Temporal and spatial characteristics of precipitation and droughts in the upper reaches of the Yangtze river basin (China) in recent five decades

Nan Zhang, Ziqiang Xia, Shaofeng Zhang and Hong Jiang

ABSTRACT

Drought is one of the most harmful natural hazards in the Upper Reaches of the Yangtze River basin (URYR) in the mid-west part of China. Alterations in precipitation will affect the severity of drought. The nonparametric Mann–Kendall (MK) test was used in this paper to examine the trend of precipitation and the standardized precipitation index (SPI) was adopted to analyze the spatial–temporal variations of meteorological drought over different time scales in the last 50 years. The MK test value of precipitation indicated that, for most of the URYR showed an increasing trend of precipitation in the months of January, February, March and June, mainly in the Min-Tuojiang, Jialingjiang and Wujiang sub-basins and a decreasing trend was observed in August to December. The most obvious decreasing trend of precipitation occurred in the Jialingjiang, upper mainstream and Wujiang sub-basins in September, with a rate ranging from –7.89mm/10 years to –39.36mm/10 years. The results show that the SPI is applicable in the URYR basin. The number of severe droughts differed among the six sub-basins, i.e., a more obvious 3-month drought takes place in the middle of the upper mainstream, Wujiang sub-basins and the southeast of Jialingjiang sub-basin and other droughts in 6, 9 and 12 month timescales have the same effect in these three sub-basins. The outcomes of the paper could provide references for droughts mitigation, local water resources management and agriculture decision making.

Key words | drought analysis, spatial-temporal distribution, standardized precipitation index, upper reaches of the Yangtze river

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INTRODUCTION

Drought is a natural, recurrent feature of climate derived from prolonged dry and warm weather causing less water availability on the land surface. It develops slowly and imperceptibly and may remain unnoticed for a long time, unlike flood and other natural hazards (Tallaksen & van Lanen 2004). In the last few years, climate change has become a major global problem that exists in many regions of the world. Under the circumstance of global climate change, it is necessary to analyze the characteristics of precipitation and drought in terms of the local water resources management, drought hazard mitigation, and to understand the course and patterns of ecological and environmental

anomalies in the arid and semi-arid regions. At the same time, changes in precipitation trigger new characteristics of drought in affected regions, especially those that affect spatial distribution and temporal patterns. There is also the necessity of improving the ability of local decision makers to prepare for, and deal with, the consequences of precipitation anomalies through the acquisition of a complete understanding of the range and likelihood of changes in precipitation and drought that a given location has undergone and may experience again (Husak et al. 2007).

According to Dracup et al. (1980), droughts are related to precipitation (meteorological), streamflow (hydrological),

soil moisture (agricultural) or any combination of the three. Droughts have been classified into four types (Wilhite & Glantz 1985): meteorological, agricultural, hydrological, and social-economic. The first three groups can be defined as environmental indicators, the last group as a water resources indicator. A number of drought monitoring indices have been used over the years, such as the Reconnaissance Drought Index (RDI) (Tsakiris *et al.* 2007), the Drought Severity Index (DSIE) (Pandey *et al.* 2008), the Streamflow Drought Index (SDI) (Nalbantis & Tsakiris 2009). However, the Standard Precipitation Index (SPI), recommended by Guttman (1998), remains a popular choice among researchers because it is simple, spatially consistent in its interpretation, and probabilistic, so that it can be used in risk management and decision analysis, and can be tailored to time periods of the user's interest. It describes the behavior of only one variable, precipitation. It is possible to experience wet conditions at one timescale and dry conditions at another simultaneously. For example, soil moisture, which typically responds to precipitation relatively quickly, may soon be depleted in a brief drought spell, whereas stream flow and groundwater, which are affected by longer-term precipitation anomalies, may still be relatively normal. Although it is quite a recent index, the SPI has been used in Turkey (Komuscu 1999), Argentina (Seiler *et al.* 2002), drought analysis in the Awash River Basin of Ethiopia (Desalegn *et al.* 2010), Spain (Lana *et al.* 2002), Korea (Min *et al.* 2003), Hungary (Domonkos 2003), China (Wu *et al.* 2005; Zhai & Qi 2009), Europe (Edwards & McKee 1997; Lloyd-Hughes & Saunders 2002; Paulo & Pereira 2006), Sicily (Bonaccorso *et al.* 2003), South Africa (Mathieu & Richard 2003), Taiwan (Shiau 2006), Iran (Morid *et al.* 2006; Raziei *et al.* 2009) and Greece (Nalbantis & Tsakiris 2009) among others, for real-time monitoring or retrospective analysis of droughts. Studies have also highlighted the use of the SPI in supporting an efficient Drought Watch System for areas of mesoscale dimensions (Tsakiris & Vangelis 2004).

In theory, the timescale of SPI is flexible. Statistically, precipitation is not normally distributed. Since non-precipitation in many days, precipitation distributions are positively skewed. Furthermore, a short timescale will increase the precipitation variability, leading to a highly skewed distribution (Barger *et al.* 1959). However, in practice a monthly precipitation series is 'smoothed' with a moving window of width equal to the number of months desired, e.g., a 3-month SPI would use a moving window of a 6-month width. Edwards & McKee (1997) selected a 3-month SPI for a short-term drought index, a 12-month SPI for an intermediate-term drought index, and a 48-month SPI for a long-term drought index. The window is non-centered such that the filtered series depends only on the present and past values of the time series. The filtered data are broken into 12 monthly time series, which McKee *et al.* (1995) individually fitted with a gamma distribution that can describe skewed hydrologic variables without needing a log transformation (Chow *et al.* 1988). It is possible to use other distributions, as long as they fit the data adequately.

