure the compatibility of a random sample with a theoretical probability distribution function. Frequency analysis is conducted for each station (and grid cell containing this station). For every individual station, there are observational data from 1961–2000, simulated data from 1951–2000, and scenario data from 2001–2050, i.e., 40, 50, and 60 years of data, respectively. With significance level α=0.1, and sample size n=40 and n=50, critical values of KS statistics are D=0.193 and D=0.173, respectively.

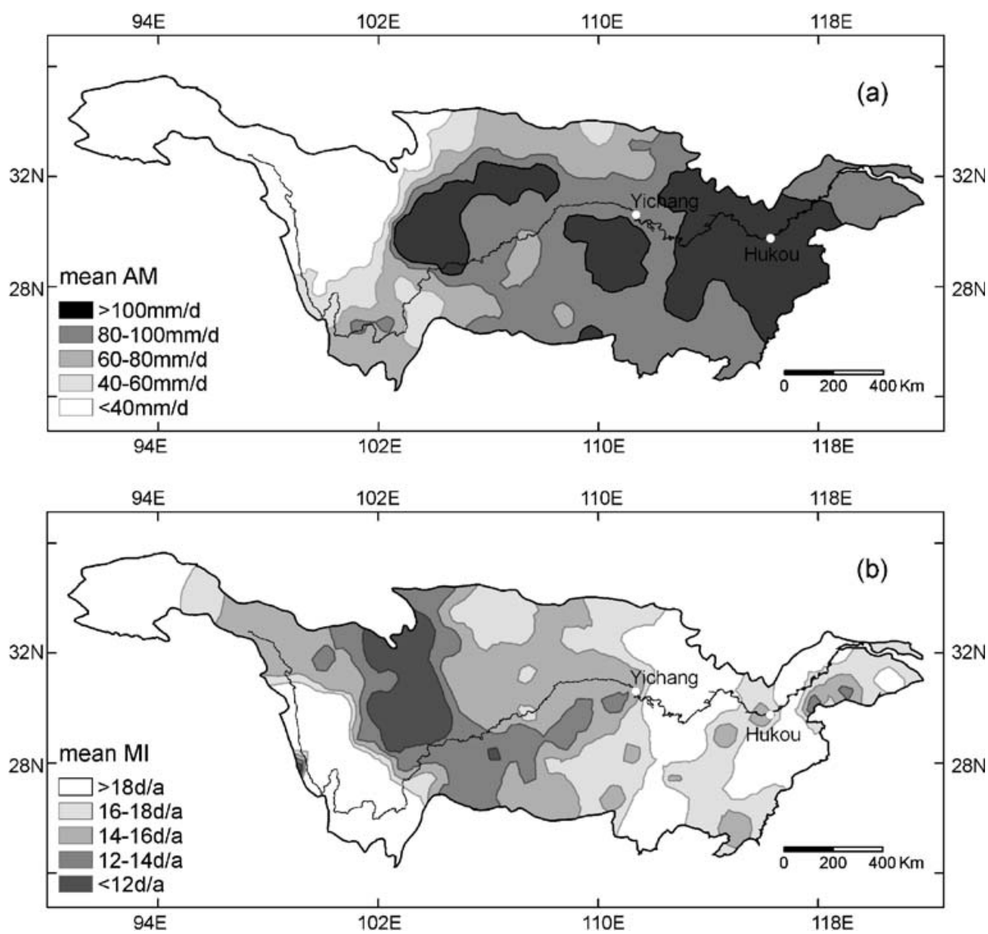


Fig. 2 Spatial distributions of observed precipitation extremes over the Yangtze River Basin. **a** mean AM; **b** mean MI

