Journal of the Meteorological Society of Japan, Vol. 85, No. 5, pp. 599–613, 2007

Modeling Annual Extreme Precipitation in China Using the Generalized Extreme Value Distribution

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(Manuscript received 27 April 2006, in final form 12 June 2007)

Abstract

Extreme precipitation events are the major causes of severe floods in China. In this study, four time series of daily, 2-day, 5-day, and 10-day annual maximum precipitation from 1951 to 2000 at 651 weather stations in China were analyzed. The generalized extreme value (GEV) distribution was used, to model the annual extreme precipitation events at each station. The GEV distribution was also modified to explore the linear temporal trends in the extreme events. The results showed that more than 12% of the stations have significant (p-value < 0.10) linear trends. Decreasing trends are mainly observed in northern China, and increasing trends are observed in the Yangtze River basin and northwestern China. The return periods of extreme precipitation have changed for stations with significant temporal trends. The 50-year event observed in parts of the Yangtze River basin, and northwestern China during 1951–60, has become a more frequent 25-year event in the 1990s. The spatial distribution of the return levels of the 651 stations are closely related to the climatic mean precipitation, and are influenced by the East Asian summer monsoon system (return levels are measures of extremity—for example, a 10 year return level is the value that can be expected to be exceeded on average once in every 10 years). The return period of extreme precipitation, that caused the 1998 severe floods in the Yangtze River basin, was also evaluated from a probabilistic perspective.

1. Introduction

Variations in frequency, and intensity of extreme weather events, greatly affect the human societies and their environments (Kunkel et al. 1999). During the past 50 years, there have been frequent extreme precipitation events causing severe floods and damaging the economy and environment in China. For example, more than 30,000 lives were lost in the catastrophic flooding in 1954 in the Yangtze River basin (NCDC 1998). The 1998 floods in the Yangtze River and northeastern China drove

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14 million people from their homes, affected a total of 240 million people, destroyed 5 million houses, damaged 12 million houses, and destroyed 25 million hectares of farmland (NCDC 1998). More than 3,000 people lost their lives in the 1998 floods, and the estimated total economic losses were over $36 billion (NCC 1998; Zong and Chen 2000).

The fast growing population, and industrialization in major river basins in China in the recent decades appear to have elevated the damage potentials of extreme precipitation, as well as other natural disasters (Zong and Chen 2000). It is thus of great importance to analyze the variation of extreme precipitation in China. In general, there are two approaches used to assess the extreme precipitation. The first approach uses a percentile, or quantile method, to assess extreme precipitation (e.g., Easterling et al. 2000; Karl and Knight 1998; Zhai et al. 1999, 2005). In this approach, daily precipitation records are sorted according to the intensity (e.g., 50 mm/day) and classified to contain a certain percentage of precipitation events for a year (or a season). The second approach uses statistical distributions to define extremes with given return periods on an annual basis (e.g., Fowler and Kilsby 2003; Hennesey et al. 1997). In this approach, statistical distributions are used to model the annual maxima series. This method produces various return periods of the annual maxima that are easily understood and can be used for flood mitigation and control (Fowler and Kilsby 2003; Guttman et al. 1994; Hennesey et al. 1997). The first approach has been frequently used to analyze the changes of extreme precipitation in China (e.g., Gong et al. 2004; Zhai et al. 1999, 2005). There are no studies, however, that have examined the statistical distribution of extreme precipitation in China.

The statistical distributions have long been applied to time series of climate extremes. Estimation of return levels is usually based on three extreme value distributions—Gumbel, Frechet, and negative Weibull—suggested by Fisher and Tippet (1928) for stochastic behavior of large samples. In this study, we use the generalized extreme value (GEV) distribution, which has all the flexibility of the above three extreme value distributions (Jenkinson 1955). The GEV distribution has been successfully used to model the extreme precipitation events for many countries and regions (Fowler and Kilsby 2003; Gilleland and Katz 2006; Katz et al. 2002; Nadarajah 2005; Nadarajah and Choi 2003; Nguyen et al. 2002). Other statistical distributions, such as Wakeby and Kappa distributions have also been used to model the summer extreme rainfall in Korea (Park et al. 2001; Park and Jung 2002). However, as argued by Nadarajah and Choi (2003), there is no theoretical justification to model annual maximum daily rainfall, by either the Wakeby or Kappa distribution, although, in practice, they may provide a reasonable fit.

In this study, we provide the first application of the GEV distribution to model annual extreme precipitation events in China. Data used were from a newly developed high quality dataset, that provides a much denser network, and covers longer periods (Feng et al. 2004). The GEV distribution is also modified to explore the temporal non-stationarity in extreme precipitation events. Several return levels, and the corresponding confidence intervals, are derived by the maximum likelihood and delta methods. The results from this study can be used for design purposes and for flood preparedness and control. The paper is organized as follows. The data used in this study is described in Section 2. Modeling techniques and their results are presented in Sections 3 and 4, respectively. A case study on the 1998 extreme precipitation that caused the severe flood in the Yangtze River basin is presented in Section 5. Section 6 contains the conclusions.

2. Data

Daily precipitation in mainland China for the period 1951–2000 was obtained from a recent developed comprehensive daily meteorological dataset (Feng et al. 2004). The dataset contains 726 stations that have long-term precipitation observations. The data had been subjected to a series of quality control, which includes homogeneity testing and adjustments to assure their reliability (Feng et al. 2004). To screen out the stations with a large amount of missing values, the following criteria were applied to each station: 1) If a year has missing precipitation for more than 10 days, that year is considered as having inadequate observations and was removed; 2) Stations that contain less than 30 years of inadequate data were excluded; and,

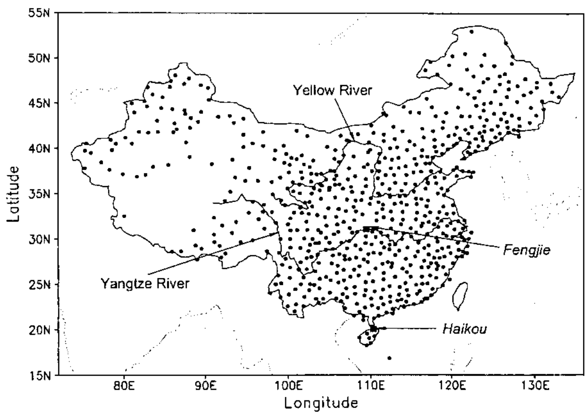

Fig. 1. Geographical distribution of the 651 meteorological stations in China. The squares indicate the stations that have been used for Figs. 2–3.