The study area in this paper is the area of the Upper Reaches of the Yangtze River (URYR), which are located between 24°37′N–35°54′N and 90°13′–111°30′E (Figure 1), it stretches from the southwest side of the Geladandong Snowmountain, is bounded on the west by the world's largest plateau, the Tibetan Plateau. The main channel flows through nine provinces (municipalities or autonomous regions), namely Qinghai, Tibet, Yunnan, Gansu, Sichuan, Shanxi, Guizhou, Chongqing, Hubei, with area of about 1.005 million km². The URYR lies in the transition zone from the first step to the second in China (according to the characteristics of the West-high and East-low, the terrain of China was divided into three step levels. The first step: the Tibetan Plateau in the southwest of China. The second step: the Tibetan Plateau to the east and north. The third step: eastern China. This contains the Qinghai–Tibet Plateau, cross-sectional mountains, Yunnan-Guizhou Plateau, Qin-Ba Mountains, the Sichuan Basin and can be further divided into the Jingshajiang sub-basin, the Yalong sub-basin, the Ming-Tuo sub-basin, the Jialinjiang sub-basin, the upper mainstream sub-basin and the Wujiang sub-basin (Figure 1). The Jingshajiang sub-basin is named after the Jishajiang River. The Yalongjiang River belongs to this sub-basin. The Jialinjiang, Ming-Tuo and Wujiang sub-basins are similarly named after the Jialinjiang River, the Ming-Tuojiang River and the Wujiang River, respectively. The URYR plays an extraordinary role in China, taking the occurrence of droughts as well as the availability of historical climate records into consideration. The region is climatologically sensitive because it is located along the demarcation line between subtropical and temperate climate that separates disparate air masses and along with its geographical position, drought is the dominant hazard and precipitation is an
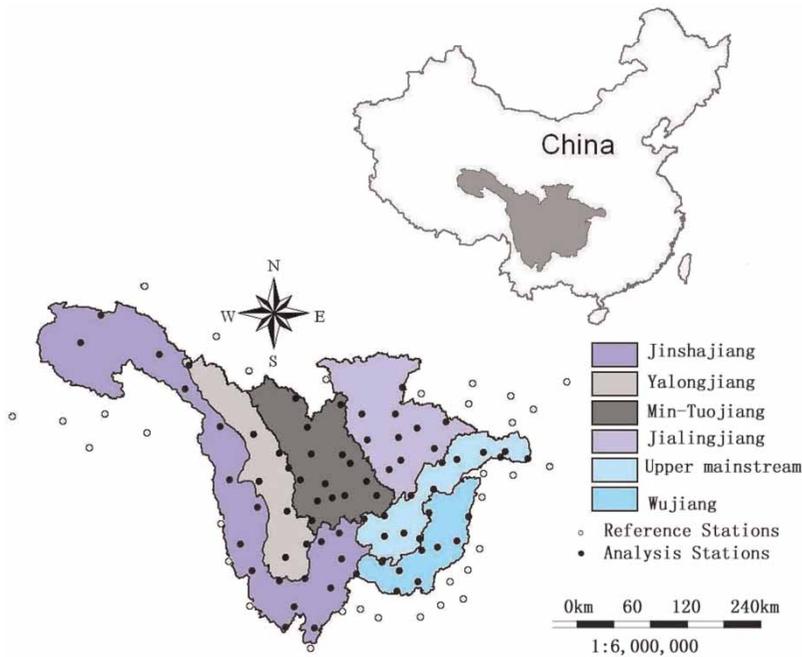
Figure 1 | Geographical location of selected pluviometric stations in the URYR.

important moisture input in this area. It is influenced by the west Pacific Ocean subtropical high pressure and its position, such that warm–humid airstreams coming from Southeast Asia have an annual and seasonal change, which consequently affects the precipitation in the URYR.

Precipitation in the URYR fluctuates severely over the inter-annual and decadal timescales. Drought hazards occur frequently in URYR and lead to huge losses in agriculture and social economy. According to drought statistical documents, URYR had suffered eight extreme droughts and 62 severe droughts between 1470 and 1990 (CWRC 2002). In the drought of 1960, about 44.24 million people were affected, and the output of grain was reduced by 4 million tonnes. In 1961, the affected population was 41.89 million, and the reduction of grain output amounted to 5.21 million tonnes. Extremely low precipitation coincided with the extreme drought, the precipitation in the last 10 years presented distinct characteristics such as 'no flood in the flood season' in URYR (Dai *et al.* 2008, 2010).

In order to comprehensively understand the trend of the precipitation and characteristics of drought, many researchers have undertaken studies on the dry/wet trend and the frequency of drought in the URYR (Dai *et al.* 2010; Zhang *et al.* 2008; Jiang *et al.* 2006; Zhai *et al.* 2009; Chen 1997; Xu *et al.*

2008; Pang *et al.* 2008; Liu *et al.* 2009). However, research on the trend of precipitation at multiple timescales and the characteristics of drought at higher resolution in URYR has not been reported yet. Thus, the purpose of this study was to identify the drought with SPI at different timescales and with higher resolution, detect the trend of precipitation, and analyze the distribution of the trend of precipitation and frequency of drought in URYR. This type of research has not been conducted in the URYR before. The results of this paper can be utilized as a reference for decision making regarding local water resources management, ecological rehabilitation, and further work defining drought events at different spatial scales and drought hazard mitigation.

METHODOLOGY

Data collection

The time series pluviometric data from 1 January 1958 to 31 December 2008 in this paper were collected from the National Meteorological Information Center (NMIC) of the Chinese Meteorological Administration (CMA). For meteorological drought analysis, 73 precipitation stations were

chosen with another 32 precipitation stations as references when spatial interpolation was conducted (Figure 1). The quality, continuity, homogeneity and the length of data records were considered to be more important than the number of stations. Quality control and homogeneity testing of the meteorological stations were performed by calculating the von Neumann ratio (N), the cumulative deviations ($Q/n^{0.5}$ and $R/n^{0.5}$), and the Bayesian procedures (Buishand 1982; Maniak 1997; Gemmer et al. 2004). The data sets of all stations proved to be homogeneous with a significance beyond the 95% confidence level. The URYR contains six regions according to its texture of drainage (Figure 1), more details can be found in Table 1. The Mann–Kendall nonparametric test was employed to define the trend of precipitation and the SPI was used to calculate aridity in these six regions.

The Mann–Kendall non-parametric test

Mann (1945) presented a non-parametric test for randomness against time, which constitutes a particular application of Kendall's test for correlation commonly known as the Mann–Kendall (MK) or the Kendall t test (Kendall 1962). Letting x_1, $x_2, …, x_n$ be a sequence of measurements over time, Mann proposed to test the null hypothesis, H_0, that the data come from a population where the random variables are independent and identically distributed. The alternative hypothesis, H_1, is that the data follow a monotonic trend over time. The MK test is widely useful in detecting trends in paired data (Sneyers 1990), as (1) data need not conform to any particular distribution, thus extreme values are acceptable (Hirsch et al. 1993); (2) missing values are allowed (Yu et al. 1993); (3) the use of relative magnitudes (ranking) rather than numerical values allows 'trace' or 'below detection limit' data to be used – they are assigned a lesser value than the smallest measured

value; (4) in time series analysis, it is unnecessary to specify whether the trend is linear or not (Sneyers 1990; Yu et al. 1993; Silva 2005). The correlation between two variables is termed as Kendall's correlation coefficient, or the Kendall statistic S. The Mann–Kendall test statistic is

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(X_j - X_i) \tag{1}$$

where

$$\operatorname{sgn}(\theta) = \begin{cases} +1 ......\theta > 0 \\ 0 ....\theta = 0 \\ -1 ......\theta < 0 \end{cases} \tag{2}$$

Under the hypothesis of independent and randomly distributed random variables, when $n \geq 8$, the S statistic is approximately normally distributed, with zero mean and variance as follows:

$$\sigma^2 = \frac{n(n-1)(2n+5)}{18} \tag{3}$$

As a consequence, the standardized Z statistics follow a normal standardized distribution:

$$Z = \begin{cases} \dfrac{S-1}{\sigma} ....if....S > 0 \\ 0 ....if....S = 0 \\ \dfrac{S+1}{\sigma} ....if....S < 0 \end{cases} \tag{4}$$

The hypothesis that there is no trend is rejected when the Z value computed by Equation (4) is greater in absolute value than the critical value Z_α, at a chosen level of significance α. When a positive value of Z indicates an upward trend, a negative value of Z indicates a downward trend. $|Z| > 1.64$

Table 1 | Precipitation and elevation in the six sub-basins of the URYR

Code	Regions	Area (million km²)	Mean elevation (m)	Mean annual precipitation (mm)	Std. Deviation	Contain stations
1	Jinshajiang sub-basin	0.50	3,161	696	72	18
2	Yalongjiang sub-basin	0.13	3,173	679	79	8
3	Min-Tuojiang sub-basin	0.03	2,836	953	162	15
4	Jialingjiang sub-basin	0.16	2,325	999	125	11
5	Upper mainstream sub-basin	0.53	1,269	1,115	178	12
6	Wujiang sub-basin	0.09	1382	1,092	111	9

indicates a significant upward/downward trend (at a significance of $\alpha = 0.05$) and $|Z| > 2.32$ indicates an extremely significant trend (at a significance of $\alpha = 0.01$). In this paper, after deriving the MK test statistic, Z, of every monthly data series, spatial interpolate was used to interpolate Z and realize the trend distribution over the URYR.