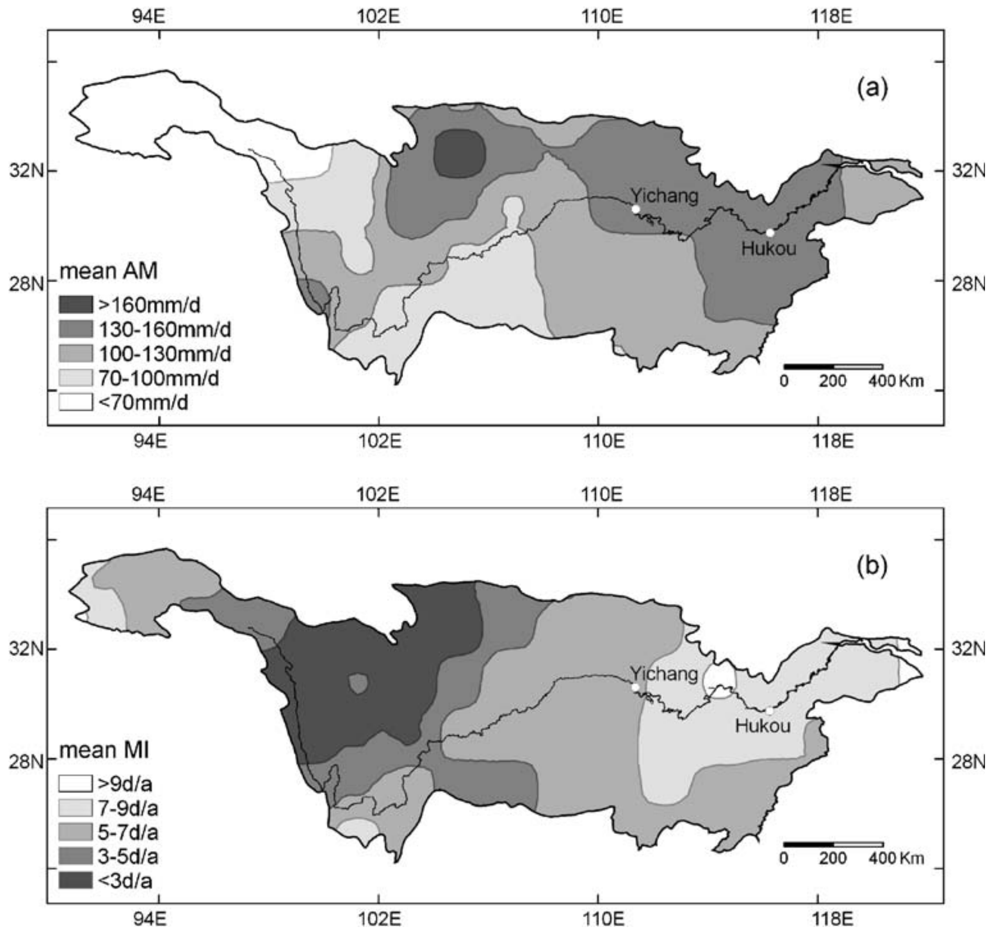


Fig. 3 Spatial distributions of simulated precipitation extremes over the Yangtze River Basin. **a** mean AM; **b** mean MI

Table 1 Distribution accepted by KS goodness of fit test (distributions computed from AM and MI series at 147 observational stations and 79 projected grids in the Yangtze River Basin)

Series	Test statistic	Distribution model	Observation	Simulation	Scenario B1	Scenario A1B	Scenario A2
AM	<0.09	GEV	118	69	72	70	71
		GL0	105	65	68	63	64
		GPA	85	46	52	42	51
		WAK	130	78	76	72	73
	<0.17	GEV	147	79	79	78	78
	(<0.19)	GL0	147	79	78	79	79
		GPA	147	79	79	78	78
		WAK	146	78	77	78	77
MI	<0.09	GEV	115	6	3	6	4
		GL0	98	3	4	2	2
		GPA	52	3	3	8	4
		WAK	127	9	6	14	10
	<0.17	GEV	146	63	64	64	69
	(<0.19)	GL0	147	62	63	61	65
		GPA	147	64	64	64	63
		WAK	146	64	65	64	66