3) Stations that were identified inhomogeneous were excluded. These screenings ensure that the data used are sufficient for the extreme precipitation modeling. There are 651 stations whose data met this set of criteria. The spatial distribution of those 651 stations is shown in Fig. 1.

Extreme precipitation is usually defined as the maximum daily precipitation within each year, so one would have as many extreme values as the total number of years. This has been the traditional method, known as the block-maxima method, for defining extreme values (Gumbel 1958). Extreme precipitation events in China frequently extend over two days due to the influence of typhoons. Since the measurement of daily precipitation at each station is based on the calendar day, the extreme precipitation may not be well captured by using only annual maximum daily precipitation. In addition, recent severe floods in China are usually caused by multi-day extreme precipitation events (NCC 1998). Therefore, in addition to the annual maxima of daily precipitation (denoted as AM1), annual maxima were extracted from 2-, 5- and 10-day moving sums of precipitation at each station to construct the time series of annual maxima of 2-, 5- and 10-day precipitation (denoted as AM2, AM5 and AM10, respectively). Similar aggregations have been used in other studies (e.g., Ferro and Porto 1999; Fowler and Kilsby 2003).

Figures 2 and 3 show the variations of annual extreme precipitations for the period 1951–2000 for two typical stations (Haikou 59758, 110°21′E, 20°02′N and Fengjie 57348, 109°30′E, 31°03′N) in China. The variations of extreme precipitation at the two stations represent the tropical and humid climate conditions, respectively. The AM1 from Haikou are usually over 200 mm, mainly due to typhoon landfall. Figure 3 shows that the extreme precipitation in *Fengjie* has been increasing for the past 5 decades. One of the aims of this study is to model these types of non-stationarity in the extreme precipitation events.

3. Methodology

The cumulative distribution function of the GEV distribution is given by:

$$F(x) = \exp\left\{-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1/\xi}\right\},$$
$$1+\xi(x-\mu)/\sigma > 0 \tag{1}$$

where μ, σ and ξ are the location, scale, and shape parameters, respectively. A particular case of Eq. (1) for $\xi \to 0$ is the Gumbel distribution:

$$F(x) = \exp\left\{-\exp\left(-\frac{x-\mu}{\sigma}\right)\right\},$$
$$-\infty < x < \infty. \tag{2}$$

The cases with $\xi > 0$ and $\xi < 0$ are known as the Frechet, and the negative Weibull distributions, respectively. The parameter ξ is usually greater than zero for precipitation data, although sometimes the Gumbel distribution is adequate.

Suppose $x_1, \ldots, x_n$ denote the annual maxima of AM1 (or AM2 or AM5 or AM10) for n years at a given station. The method of maximum likelihood is used to fit Eq. (1) to these data. Assuming independence of the data, the likelihood is the product of the densities of Eq. (1) for the observations $x_1, \ldots, x_n$. Mathematically,

$$L(\mu,\sigma,\xi) = \frac{1}{\sigma^n}\prod_{i=1}^{n}\left(1+\xi\frac{x_i-\mu}{\sigma}\right)^{-(1/\xi+1)}$$
$$\times \exp\left\{-\sum_{i=1}^{n}\left(1+\xi\frac{x_i-\mu}{\sigma}\right)^{-1/\xi}\right\}. \tag{3}$$

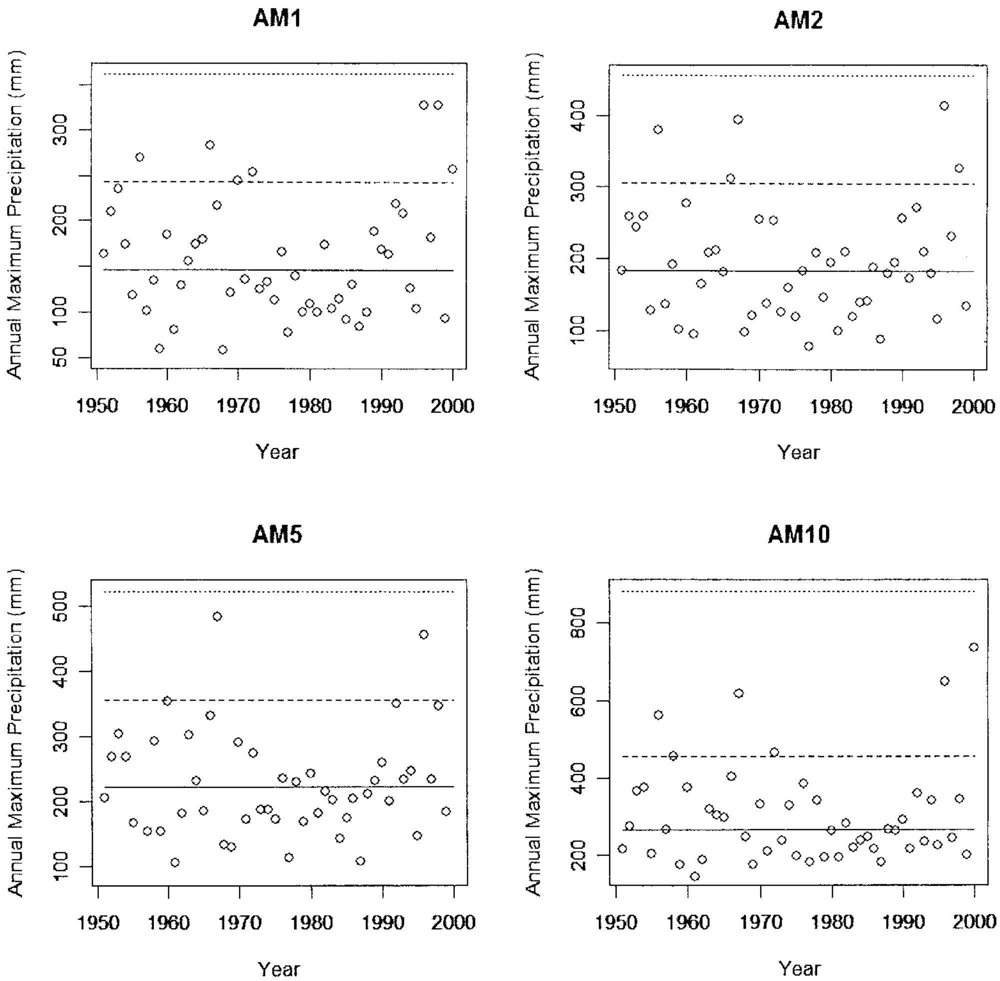

Fig. 2. Time series of AM1, AM2, AM5, and AM10 for station Haikou (59758). The solid, dashed and dotted lines indicate the median, 10-year return level and the 100-year return level, respectively.