Terrain will affect the rainfall statistics and the trends. To obtain a spatial coverage of MK and drought indices over the whole basin, we interpolated the three rainfall factors (elevation of the precipitation stations, slope, and distance between nearest vicinity stations). Details are as follows: based on the DEM to calculate the rainfall in each grid cell,

$$Y = \sum_{i=1}^{n} \alpha_i (G \cdot (H - h_i) + B_i) \tag{5}$$

where Y is the result of rainfall interpolation; n is the number of precipitation stations in interpolation; G is the gradient for the rainfall with the elevation change; α_i is the weight of station i, Here, weight is related to the elevation of station; H_i is the elevation of station i; B_i is original rainfall data.

Standardized precipitation index

The SPI is an index based on the probability of distribution in precipitation (Thom 1966; McKee *et al.* 1995; Wilks 1995; Guttman 1998, 1999), and is a widely used drought index based on the probability of precipitation for multiple time-scales, e.g., 1-, 3-, 6-, 9-, 12- and 24-month (Wu *et al.* 2007; Türkeş & Tatlı 2009). It provides a comparison of the precipitation over a specific period with the precipitation totals from the same period for all the years included in the historical record. Consequently, it facilitates the temporal analysis of wet and dry phenomena.

To compute SPI, historic rainfall data of each station are fitted to a gamma probability distribution function (Abramowitz & Stegun 1965; Thom 1996):

$$g(x) = 1/(\beta^\alpha \Gamma(\alpha)) x^{\alpha-1} e^{-x/\beta} \quad (x > 0) \tag{6}$$

$$\Gamma(\alpha) = \sum_{0}^{\infty} x^{\alpha-1} e^{-x} dx \tag{7}$$

where $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, $x > 0$ is the amount of precipitation and $\Gamma(\alpha)$ defines the gamma function.

Initial estimates for the shape and scale parameters are calculated by

$$\hat{\alpha} = (1 + \sqrt{1 + 4A/3})/4/A \tag{8}$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{9}$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{10}$$

where n is the number of precipitation observations and $\bar{x}$ is the mean precipitation over the time scale of interest, x_i is the sample of the pluviometric data, and A is measure of the skewness of distribution (Husak *et al.* 2007). For the calculation of $\bar{x}$ and $\ln(\bar{x})$, it must be noted that only the number of weeks or months with positive accumulations were used, and only the non-zero observations in the records were utilized in the estimation of the gamma distribution parameters.

This allows the rainfall distribution at the station to be effectively represented by a mathematical cumulative probability function given by

$$G(x) = \int_0^x g(x) ds = 1/(\beta^\alpha \Gamma(\alpha)) \int_0^x x^{\alpha-1} e^{-x/\beta} dx \tag{11}$$

Letting $t = x/\beta$, this equation becomes the incomplete gamma function,

$$G(x) = 1/\Gamma(\alpha) \int_0^x t^{\hat{\alpha}-1} e^{-t} dt \tag{12}$$

As the gamma function is undefined for $x = 0$ and a precipitation distribution may contain zeros, the cumulative probability becomes

$$H(x) = q + (1-q)G(x) \tag{13}$$

where q is the probability of a zero. If m is the number of zeros in a precipitation time series, q can be estimated by m/n.

The cumulative probability, $H(x)$, is then transformed into the standard normal random variable $Z(\mu = 0, \sigma^2 = 1)$, which is the value of the SPI.

Since it would be cumbersome to produce these types of figures for all stations at all time scales and for each month of the year, the Z or SPI value is more easily obtained computationally using an approximation provided by Abramowitz & Stegun (1965) that converts cumulative probability to the standard normal random variable Z:

$$Z = \text{SPI} = -(t - (c_0 + c_1 t + c_2 t^2)/(1 + d_1 t + d_2 t^2 + d_3 t^3))$$
$$0 < H(x) <= 0.5 \qquad (14)$$

$$t = \sqrt{\ln\left[1/H(x)^2\right]} \qquad (15)$$

$$Z = \text{SPI} = (t - (c_0 + c_1 t + c_2 t^2)/(1 + d_1 t + d_2 t^2 + d_3 t^3))$$
$$0.5 < H(x) < 1 \qquad (16)$$

$$t = \sqrt{\ln\left[1/(1 - H(x))^2\right]} \qquad (17)$$

$c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$,
$d_1 = 1.432788$, $d_2 = 0.189269$, $d_3 = 0.001308$.

The values of SPI can be categorized according to the classes indicated in Table 2 (Vermes 1998).

We use this method to calculate the rainfall in each grid cell with the elevation change. Thus, the each cell represents the spatial databases while the MK/drought indices computed at their respective cells represent each of their attribute databases. As the links between spatial and attribute

Table 2 | Classification of SPI values

Scale	SPI classes	Period classification
1	>2	Extreme wet
2	(1.5, 2)	Very wet
3	(1, 1.5)	Moderately wet
4	(–1, 1)	Near normal
5	(–1.5, –1)	Moderate dry
6	(–2, –1.5)	Severely dry
7	<–2	Extreme dry

databases exit, a series of maps with spatially varying drought severity are obtained. We can also use this method to calculate the monthly or annual precipitation in each sub-basin.

RESULTS

The spatial–temporal distribution of the precipitation

Based on the monthly precipitation time series of the six sub-basins in the URYR, the MK test of precipitation was carried out, and the changing rate of precipitation was calculated by the least-squares linear fitting (Table 3). Table 4 presents the statistical analysis results of different stations.