Of the four distributions, WAK distribution is the most robust distribution as regards the model with the lower value of K-S statistic. For example, differences between the theoretical WAK distribution and the experimental distribution in AM series are below 0.09 for 88% of the observational stations and 99% of the simulated grids, as compared to about 80%, 71%, and 58% of the stations, and 87%, 82%, and 58% of the grids, respectively, for GEV, GLO and GPA distribution. Same distribution fitting results also can be obtained for AM series from future scenarios and MI series from observational, simulated and scenario data

3 Variability of precipitation extremes

The spatial distributions of the observed AM and MI indices are displayed in terms of arithmetic mean for 1961–2000, employing the inverse-distance weighted interpolation to the station data (Fig. 2a,b). Mean AM is higher over the eastern Yangtze than over the western Yangtze. In most parts of the mid-lower Yangtze reaches it exceeds 80 mm/d, while in the western parts of the upper Yangtze reaches it is below 60 mm/d. There are three local areas of heavy precipitation, with AM exceeding 100 mm/d, located: (i) around the mid-lower Mintuojiang and Jialingjiang sub-catchment in the upper Yangtze reaches; (ii) over the Dongting Lake area; and (iii) over the Poyang Lake area and the main stream section in the mid-lower Yangtze reaches (Fig. 2a). According to the spatial pattern of MI, the drought situation is less severe in the upper reaches than in the mid-lower reaches. Except for Jinshajiang sub-catchment, MI is below 16 d/a over the upper reaches and the lowest value located at the Mintuojiang sub-catchment, below 12 d/a, while for most parts of the mid-lower reaches, MI exceeds 16 d/a. Three longitude-orientated drought centers with MI above 18 d/a are located (i) at the upper and the lower Jinshajiang sub-catchment; (ii) at the lower Hanjiang sub-catchment, the middle main stream section and the Dongting Lake sub-catchment; and (iii) over the lower main stream section and the Poyang Lake sub-catchment (Fig. 2b).

Evaluation of the hydrological cycle in the ECHAM 5 model was conducted by Hagemann et al. (2006) by comparing model simulations with observational data in a number of catchments, which shows that the precipitation bias is below 10% in 50% of all catchments. Despite larger errors (about 35% averaged over the basin) was found in the precipitation over the Yangtze River Basin simulated by ECHAM 5, simulation results from other GCM, such as HadCM, also display the similar trend in this region (Xu 2005). The differences between simulated values and observed records have shown that the ECHAM5/MPI-OM model still cannot capture the precipitation extremes over the Yangtze River Basin in a satisfactory way, but the model projections constitute a theoretical background for studying the climate change. Figure 3 presents the calculated AM and MI pattern from the ECHAM5/MPI-OM simulation series for the climate of the late 20th century (1961 to 2000). It can be seen from Fig. 3a that higher values of simulated AM are clustered at the upper Mintuojiang and Jialingjiang sub-catchment in the upper