Estimates of μ, σ, and ξ—say $\hat{\mu}$, $\hat{\sigma}$, and $\hat{\xi}$—are taken to be those values which maximize the likelihood L. This maximization was performed using a quasi-Newton iterative algorithm (Ihaka and Gentleman 1994). The standard errors of the estimates were computed by inverting the Fisher information matrix (Prescott and Walden 1980).

The basic model fitted was the GEV [or Eq. (1)] with μ, σ, and ξ constant (to be referred to as M1). As mentioned above, sometimes the Gumbel distribution gives as good a fit as the GEV for precipitation data, so we also fitted Eq. (2) with μ and σ constant (to be referred to as M0). M0 is a submodel of M1, and a standard way to determine the better fitting model is the likelihood ratio test (Wald 1943). If L_1 is the maximum likelihood of M1, and L_0 is the maximum likelihood of M0, then under the simpler model the test statistic $\lambda = -2\log(L_0/L_1)$ would be assumed to be distributed as a chi-squared random variable, with 1 degree of freedom (since the numbers of parameters differ by 1). In hypothesis testing problems this would be asymptotically true as the number of data approaches to infinity. Thus, at the 90% significance level ($p < 0.10$), the simpler two parameter model (M0) would be preferred if $-2\log(L_0/L_1) < \chi^2_{1,0.90} = 2.71$. In practice, because of the lack of complete independence of the annual maxima, this would probably have to be interpreted conservatively.

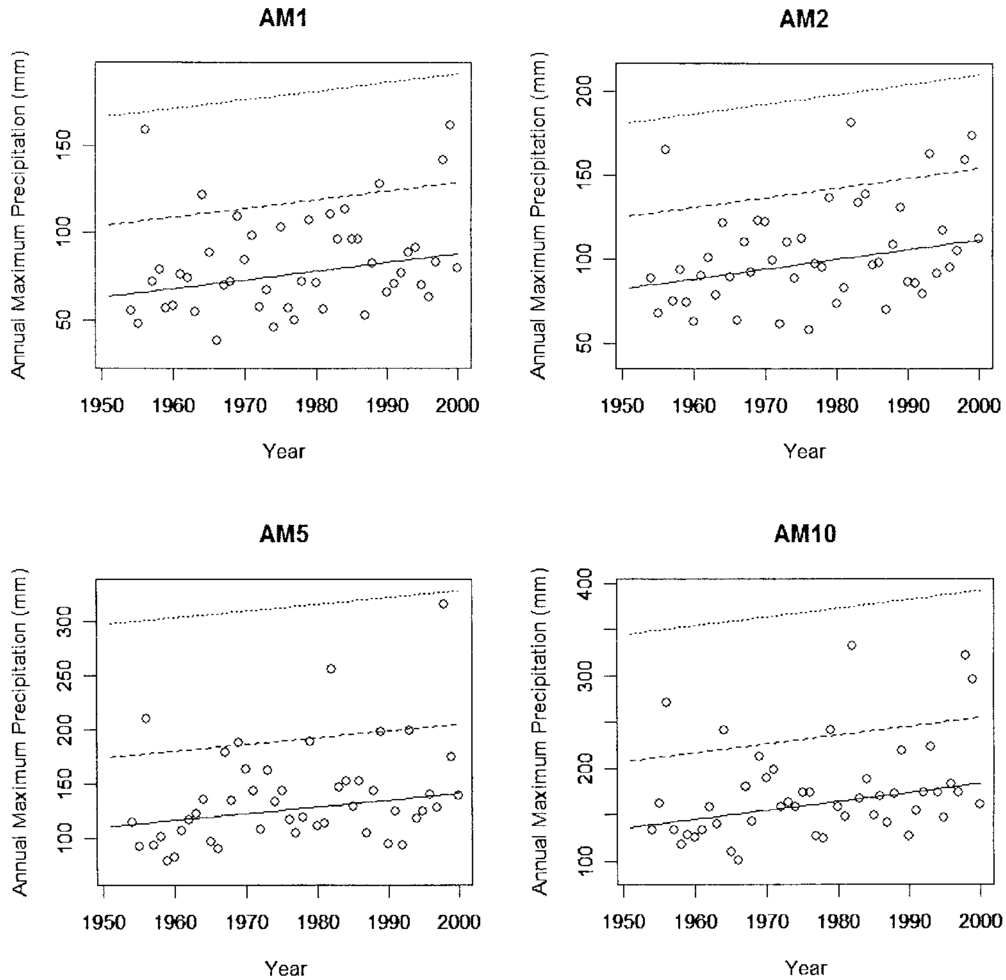

Fig. 3. Same as Fig. 2, but for Fengjie (57348).

Extreme precipitation could possibly exhibit trends, with respect to time for some of the stations (such as Fengjie, see Fig. 3). To investigate the temporal non-stationarity in extreme precipitation events, the following variation of M1 is used to investigate the linear trend in the extreme precipitation events:

M2: $\mu = a + b \times (\text{Year} - t_0 + 1)$, $\sigma = \text{const}$, $\xi = \text{const}$, a four-parameter model with μ allowed to vary linearly with time. In this model, t_0 denotes the year the records started (for example, $t_0 = 1951$ for Fengjie). A negative (positive) b would mean that the extreme precipitation events have a decreasing (increasing) trend for the past 5 decades.

The standard likelihood ratio test was used to determine whether the trends described by M2 were significant or not. If M2 is determined as the best fitting model for a given station, the extreme precipitation events at that station would have a significant trend ($p < 0.10$) for the past 50 years.

The goodness of fit of models M0-M2 was examined by quantile plots. A quantile plot is where the observed quantile is plotted against the predicted quantile by the fitted model. For example, to check the goodness of fit of M1, we would plot the sorted values (in the ascending order) of the observed annual extreme precipitation, vs. the expected quantiles y_i determined by $F(y_i) = (i - 0.375)/(n + 0.25)$ (Royston 1982), where F is given by Eq. (1). Similarly to check the goodness of fit of M0, we would plot the sorted values of the observed annual ex-

Table 1. The models fitted and estimated parameters for station *Haikou* (59758). "*" indicates the best fitting model. N/A indicates the parameters are not estimated for those models.