From Table 3 it can be seen that from January to May the rate of change of the precipitation in Jinshajiang sub-basin showed positive slopes from 1.85 to 8.31 mm/10 years and the maximum value of 8.31 mm/10 years occurred in May. For these five months, the number of stations which showed significant increasing trends in the Jinshajiang sub-basin are 8, 4, 5, 3 and 10 (Table 4), with percentages of 44.4, 22.2, 27.7, 16.7 and 55.6% respectively. Liu & Ding (2009) have indicated that from June to September is an important time period, during which the precipitation in the URYR is simultaneously influenced by the co-action of the western climatological intraseasonal oscillation (CISO), which comes from the tropical western Pacific and the eastern CISO from the tropical Indian Ocean, and the effect of precipitation on the region's flood control is important. From Tables 3 and 4, Jialingjiang sub-basin had significant (over 0.05 confidence interval, for some stations) positive changes in precipitation observed in June for 45.5% of the stations, the positive slope was 6.13 mm/10 years. Similarly, in September, 45.5%, 16.67%, and 22% of the stations showed a significant negative trend in precipitation for Jialingjiang, Upper mainstream, Wujiang sub-basins, respectively, with negative slopes of −6.13, −1.97, −2.14, −1.83mm/10 years, severally. October to December is the season of winter in China; from Tables 3 and 4, only the Jinshajiang sub-basin in this three-month period showed positive slopes (2.44, 2.63, 0.76 mm/10 years). For Yalongjiang sub-basin, only November showed obvious change, where the MK value was 2.75, with confidence interval up to 0.01. Of the number of changed stations viewed, 11%, 22% and 17% showed positive

Table 3 | Results of the application of the MK test and of least-squares linear fitting to the monthly precipitation for all pluviometric data series

Region	January mm decade^{-1} M	b ± σ	February mm decade^{-1} M	b ± σ	March mm decade^{-1} M	b ± σ	April mm decade^{-1} M	b ± σ	May mm decade^{-1} M	b ± σ	June mm decade^{-1} M	b ± σ
Jinshajiang sub-basin	6.04**	2.37 ± 4.91	3.53**	1.85 ± 5.77	5.21**	3.26 ± 7.73	2.84**	2.72 ± 9.08	3.38**	8.31 ± 24.19		
Yalongjiang sub-basin					4.13**	2.36 ± 7.69	2.76**	1.94 ± 8.03				
Min-Tuojiang sub-basin	2.42**	0.87 ± 3.46			2.57**	2.71 ± 10.80	2.27*	3.60 ± 16.47				
Jialingjiang sub-basin	2.75**	1.07 ± 3.60	2.00*	1.18 ± 6.85							1.93*	6.13 ± 38.03
Upper mainstream sub-basin	2.49**	1.64 ± 6.51	2.22*	1.88 ± 9.63					−1.69*	-5.60 ± 30.58		
Wujiang sub-basin	4.42**	3.33 ± 9.22	2.14*	2.36 ± 10.03								

Region	July mm decade^{-1} M	b ± σ	August mm decade^{-1} M	b ± σ	September mm decade^{-1} M	b ± σ	October mm decade^{-1} M	b ± σ	November mm decade^{-1} M	b ± σ	December mm decade^{-1} M	b ± σ
Jinshajiang sub-basin							1.66*	2.44 ± 18.15	4.16**	2.63 ± 6.90	3.02	0.76 ± 2.75
Yalongjiang sub-basin									2.75**	1.46 ± 5.66		
Min-Tuojiang sub-basin												
Jialingjiang sub-basin					−1.97*	−39.36 ± 57.25						
Upper mainstream sub-basin					−2.14*	−11.08 ± 57.00						
Wujiang sub-basin					−1.83*	−7.89 ± 44.29						

M is the Mann-Kendall test value; b(percentage contribution/decade) is the linear regression coefficient; σ is the root mean square of error. *Through 95% confidence test. **Through 99% confidence test.

change in Jinshajiang sub-basin for October to December and 25% in Yalongjiang sub-basin for November. This change in precipitation in winter coincides with the results of Jiang et al. (2005) and Zeng et al. (2008).

To further confirm the pattern of the temporal and spatial trends, the monthly MK test values were spatially interpolated (Figure 2). Solid lines represent positive values and dashed lines represent negative values.

In January, with the exception of Jinshajiang upper reaches, the results show an upward trend in monthly precipitation for the other basins. The significant upward trend (indicates a significant upward/downward trend (pass a significance of $\alpha = 0.05$)), with number placed (the numbers on maps were

interval from the test values) was in the southeast of the URYR, mainly located in Wujiang sub-basin.

In February, a slightly downward trend of the precipitation was shown in the middle of Yalongjiang sub-basin, south part of Min-Tuojiang sub-basin, which is the famous area known as Sichuan basin. In July, the downward trend focus was on Jialingjiang sub-basin. In November, the downward trend was located in Jialingjiang, Wujiang and the upper mainstream sub-basins. In December, the upward trend was located on the north of Jialingjiang and southeast of Jinshajiang sub-basins. In these four months, the change was not significant, with the values of MK not up to the 0.05 confidence interval.

Table 4 | Station statistics of change trends of monthly precipitation in the sub-basins of the URYR (pass 0.05 confidence interval)

Region	January +	−	February +	−	March +	−	April +	−	May +	−	June +	−
Jinshajiang sub-basin	8	0	4	0	5	0	3	0	10	0	3	1
Yalongjiang sub-basin	0	1	0	1	3	0	2	0	1	0	1	0
Min-Tuojiang sub-basin	1	0	1	0	3	0	3	0	1	0	0	0
Jialingjiang sub-basin	2	0	2	0	0	1	0	2	0	0	5	0
The upper mainstream sub-basin	5	0	5	1	2	2	2	0	0	1	0	0
The Wujiang sub-basin	9	0	5	0	4	0	0	2	0	0	0	1

Region	July +	−	August +	−	September +	−	October +	−	November +	−	December +	−
Jinshajiang sub-basin	1	0	3	0	4	1	2	0	4	0	3	0
Yalongjiang sub-basin	0	0	0	0	1	1	2	0	2	0	0	1
Min-Tuojiang sub-basin	0	3	0	4	0	1	0	6	0	2	0	3
Jialingjiang sub-basin	0	1	0	2	0	5	0	3	0	1	1	0
Upper mainstream sub-basin	2	0	0	0	0	2	0	1	0	1	1	1
Wujiang sub-basin	3	0	0	0	0	2	0	0	0	0	0	1

+ represents increase trend; − represents decrease trend.

In March, a downward trend occurred in the east of Jialingjiang and Upper mainstream sub-basins. Similarly, a downward trend covered the whole Jialingjiang sub-basin and most of the upper mainstream and whole Wujiang sub-basins in April and May. These are the areas where the spring drought occurred frequently, i.e., a 'Dry nine decades' as mentioned in the CWRC (2002). In March, a significant upward trend occurred in the middle and lower reaches of Jinshajiang sub-basin, pass 0.05 confidence interval. A noticeable significant positive trend was apparent in the middle of Jinshajiang sub-basin in April and a similar remarkably positive trend can be seen in the headwater of Jinshajiang sub-basin (0.01 confidence interval) in May and June.

In August, September and October, the significant upward trend located on the headwater of Jinshajiang sub-basin, especially the significant downward trend distributed in the junction of upper mainstream and the whole of Jialingjiang sub-basins. From the whole space distribution of MK values, a downward trend covers most of the URYR basin, mainly focused on the middle-east of the URYR basin, which includes the entire Min-Tuojiang, Wujiang, Upper mainstream, Jialingjiang sub-basins and the south of the Jinshajiang, Yalongjiang sub-basin. The summer and autumn natural drought occurred frequently with seasonality and regionally.

For the whole URYR basin, the increasing trend appears in the months of January, February, March and June, while in other months the annual precipitation shows a decreasing trend, especially in the months from August to December. A dry Summer–Autumn would influence the growth of the crops, which are widely planted in SiChuan basin, including Min-Tuojiang, Jialingjiang and Wujiang sub-basins. Consequently, more attention should be focused on the threat of droughts in the URYR basin, especially in the SiChuan basin.