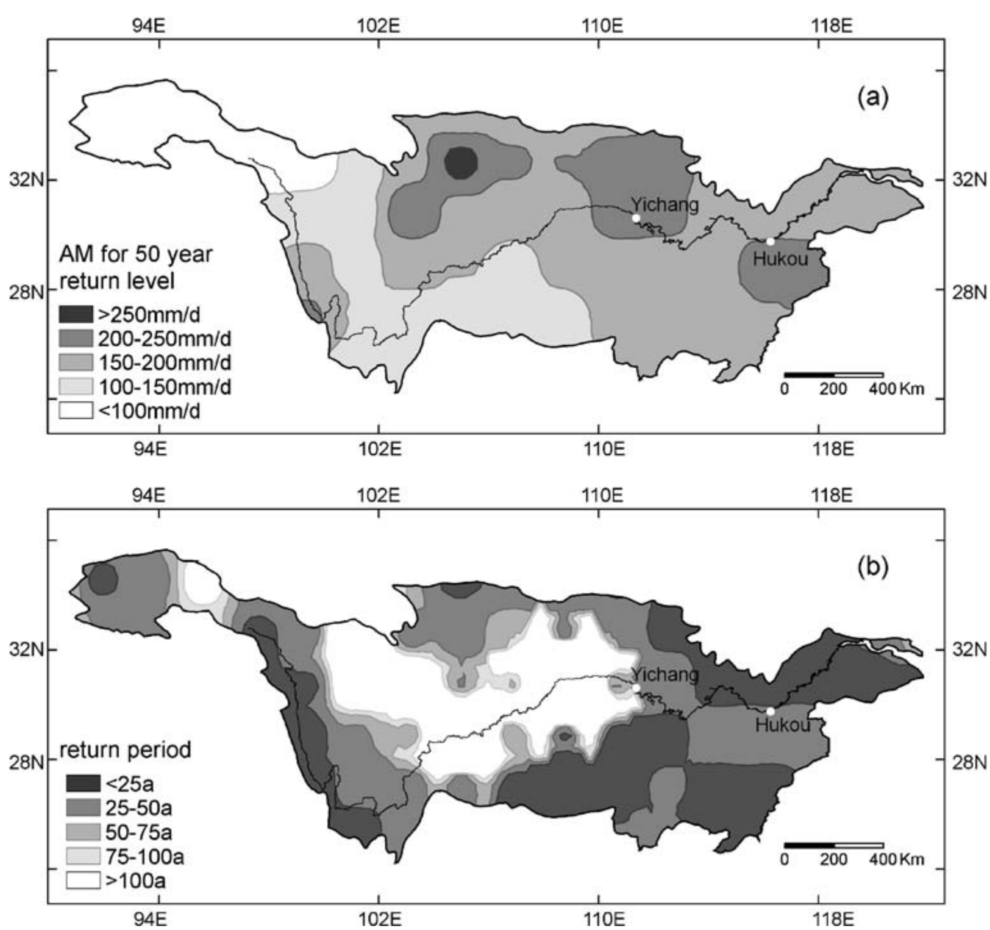
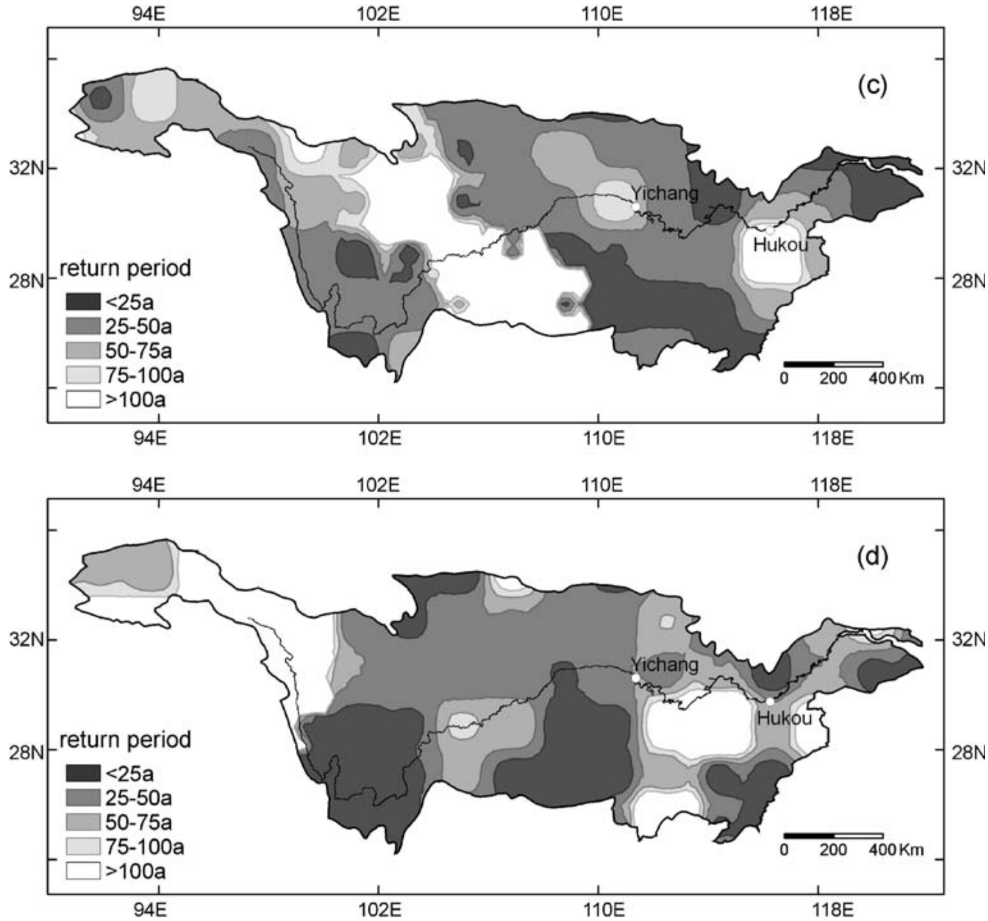