Extremes	models	μ	σ	ξ	$-2\log L_i$	a	b
AM1	M0*	128.35	50.66	N/A	551.66	N/A	N/A
	M1	127.31	49.95	0.039	551.56	N/A	N/A
	M2	N/A	49.65	0.043	551.50	127.19	5.00
AM2	M0*	160.60	64.23	N/A	576.90	N/A	N/A
	M1	156.39	60.65	0.13	575.82	N/A	N/A
	M2	N/A	60.61	0.13	575.80	156.40	33.56
AM5	M0*	196.10	70.85	N/A	588.62	N/A	N/A
	M1	190.17	65.69	0.17	585.84	N/A	N/A
	M2	N/A	65.17	0.17	585.71	189.94	9.82
AM10	M0	249.26	80.77	N/A	603.53	N/A	N/A
	M1*	239.80	70.04	0.27	597.56	N/A	N/A
	M2	N/A	66.38	0.35	596.43	235.76	27.41

treme precipitation, versus the expected quantiles determined by the F, from Eq. (2).

Once the best model for the data has been determined, the interest is to derive the return levels of extreme precipitation. The T year return level, say x_T, is the value occurring on average once in every T years. For example, the 2-year return level is the median of the distribution of AM1 (or AM2, AM5 or AM10). If M1 is assumed, then on inverting $F(x_T) = 1 - 1/T$ we get:

$$x_T = \mu - \frac{\sigma}{\xi}\left[1 - \left\{-\log\left(1 - \frac{1}{T}\right)\right\}^{-\xi}\right]. \qquad (4)$$

If on the other hand M0 is assumed, the corresponding expression is:

$$x_T = \mu - \sigma \log\left\{-\log\left(1 - \frac{1}{T}\right)\right\}. \qquad (5)$$

By substituting $\hat{\mu}$, $\hat{\sigma}$ and $\hat{\xi}$ into Eqs. (4)–(5), we obtain the maximum likelihood estimates of the return levels. Confidence intervals for the return level estimates are obtained by means of the delta method (Rao 1973).

4. Results

M0-M2 were fitted to AM1, AM2, AM5 and AM10 series at each of the 651 stations. The method of maximum likelihood was used throughout. For simplicity, we let L_i denote the maximized likelihood of Mi for $i = 0, 1, 2$.

For station *Haikou*, the fitted models, and the estimated parameters are shown in Table 1. For AM1, M0 gave $-2\log L_0 = 551.66$, and M1 gave $-2\log L_1 = 551.56$. Because $-2\log(L_1/L_0) < \chi^2_{1,0.90} = 2.71$, it follows by the standard likelihood ratio test that M0 should be preferred to M1, that is, the two-parameter Gumbel distribution provides as good a fit as the three-parameter GEV distribution. When M2 was fitted to AM1 data, we obtained $-2\log L_2 = 551.50$ (see Table 1). Because $-2\log(L_2/L_0) < \chi^2_{2,0.90} = 4.61$, the AM1 at *Haikou* has no significant temporal trends. We conclude that among the models considered, the best fit for AM1 at *Haikou* is provided by M0. The above procedures were repeated to model the AM2, AM5 and AM10 series of Haikou, and the parameter estimates are shown in Table 1. Again, there are no significant trends, and the best fitting model is either M0 or M1. These findings are supported by Fig. 4, where we have shown the quantile plots of the fits for the four time series. Figure 4 shows that the fit provided by M0 and M1 are good, especially in the upper tail area, which is the area of most interest. Further checks were performed by

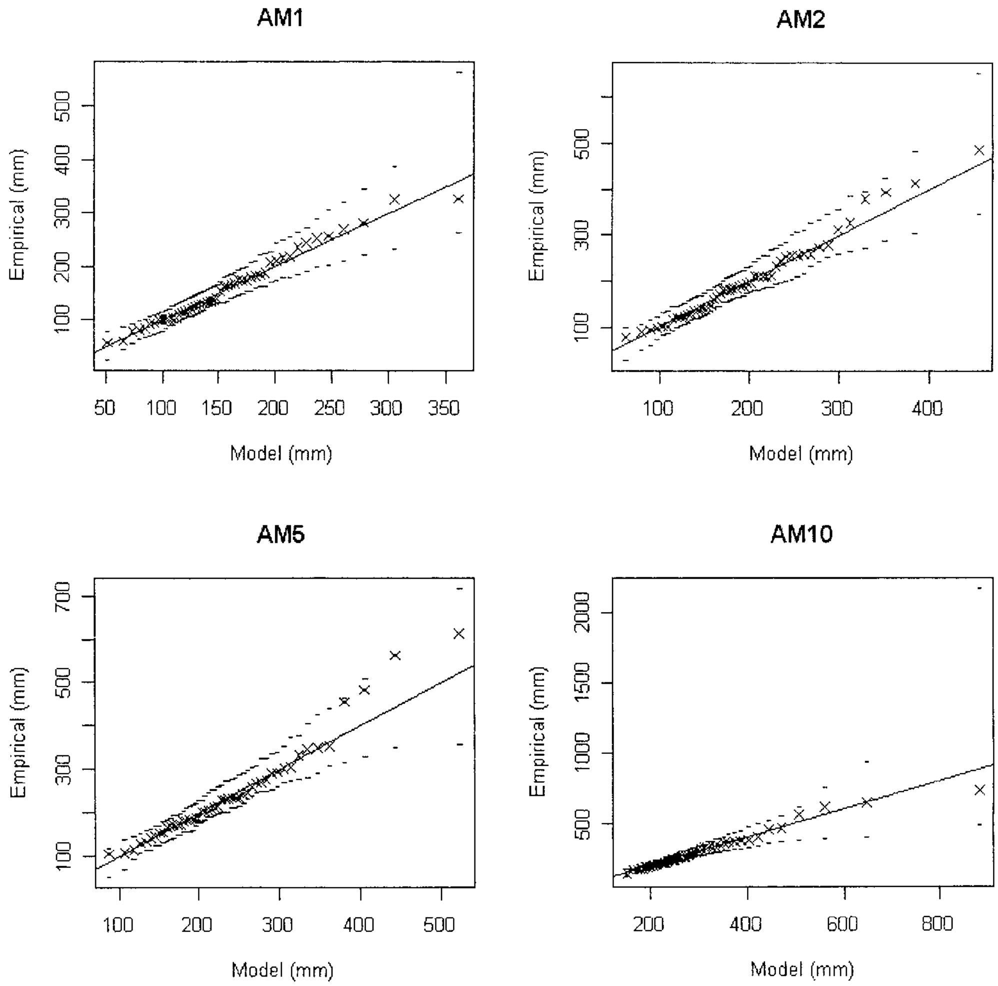

Fig. 4. Quantile plots for AM1, AM2, AM5, and AM10 for station Haikou (59758).

plotting the residuals, the differences between the observed and predicted quantiles, and by means of the one sample Kolmogorov-Smirnov test (Conover 1971) (figures not shown here). All of these results suggested that M0, and M1 provided good fits for all of the four time series at Haikou. Figure 5 shows the return levels, along with 95% confidence intervals for the return periods $T = 2, \ldots, 100$ years [computed using (4)–(5) and the delta method] for Haikou. Figures of this kind can be used to infer measures for flood protection.