Frequency of drought

The number of months N_i in each class of drought intensity according to Table 2 was computed for 3, 6, 9, 12, 24 and 48 month timescales. The number of droughts per 100 years was calculated as (Łabedzki 2007)

$$N_{i,100} = \frac{N_i}{i \cdot n} \cdot 100 \tag{18}$$

where $N_{i,100}$ = the number of droughts for a timescale i in 100 years, N_i = the number of months with droughts for a timescale i in the n year set, i = the timescale (1, 3, 6, 12,

… months), and $n =$ the number of years in the data set (from 1958 to 2008).

Edwards & McKee (1997) indicated that the SPI has a standard normal distribution with an expected value of zero and a variance of one. But this is not always the case for the SPI at short timescales because of the skewed precipitation distribution. Especially for dry climates or those with a distinct dry season where zero values are common, there will be too many zero precipitation values in particular seasons. When the timescales were increased and more months were considered, this problem was solved (Kangas & Brown 2007). On the other hand, because of data limitations, timescales >24 months may be unreliable (Guttman 1999). Given the inclusion within the study area of different climatic regions, particularly
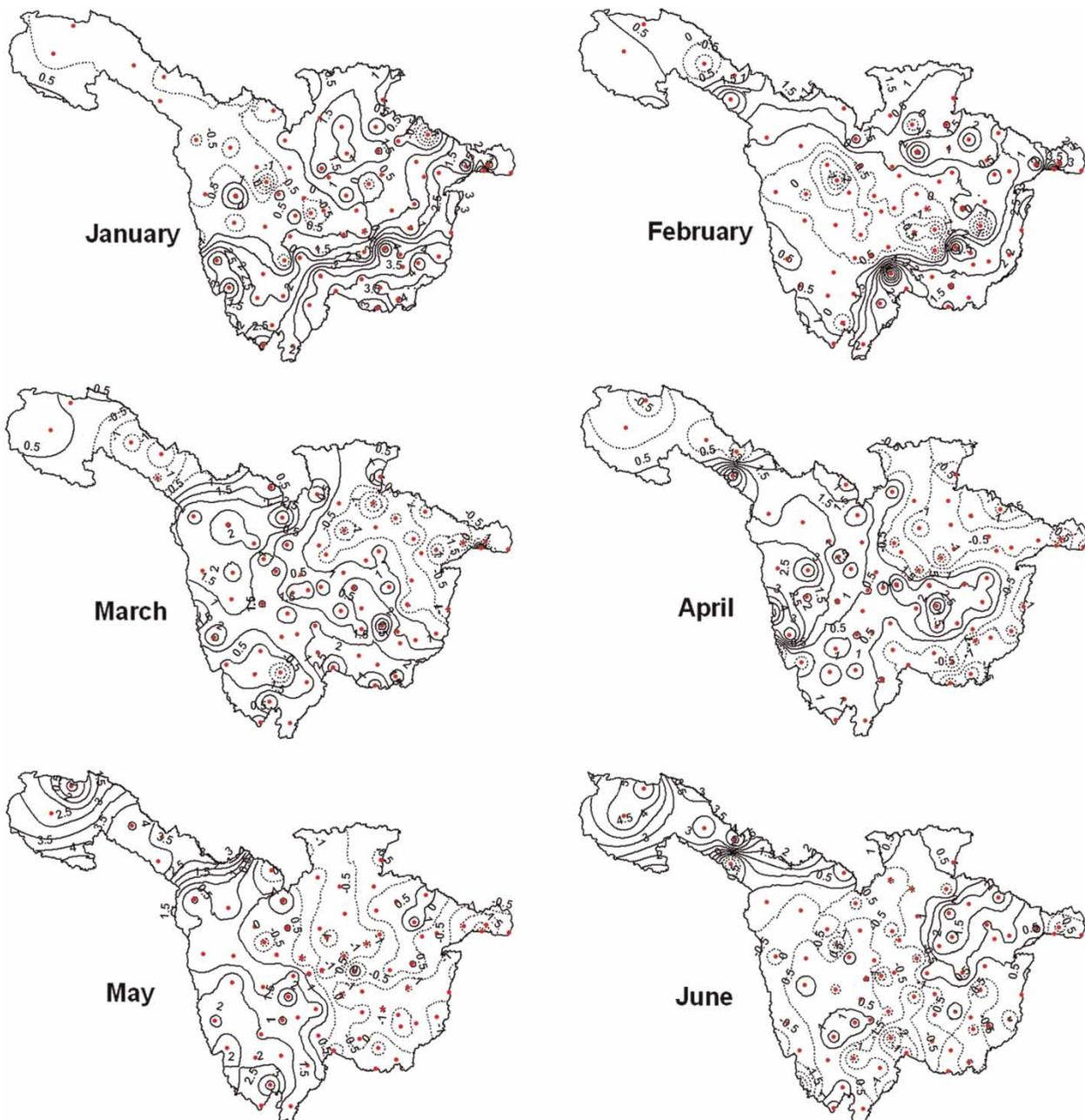
Figure 2 | Results of the MK test for every month in the URYR. Solid lines represent positive values and dashed lines represent negative values.
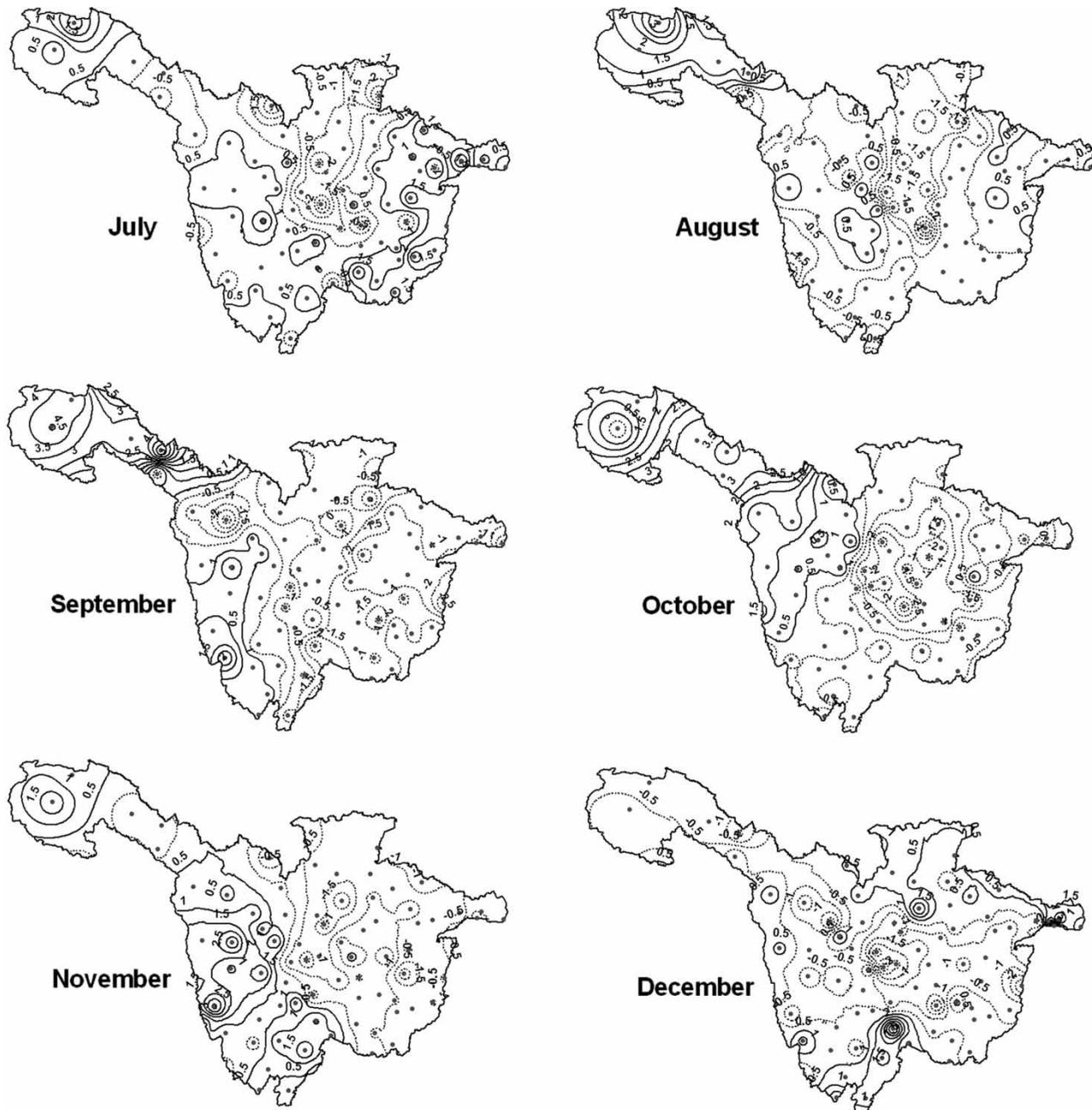
Figure 2 | continued