Fig. 4 Return period of extremely heavy precipitation in 2001–2050 corresponding to 50-year events in 1951–2000 over the Yangtze River Basin. **a** 50-year events in 1951–2000; **b**, **c**, **d** Return period of extremely heavy precipitation in 2001–2050 under SRES scenario B1, A1B, and A2

Fig. 4 (continued)



Yangtze reaches; the Hanjiang sub-catchment, the main stream section, and the Poyang Lake area in the mid-lower Yangtze with intensity above 130 mm/d. Lower AM values are clustered in the headwater area, where maximum intensity drops below 70 mm/d. As for simulated MI (Fig. 3b), rainfall deficits last longer at the upper and the lower Jinshajiang sub-catchment in the upper Yangtze reaches and in the mid-lower Yangtze reaches with values above 7 d/a. On the other hand, rainfall deficits are weaker around the northwestern upper Yangtze reaches, including the mid Jinshajiang sub-catchment and the Mintuojiang sub-catchment, with values less than 3 d/a on the average.

Comparing Figs. 2 and 3, one can state that the general geographical distribution of simulated extreme precipitation conforms to that of observational pattern, e.g., higher AM in the east, the lowest AM at headwater area; higher MI at the northeast, southwest and headwater area, the lowest MI at the northwestern Yangtze. However, in quantitative terms, the mean AM value from the ECHAM5/MPI-OM model projections is much higher while the mean MI value is much lower than the observational data and location of the heavy precipitation centers and drought centers are shifted in the north-south direction.

4 Distribution fitting

The selection of an appropriate frequency distribution for extreme precipitation over the Yangtze River Basin is made with an aim to identify a distribution that best fits the observed, simulated, and scenario data. The best fit is determined by measuring the distance between the theoretical distribution and the experimental distribution defined by the KS goodness-of-fit test.

As summarized in Table 1, results of KS test for all four distributions (GEV, GLO, GPA and WAK) used to describe extreme precipitation over the Yangtze River Basin are close to each other. Nearly all of them represent the probability distribution of AM precipitation series with sufficient accuracy. However, for MI series, they fit well to the observational data, but do not fit to about 20% of the projected grid data at 0.1 significance levels.

5 Application of WAK model to Yangtze extreme precipitation

For showing the changes in intensity of extreme events, return levels of 50-year extreme precipitation in 2001–2050 are compared to those for the period 1951–2000. This was done by using the parameters estimated by L-moment method based on the AM, MI series from simulated and scenario data. At first, the 50-year return level for 1951–2000 was estimated and then a corresponding return period in 2001–2050 was determined.