The above procedures of model selection were repeated for Fengjie. The standard likelihood ratio test, showed that M2 with b positive provided the best fits for all of the four time series, suggesting that the extreme precipitation at Fengjie is experiencing a significant upward trend. The 10 and 100 years return levels for Haikou and Fengjie are shown in Figs. 2 and 3. It is clear that at each station, there are only 4–6 observed annual extreme events of precipitation (AM1 to AM10), that exceeded the 10 year return level. None of the observed annual extreme events have exceeded the 100 year return level in both stations.

The above procedures of model selection were repeated for all of the other stations. M0 and M1 provided the best fits for most of the locations (see Table 2). About 12.1–15.5% of the stations exhibited linear trends during the analyzed periods. AM10 has the most stations with linear trends (Table 2), possibly because short duration extreme precipitations (AM1, AM2 and AM5) were greatly impacted by local factors (e.g., Prudhomme and Reed 1998), whereas

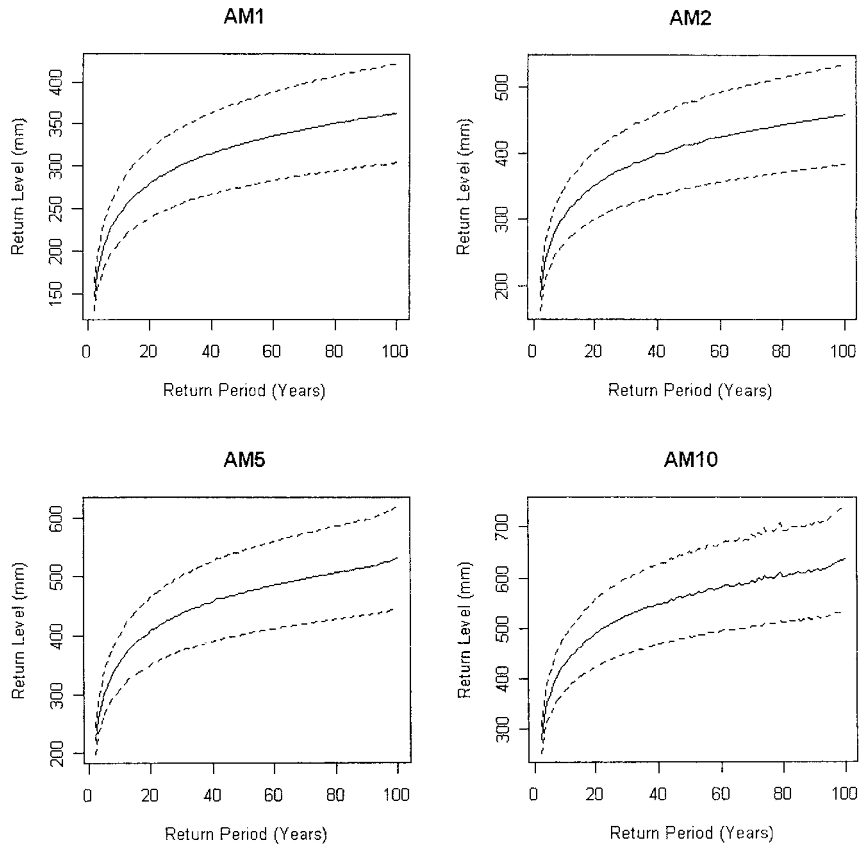

Fig. 5. Return levels (solid lines) and their 95% confidence intervals (dashed lines) for return periods $T = 2, 5, \ldots, 100$ years for AM1, AM2, AM5, and AM10 at station Haikou (59758).

Table 2. Numbers and percentages (in parentheses) of stations with the best fitting models (M0-M2) in China. M2 is the model showing significant long-term trends in the past 5 decades.

Models	AM1	AM2	AM5	AM10
M0 or M1	566 (86.9%)	572 (87.9%)	565 (86.8%)	550 (84.5%)
M2	85 (13.1%)	79 (12.1%)	86 (13.2%)	101 (15.5%)

long duration extreme precipitations (AM10), were impacted by large scale atmospheric circulation anomalies (e.g., Wang et al. 2003; Zhan et al. 2004). The best fitting models for all of the 651 stations are shown in Fig. 6. The stations with decreasing trends are mainly observed in northern China, a result suggesting that the extreme precipitation events, during the 1990s, have become less extreme than the events during the 1950s. The decreasing trends in annual extremes in northern China are consistent with the decreasing rainy days, and frequent droughts in recent years (Gong et al. 2004; Hu and Feng 2001; Zhai et al. 2005). Increasing trends are mainly observed in the Yangtze River basin and northwest China, a result consistent with the frequent flooding in those regions in the 1990s (Gong and Ho 2002; Jiang et al. 2005). In addition, the temporal changes in extreme precipitation over eastern China are consistent with the southward shift of the summer rain belt over eastern China (Hu and Feng 2001; Zhai et al. 2005), and the multidecadal changes of the East Asian sum-