the arid URYR basin, where the data set included several zero or near zero precipitation values. In this paper, 3, 6, 9 and 12 month droughts (moderate/severe/extreme, abbreviated as MOD/SEV/EXT) were calculated (Table 5, Figures 3 and 4).

From Table 5, it can be seen that the mean of 3, 6, 9 and 12 month extreme droughts per 100 years were 2.54, 1.79, 1.67, and 0.81, respectively, for Jinshajing sub-basin. The numbers

of moderate and severe droughts were 24.69, 10.51, 7.68, 4.45 and 9.19, 7.52, 2.66, 1.83 also in Jinshajiang sub-basin, respectively. In Yalongjiang, Min-Tuojiang, Jialingjiang, Wujiang and Upper mainstream sub-basin, the number of 3-month time scale droughts of different severity per 100 years were greater than those in Jinshajiang sub-basin. Meanwhile, for 9 and 12-month time scales, the numbers of

Table 5 | Number of drought events in 100 years of different time periods at 3–12 month timescales

		Jinshajiang sub-basin	Yalongjiang sub-basin	Min-Tuojiang sub-basin	Jialingjiang sub-basin	Upper mainstream sub-basin	Wujiang sub-basin
Frequency of moderate drought	MOD3	24.69	20.75	26.32	25.25	25.27	28.4
	MOD6	10.51	13.59	14.9	14.53	15.38	16.54
	MOD9	7.68	8.23	9.23	9.74	9.33	10.14
	MOD12	4.45	5.39	4.48	6.63	6.36	8.16
Frequency of severe drought	SEV3	9.19	11.26	14.37	14.41	15.73	16.64
	SEV6	7.52	7.77	7.75	7.00	7.83	7.88
	SEV9	2.66	3.00	3.67	4.02	4.31	4.44
	SEV12	1.83	2.00	2.51	2.64	2.72	2.84
Frequency of extreme drought	EXT3	2.54	3.31	4.43	5.37	5.44	5.1
	EXT6	1.79	2.31	3.22	3.84	4.16	3.88
	EXT9	1.67	2.00	2.07	2.49	2.76	2.52
	EXT12	0.81	1.00	1.26	1.45	1.64	1.61
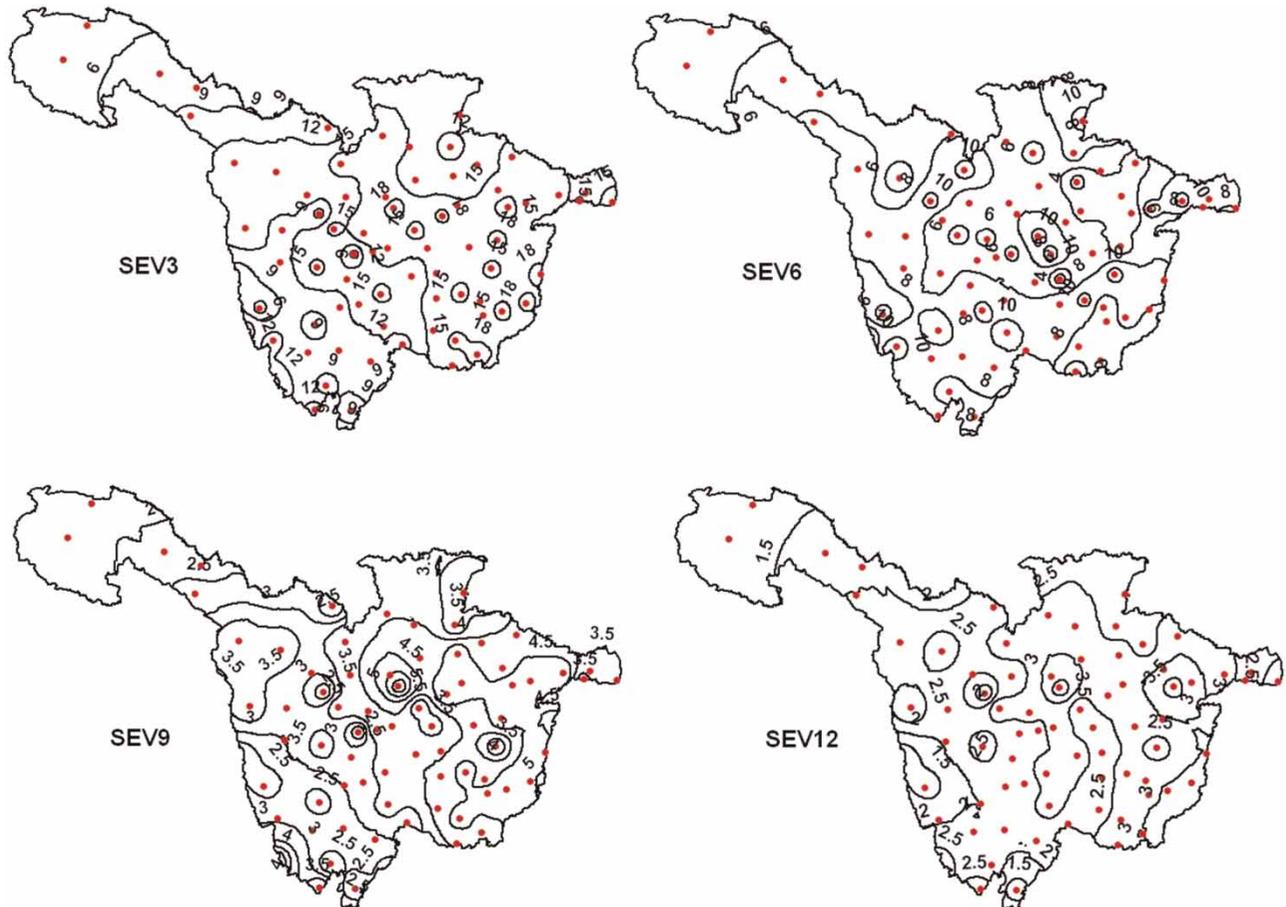
Figure 3 | Distribution of SEV 3–12 month (number of severe drought in 100 years).
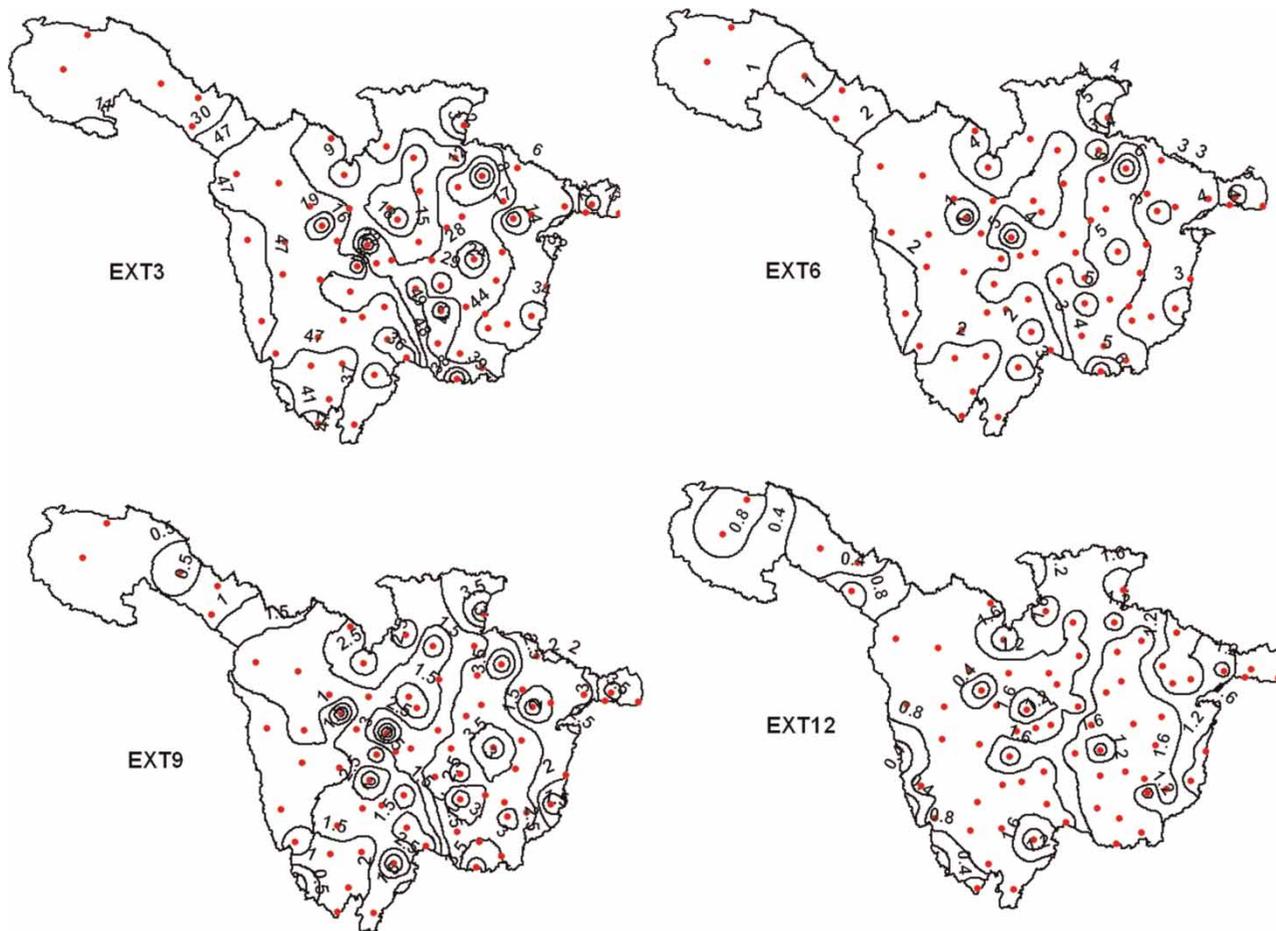
Figure 4 | Distribution of EXT 3–12 month (number of extreme drought in 100 years).

severity droughts were approximately the same. The stations subjected to a 3-month severe drought were concentrated in the Upper mainstream and Wujiang sub-basins, southeast of the Jialingjiang sub-basin (Figure 3), which were spring and summer drought areas (Shen 1996; Chen 1997). For the 6-month time scale, the stations subject to severe drought were concentrated in Jialingjiang and lower Jinshajiang sub-basin, which is the southwest part of Sichuan province and within Sichuan basin. The stations likely to suffer 6-month extreme droughts were mainly located in the middle of Jialingjiang, Wujiang and the upper mainstream sub-basin. No significant differences in the frequency of extreme and severe drought were apparent in Yalongjiang sub-basin. These results are consistent with others in recent years (Liu et al. 2009).