Figure 4a is the interpolation of estimated return levels for 50-year return period for AM time series in 1951–2000 at each grid. The 50-year return levels of AM during 1951–2000 are less than 150 mm/d over most parts of the western upper Yangtze. In the headwater area, they are below 100 mm/d. The high return levels are found at northern and southeastern Yangtze with intensity above 200 mm/d (Fig. 4a). Future behavior of AM as shown by Fig. 4b–d indicates that the projections of heavy precipitation differ under various scenarios. The 50-year heavy precipitation from the control period is projected to occur more frequently in the mid-lower reaches and the Jinshajiang sub-catchment in the upper reaches, and less likely to occur at the central and northwestern Yangtze during 2001–2050 under the B1 and A1B scenarios. This finding agrees with the trends of extreme precipitation observed in the last few decades in an earlier study (Su et al. 2005). In the northeastern Yangtze, the southern Yangtze, and the southwestern Yangtze, the return period of 50-year events in the control period is projected to change to less than 25 years. This means that in these regions extreme heavy precipitation that rarely occurred in the past are projected to occur at a higher rate in the future (Fig. 4b–c). Under the A2 scenario, geographical distribution of the 50-year return period of AM during 1951–2000 exhibits different spatial pattern than these of the B1 and A1B scenarios. It can be seen from Fig. 4d that heavy precipitation is projected to occur more frequently in the south and southwestern Yangtze, but not in the mid-lower Yangtze reaches (Fig. 4d). Despite the uncertainty of projection, one can deduce from the simulated and scenario data that the area frequently stricken by extremely heavy precipitation is likely to be enlarged in the future.

The drought events with return period of 50 years in 2001–2050 were compared to the 1951–2000 period. Measured by the MI index, they are higher in the mid-lower Yangtze reaches than the upper reaches. The value of MI is high in the northeastern Yangtze Basin with drought period of more than 20 days, whereas in the northwestern Yangtze Basin it is less than five days (Fig. 5a). Future behavior of MI shown in Fig. 5b–d indicates that return periods corresponding to 50-year events in the control