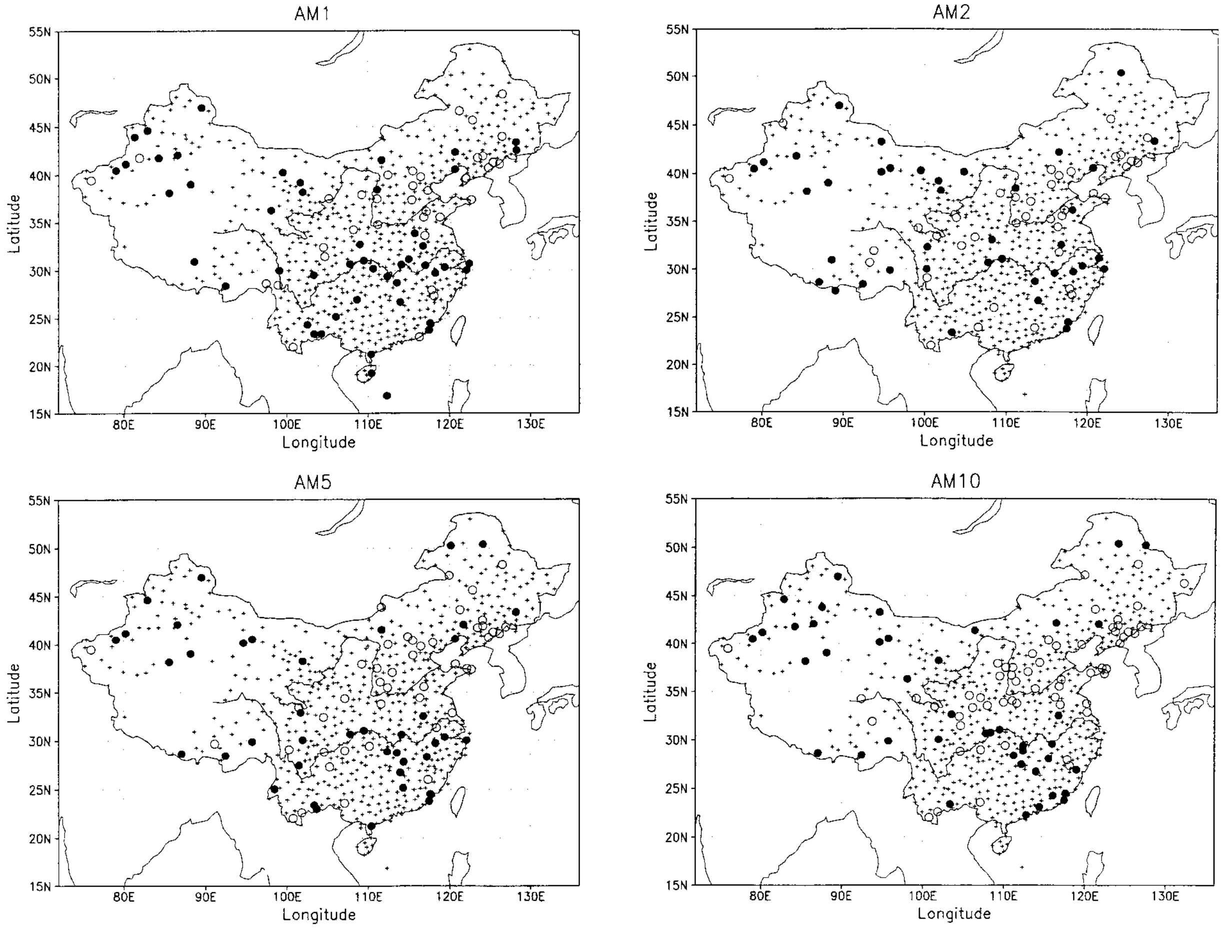

Fig. 6. Spatial distribution of the best fitting models. The crosses indicate that the best fitting model is either M0 or M1, and the circles indicate that the best fitting model is M2. Open (closed) circles indicate that the *b* in M2 is negative (positive), and suggest that the extreme precipitations, in those stations, have been significantly ($p < 0.10$) decreasing (increasing) in the past 5 decades.

mer monsoon system (Feng and Hu 2004; Gong and Ho 2002; Li and Zeng 2002, 2005).

If a station exhibits a significant temporal trend, the return periods of extreme events will follow that trend too (see Fig. 3). Table 3 shows the changes in average return period for a 50-year extreme precipitation event in 1991–2000, compared to the period 1951–60. This was done by estimating the 50-year return level in the 1950s, and its return period in the 1990s. Table 3 shows that the return periods of a 50-year extreme precipitation event in the 1950s have increased in northern China, but decreased in the Yangtze River basin and northwest China. The 50-year event during 1951–1960 has become a less than 38-year event in the Yangtze River basin and northwest China. In some stations in both regions, the 50-year event has become a less than 25-year event. In other words, the extreme events that rarely occurred in the 1950s occurred at a higher rate in the 1990s. In most parts of northern China, the 50-year event during 1951–60 has changed to a more than 80-year event during 1991–2000. Similar changes were noted by Fowler and Kilsby (2003), in studies of extreme precipitation in the United Kingdom, when their data were partitioned into decades (1961–70, 1971–80, 1981–90 and 1990–2000). Instead of truncating the data into shorter subsets as in Flowler and Kilsby, we have modified the GEV distribution to explore the trends in return

Table 3. Return period (years) of extreme precipitation events in 1990–2000, corresponding to a 50-year event in 1951–60.

Regions	Station	Lon(E)	Lat(N)	Return periods of AM1 (years)	Return periods of AM2 (years)	Return periods of AM5 (years)	Return periods of AM10 (years)
Northern China	53764	111°06′	37°30′	108	146	288	170
	53868	111°30′	36°04′	129	65	89	79
	54351	124°05′	41°55′	99	82	82	99
	54365	125°21′	41°16′	76	158	171	93
	54493	124°47′	40°43′	95	81	100	99
	54916	116°51′	35°34′	72	63	82	91
Yangtze River basin	57348	109°30′	31°03′	24	19	32	27
	57426	107°48′	30°41′	34	29	25	24
	58215	116°47′	32°33′	29	27	37	37
	58445	119°25′	30°21′	27	31	14	30
	58477	122°06′	30°02′	28	33	35	35
	58531	118°17′	29°43′	14	15	38	38
Northwest China	51087	89°31′	46°59′	22	17	6	4
	51628	80°14′	41°10′	28	35	38	38
	51855	85°33′	38°09′	36	36	36	35
	52418	99°41′	40°09′	32	34	34	32
	52424	95°46′	40°32′	34	34	34	33
	52674	101°58′	38°14′	25	25	26	16

levels. Our method may also be used to predict the future behavior of extreme precipitation (Nadarajah and Choi 2003; Nadarajah 2005). Because the society has become more vulnerable to extreme precipitation due to population increase and economic growth (Kunkel et al. 1999), the changing nature of return levels of extreme precipitation, should be taken into account for design practices and flood protection.

The best fitting model was used to estimate the return levels for selected return periods (5, 10, 20, 50, 100, 200 and 500), for all of the four time series at each station. For stations with significant trends, the return levels were taken to be the averages during the analyzed periods. Figure 7 shows the spatial distribution of the 10-year return levels of the annual extreme event of precipitation for all the 651 stations. The 10-year return levels of AM1, are less than 20 mm over the Tarim basin in the arid northwest China. The annual number of rainy days in this desert region is usually fewer than 10 days (Domros and Peng 1988). The high return levels are observed in wet and semi-wet parts of eastern China, a region usually with more than 4 rain storms of >50 mm per day and more than 1 strong rain storms of >100 mm per day per year (Domros and Peng 1998). The highest return levels are located in the southern most part of China, which is a region with frequent typhoon landfalls (Chen and Shi 2000). Because extreme precipitations in eastern China are mainly caused by the seasonal evolutions of the summer monsoon (e.g., Wang et al. 2003), the spatial distributions of the 10-year return level show the apparent