The 100-year frequency of severe drought events is greater in the middle part than that in the east part of the URYR basin. The Min-Tuojiang and low areas of Jinshajiang, Jialingjiang

sub-basins were subjected to severe drought events at 3, 6, 9 and 12 month timescales (Figure 3). This region is mainly in the Sichuan basin, which is the agricultural area in the URYR basin and frequent droughts result in reduced agricultural production and influence drinking water supply. Among different timescales, 3-month severe drought events (SEV3) happened mainly in the middle of Upper mainstream and Wujiang sub-basins, southeast of Jialingjiang sub-basin. The maximum is 16.64 for such events per 100 years. It means that there was one severe drought nearly every six years. The 6- and 9-month severe droughts (SEV6, SEV9) applied to the majority of Min-Tuojiang, Yalongjiang and Wujiang sub-basin. The 12-month severe drought (SEV12) occurred in the north of Jialingjiang sub-basin and middle part of the Upper mainstream sub-basin. This situation would have mainly affected the growth and propagation of Chinese sturgeon in the upper river stem, where is the main habitat of the fish.

Figure 4 shows that the frequency of extreme drought in the east part of URYR was greater than that in the west part. Wujiang and Upper mainstream sub-basin were subjected to extreme drought at 6, 9 and 12 month timescales. This region is mainly the rain-fed agricultural area in the URYR basin. The frequent droughts result in a reduction of agriculture and influence drinking water supply for local people. The statistics show that the ratio of water deficiency exceeds 30% and 10–30% in Wujiang and the Upper mainstream sub-basins, respectively (CWRC 2002). Figure 4 shows that 3-month extreme drought (EXT3) mainly occurred in the east of the URYR basin, including Upper mainstream, Jialingjiang and Wujiang sub-basins with maximum times for extreme drought of 8.99 in 100 years, which means there would be one devastating drought per 11 years. The 6- and 9-month extreme droughts (EXT6, EXT9) lessened within the area of the Upper mainstream and the south part of Jialingjiang sub-basins. This affected the ecosystem of the Upper main stream, leading to the hydrologic regime of the lower-middle reaches of Yangtze River.