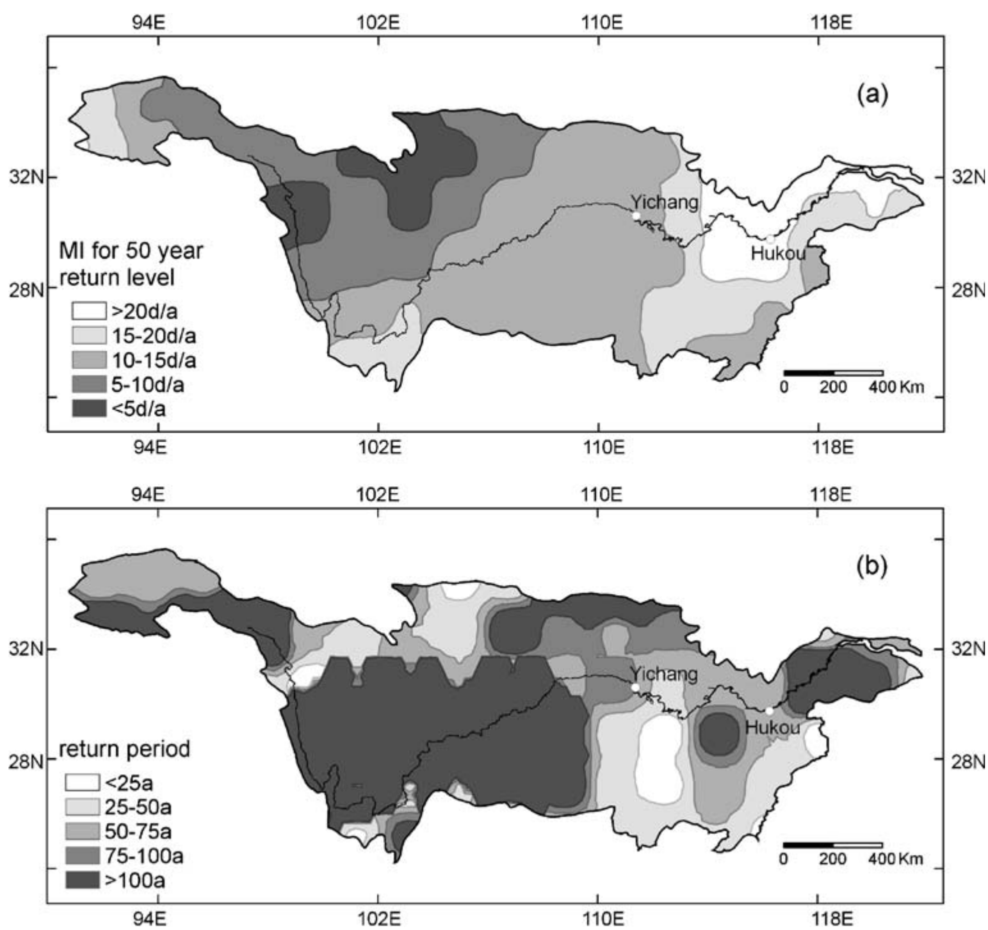
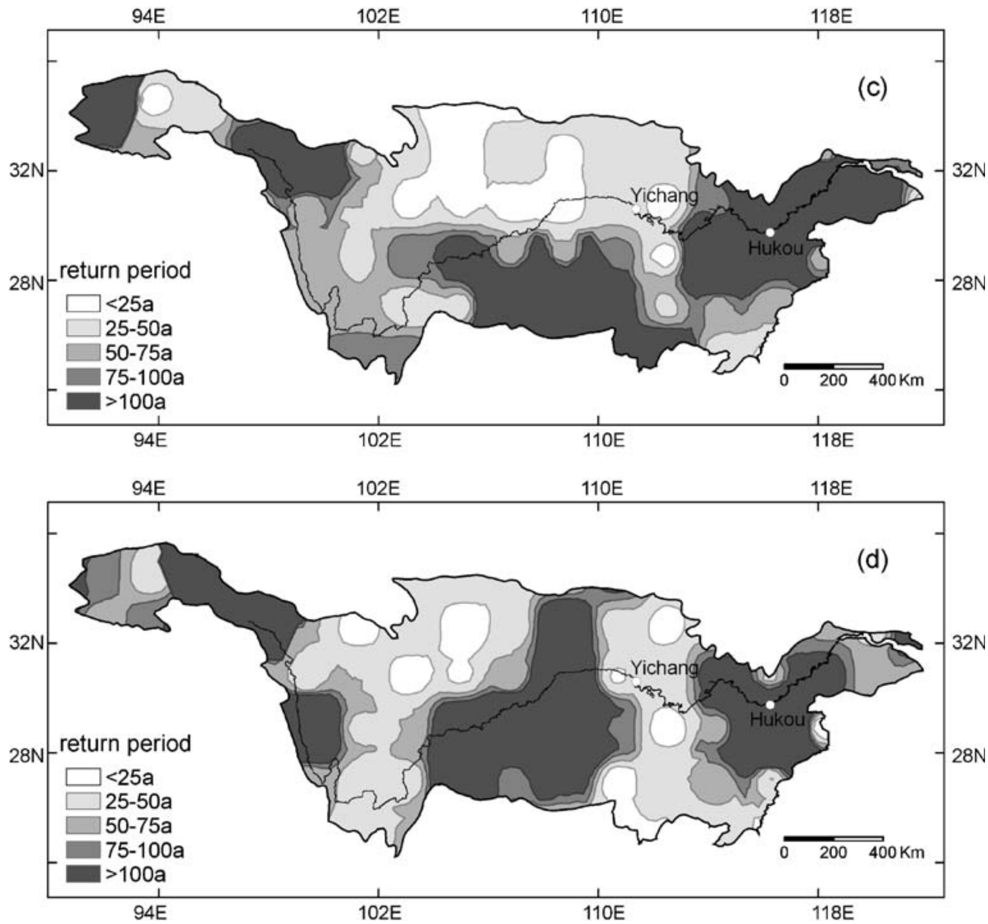