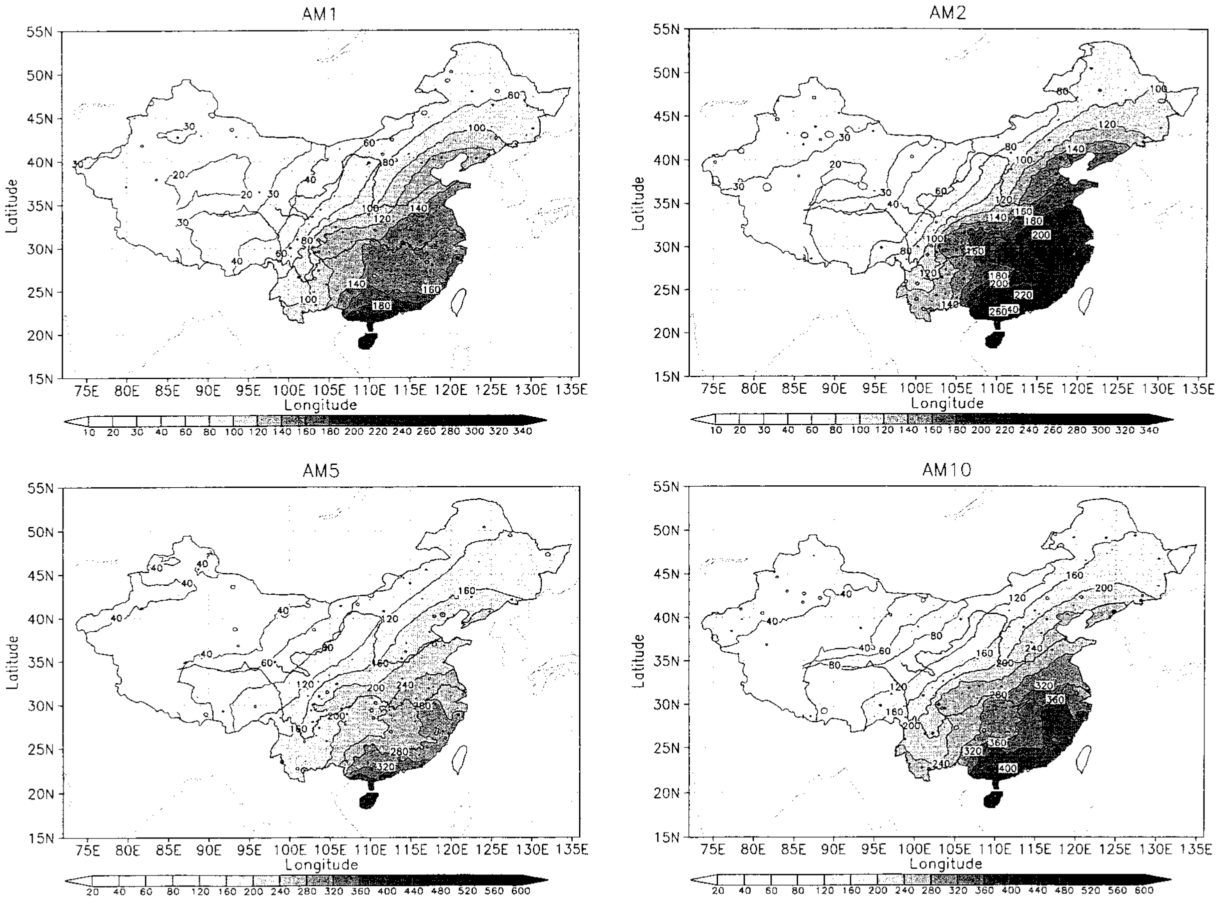

Fig. 7. Spatial distributions of the estimated 10-year return levels (unit: mm) for AM1, AM2, AM5, and AM10, respectively.

footprint of the East Asian summer monsoon system. For example, the 100 mm isohyets line of AM1, the 120 mm isohyets line of AM2, the 160 mm isohyets line of AM5, and the 200 mm isohyets line of AM10 are nearly identical with the north and west boundary of the East Asian summer monsoon (Wang and Linho 2002, see their Fig. 9). This suggests that the return periods of extreme precipitation in eastern China can be used as a proxy for the return periods of the East Asian summer monsoon intensity.

5. The 1998 extreme precipitation from probabilistic perspective

The 1998 severe flooding in Yangtze River basin has caused widespread damage to societies, homes and agricultural lands (NCC 1998). Our results discussed above can help to answer the following question: how rare was the 1998 extreme precipitation? The answer is important for rebuilding processes because decision makers should take into account the risks of other floods of similar magnitude and their consequences.

There were two significant episodes of extreme precipitation that caused the 1998 flooding in the Yangtze River basin (Wang et al. 2003). These extreme precipitation events were associated with the East Asian summer monsoon, the west Pacific subtropical high (WPSH) ridge, and the Mei-Yu fronts over East Asia (Wang et al. 2003; Zhan et al. 2004). In the following, the return periods of the 1998 extreme precipitation in the middle and lower Yangtze River basin, where the severe floods occurred (Zong and Chen 2000), are estimated. Among the 107 stations in the middle and lower Yangtze River basin, more than 22.4% of the sta-

Table 4. Return periods of the 1998 extreme precipitation in the middle and lower Yangtze River basin. The numbers (percentages) in each column are the numbers (percentages) of stations that the observed 1998 extreme precipitation could be expected to occur once in the corresponding return period.

Return periods	<5 year	5–10 year	10–20 year	20–50 year	>50 year
AM1	67 (62.6%)	11 (10.3%)	9 (8.4%)	13 (12.1%)	7 (6.5%)
AM2	63 (58.9%)	17 (15.9%)	10 (9.3%)	10 (9.3%)	7 (6.5%)
AM3	67 (62.6%)	16 (15.0%)	8 (7.5%)	10 (9.3%)	6 (5.6%)
AM4	60 (56.1%)	20 (18.7%)	11 (10.3%)	11 (10.3%)	5 (4.7%)

tions have the return period of the 1998 extreme precipitation longer than 10 years (Table 4). More than 5 stations have the return period of the extreme precipitation longer than 50 years. In addition, the AM1 in 2 stations, AM2 in 3 stations, AM5 in 4 stations and AM10 in 2 stations have the return periods longer than 100 years, that is, the extreme precipitation in those stations was expected to occur once in more than 100 years. These observed extreme events are the cause of the floods in the Yangtze River in 1998.

Figure 8a shows the spatial distribution of the return period of AM10 in 1998. The AM10 in the lower Yangtze River were not so extreme, with their return periods usually less than 10 years. High return periods, however, were mainly observed in the south side of the middle Yangtze River basin. The region that contributed greatly to the development of flooding in the Yangtze River (Hu et al. 2007). The spatial distribution of the high return periods of AM10 is also consistent with the exceptional high water levels in the middle Yangtze River (Zong and Chen 2000). The maximum water levels in 1998 at Shashi, Chenglingji and Hukou hydrological stations, all located at the middle Yangtze River, exceeded the historical maximum (Zong and Chen 2000).

To verify the results shown in Fig. 8a and Table 4, we show, in Table 5, the ranking of the 1998 extreme precipitation over the past 5 decades. Tables 4 and 5 suggest that the estimated return periods are robust and accurate. For example, the number of stations with the 1998 extreme ranked 11 or lower is identical with the number of stations with return period less than 5 years. The number of stations with the 1998 extreme precipitation ranked 1st is also consistent with the number of stations with the return period longer than 50 years. In addition, more than 23.4% of the stations in the middle, and lower Yangtze River basin, with the 1998 extreme precipitation ranked 1–5 is identical with the number of stations that

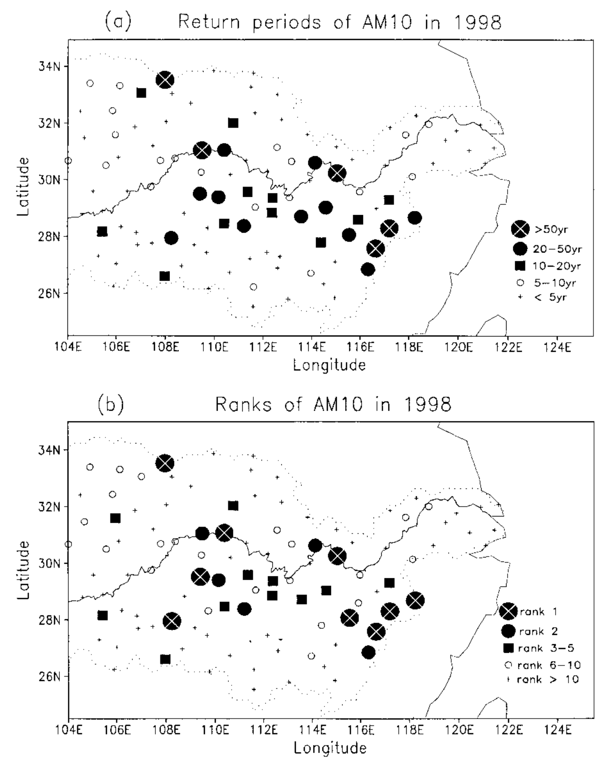

Fig. 8. The spatial distribution of (a) the return periods, and (b) the ranks of AM10 in 1998 in the middle and lower Yangtze River basin. The region confined by the dotted line, is the discharge area of the middle and lower Yangtze River basin.

Table 5. Ranking of the 1998 extreme precipitation in the middle and lower Yangtze River basin. The numbers (percentages) in each column are the numbers (percentages) of stations with the corresponding rank.

Extreme Precipitations	Ranks 11 or lower	Ranks 6–10	Ranks 3–5	Rank 2	Rank 1
AM1	67 (62.6%)	10 (9.3%)	15 (14.0%)	8 (7.5%)	7 (6.5%)
AM2	63 (58.9%)	16 (15.0%)	13 (12.1%)	7 (6.5%)	8 (7.5%)
AM3	65 (60.7%)	16 (15.0%)	11 (10.3%)	8 (7.5%)	7 (6.5%)
AM4	59 (55.1%)	23 (21.5%)	11 (10.3%)	5 (4.7%)	9 (8.4%)

showed the return period longer than 10 years (Tables 4 and 5). The spatial distribution of the ranks of the AM10 in 1998 is consistent with the spatial distribution of the return periods. As shown in Fig. 8b, the stations with high return periods, of the 1998 extreme, have high ranks, and stations with low return periods have low ranks. When all the stations, in the middle and lower Yangtze River basin added together, the AM1, AM2 and AM5 in 1998 ranked 1st, and AM10 ranked 2nd. In addition, the 1998 extreme precipitation ranked 2nd (with the 1954 extreme precipitation ranked 1st), when all the stations in the entire Yangtze River basin added together. These results suggest that the 1998 extreme precipitation was rare, and can be considered as a 20–50 year event.

6. Conclusions

Using a recent quality controlled, comprehensive daily precipitation dataset, we have conducted an extreme value analysis of annual maxima of daily, 2-, 5- and 10-day precipitation events for 651 stations in China for the past 50 years. The GEV distribution was used to model the extreme precipitation events at each station. The GEV distribution was also modified to explore the temporal non-stationary trend, in the extreme precipitation events. The extreme precipitation, at more than 12% of the stations, showed significant linear trends ($p < 0.10$) over the past 50 years. Significantly decreasing trends mainly occurred in northern China, while significantly increasing trends mainly appeared in the Yangtze River basin and northwest China. The changes in extreme precipitation in eastern China, are associated with the changes in the East Asian summer monsoon. The return levels have changed for stations with significant trends. The 50-year event, in parts of the Yangtze River, and northwest China during 1951–60, has become a less than 25-year event, during the 1990s. The return periods, in parts of northern China, have become longer.

The return levels corresponding to various return periods, and their confidence intervals, have been estimated based on the GEV distribution. The isohyets maps of the 10-year return level have been presented. The spatial distribution, of the 10-year return level, is closely related to climatic mean precipitation in China. The low return levels appear in the arid northwest China, whereas the high return levels are observed at the wet and humid parts of eastern China. The highest return levels, are located in the southern—most parts of China. The spatial distribution of return levels, of extreme precipitation in eastern China, are related to the seasonal evolutions of the East Asian summer monsoon, and the Typhoon landfall.

The 1998 severe flooding, in the Yangtze Rive basin, has been analyzed as a case study from a probabilistic perspective. The return periods of the observed 1998 extreme precipitation have been estimated. The results showed that the 1998 extreme precipitation, at more than 22.4% of the stations in the middle and lower Yangtze River basin were rare, and could occur only once in more than 10 years. In addition, the 1998 extreme precipitation ranked 1st to 5th in more than 23.4% of the stations. Overall, the 1998 extreme precipitation, in the middle and lower Yangtze River basin, could be considered as a 20–50 year event.

It is important to recognize that the estimated return levels, are based on observations of about 50 years. We thus caution the readers that the confidence in return levels corresponding to long return periods (greater than 100) is low. Further investigation will be necessary, when longer data records become available. The return levels can be used, however, in a qualitative and comparative sense.

Acknowledgment

We would like to thank the Editor, and two anonymous referees for their useful comments, which have led to great improvement of this paper.

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