Fig. 5 Return period of drought events in 2001–2050 corresponding to 50-year events in 1951–2000 over the Yangtze River Basin. **a** 50-year events in 1951–2000; **b**, **c**, **d** Return period of drought events in 2001–2050 under scenario B1, A1B, and A2

Fig. 5 (continued)



period for the three scenarios are shortened in the northeastern Yangtze where drought intensity is higher than in the surrounding area. This means that the drought hazard will be aggravated in this region. But obvious shortening of the return period is also projected to take place in the southeastern Yangtze Basin (under scenarios B1 and A2), the northern and the northwestern Yangtze Basin (under scenario A1B) and the southwestern Yangtze Basin (under scenarios A1B and A2). The higher frequency of occurrence of drought events in the northern and the southeastern Yangtze Basin (corresponding to the Hanjiang sub-catchment and Poyang Lake sub-catchment in the mid-lower reaches) and the southwestern Yangtze where MI intensity is comparatively high, and shortening of return period marks the increase of drought hazard in the future. On the other hand, at a large area in the south and southwestern Yangtze region, return period of the 50-year event from the control period will grow to more than 100 years.

6 Concluding remarks

Changes in precipitation over the Yangtze River Basin are of primary importance for the national economy and various aspects raise considerable interest, cf. quasi periodicities of extreme precipitation (Becker et al. 2007) and climate shift–nonstationarity of precipitation (Qian and Qin 2007). Distribution character and changes of precipitation extremes over the Yangtze River Basin are analysed based on the observations, simulations, and projections for the last and the future half century. Time series of maximum daily precipitation (AM) and longest period of consecutive days with low rainfall (MI) within each year are constructed to define the records of heavy precipitation and precipitation deficit. In this way, the number of data points is equal to the total number of years, so that one can calculate the frequency distribution for each observational station or for each grid cell of projections. The following conclusions are drawn from the current study:

(i) The GCM-scenario simulation for 1961–2000 is compared to climate observation data in same period to validate the capability of ECHAM5 to capture precipitation extremes over the Yangtze River Basin. In general, intensity of extremely heavy precipitation and severity of precipitation deficit are more severe in the mid-lower Yangtze reaches than in the upper reaches.

(ii) According to the KS goodness-of-fit test, five-parameter WAK distribution proves to be a robust distribution for fitting to the observation, simulation and scenario data. Although the other three candidate distribution GEV, GLO, and GPA can be also accepted at the 0.1 significance level, the WAK model yields the minimum value of the K-S statistic.

(iii) The return period of precipitation extremes will obviously change in the next half century, possibly with some differences in regional behavior. The 50-year heavy precipitation events during 1951–2000 are projected to become more frequent (becoming 25-year events) at most parts of the mid-lower Yangtze reaches under scenario B1 and A1B, and at the south and southwestern Yangtze under scenario A2, which indicate that the possibility of increase of the flood hazard and flood risk during 2001–2050. Meanwhile, the 50-year precipitation deficits during 1951–2000 will become more than 75-year, even more than 100-year events at the northeastern Yangtze where drought intensity was highest in the past century. This indicates that the severity of droughts is projected to be alleviated in this region. But more frequent occurrence of drought events at the northern Yangtze, the southeastern Yangtze and the southwestern Yangtze basins where MI intensity is relatively high, increases the future drought. The changing character of return levels of precipitation extremes should be taken into account in the future water resources management.

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