From Table 5, Figures 3 and 4, the frequencies of drought for varying time periods are very different. According to the classification of SPI values and its cumulative probability of different events (Table 2), the frequency of drought for all time scales for a certain drought severity should be very close. The frequency of the certain drought for all timescales approached about 14.42, 6.43 and 3.07 for moderate, severe and extreme drought, respectively.

CONCLUSIONS

In order to understand the drought characteristics in the URYR basin, time series of drought index were calculated with SPI method from station-based meteorological data across the basin for the period of 1958–2008. The URYR basin was divided into six sub-basins according to the river system. The results from tables and maps are summarized in terms of occurrences of droughts in order to identify areas in the basin that were most frequently hit by drought events. Considering the severe and extreme drought category in the 12-month timescale, it occurred most frequently in the Upper mainstream basin. When the overall categories of drought were considered (severe and extreme

drought), areas in all sub-basins except Yalongjiang were most frequently hit by droughts.

Most parts of URYR basin showed a downward trend in precipitation for specific months. The changes of precipitation in Min-Tuojiang, east of Jinshajiang, west of Wujiang, west-middle of Upper mainstream sub-basins were detrimental to agricultural production and the ecosystem. In particular, the middle-western region of URYR requires a more efficient regulation to manage water resources in order to meet agricultural and drinking water demands.

More attention should be focused on precipitation trends and drought distribution for agricultural development decision-making process and drought hazards mitigation. Increasingly drier Summer-Autumn seasons can result in water logging damage in summer and insufficient soil moisture content in autumn.

Six, 9, and 12-month timescales drought have affected the Yalongjiang sub-basin less than the other sub-basins. This situation mainly affects lives of both urban and rural people as well as the agricultural development of the URYR basin.

Future studies are needed to investigate specific effects by droughts on the regional ecology environment.

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REFERENCES

Abramowitz, M. & Stegun, I. (eds) 1965 *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*. Dover, New York.

Barger, G. L., Shaw, R. H. & Dale, R. F. 1959 *Chances of Receiving Selected Amounts of Precipitation in the North Central Region of the United States*. Agricultural and Home Economics Experimental Station, Iowa State University, Ames, Iowa.

Bonaccorso, B., Bordi, I., Cancelliere, A., Rossi, G. & Sutera, A. 2003 Spatial variability of drought: an analysis of SPI in Sicily. *Water Resour. Manag.* **17**, 273–296.

Buishand, T. A. 1982 Some methods for testing the homogeneity of rainfall records. *J. Hydrol.* **58**, 11–27.

Chen, G. R. & Cheng, G. W. 1997 Drought analysis in the upper basin of ChangJiang river and disaster prevention/ abatement measures. *Resources and Environment in the Yangtze Valley* **6** (1), 75–78.

Chow, V., Maidment, R. & Mays, W. 1988 *Applied Hydrology*. McGraw-Hill, New York.

CWRC 2002 *CWRC 2002. Published Books of Flood and Drought Hazards in China*. China WaterPower Press, pp. 203–324.

Dai, Z. J., Du, J. Z., Li, J. F., Li, W. H. & Chen, J. Y. 2008 Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam. *Geophys. Res. Lett.* **35**, L07406.

Dai, Z. J., Chu, A., Du, J. Zh., Stive, M. & Yang, H. 2010 Assessment of extreme drought and human interference on baseflow of the Yangtze River. *Hydrol. Process.* **11** (6), 749–756.

Desalegn, C. E., Babel, M. S. & Das Gupta, A. 2010 Drought analysis in the Awash River Basin, Ethiopia. *Water Resour. Manag.* **24** (7), 1441–1459.

Domonkos, P. 2003 Recent precipitation trends in Hungary in the context of larger scale climatic changes. *Natural Hazards* **29** (2), 255–271.

Dracup, J. A., Lee, K. S. & Paulson Jr, E. G. 1980 On the definition of droughts. *Water Resour.* **16** (2), 297–302.

Edwards, D. & McKee, T. 1997 *Characteristics of 20th Century Drought in the United States at Multiple Scale*. Atmospheric Science Science Paper No. 634.

Gemmer, M., Becker, S. & Jiang, T. 2004 Observed monthly precipitation trends in China 1951–2002. *Theor. Appl. Climatol.* **77**, 39–45.

Guttman, N. B. 1998 Comparing the Palmer drought index and the standardized precipitation index. *J. Am. Water Resour. Assoc.* **34**, 113–121.

Guttman, N. B. 1999 Accepting the standardized precipitation index: a calculation algorithm. *J. Am. Water Resour. Assoc.* **35**, 311–322.

Hirsch, R., Helsel, D., Cohn, T. & Gilroy, E. 1993 Statistical analysis of hydrologic data. In: *Handbook of Hydrology* (D. Maidment ed.). McGraw-Hill, New York.

Husak, G., Michaelsen, J. & Funk, C. 2007 Use of gamma distribution to represent monthly rainfall in Africa for drought monitoring applications. *Int. J. Climatol.* **27**, 935–944.

Jiang, T., Su, B. D., Wang, X. J., Zhang, Q., Qin, N. X. & Shi, Y. F. 2005 Trends of temperature, precipitation and runoff in the Yangtze River basin from 1961 to 2000. *Adv. Climate Change Res.* **1** (2), 65–68.

Jiang, T., Zhang, Q., Zhu, D. M. & Wu, Y. J. 2006 Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). *Quatern. Int.* **144** (1).

Jiang, T., Su, B. D. & Hartmann, H. 2007 Temporal and spatial trends of precipitation and river flow in the Yangtze River Basin, 1961–2000. *Geomorphology* **85** (3), 143–154.

Kangas, R. & Brown, T. 2007 Characteristics of US drought and pluvials from a high-resolution spatial dataset. *Int. J. Climatol.* **27**, 1303–1325.

Kendall, M. G. 1962 *Rank Correlation Methods*. Hafner, New York.

Komuscu, A. U. 1999 Using the SPI to analyze spatial and temporal pattern of drought in Turkey. *Drought Netw. News* **11**, 7–13.

Łabedzki, L. 2007 Estimation of local drought frequency in central Poland using the standardized precipitation index SPI. *Irrig. Drain* **56**, 67–77.

Lana, X., Serra, C. & Burgueno, A. 2002 Patterns of monthly rainfall shortage and excess in terms of the standardized precipitation index for Catalonia (NE Spain). *Int. J. Climate* **21** (13), 1669–1691.

Lloyd-Hughes, B. & Saunders, M. A. 2002 A drought climatology for Europe. *Int. J. Climatol.* **22**, 1571–1592.

Liu, Y. Y. & Ding, Y. H. 2009 Influence of the Western North Pacific Summer Monsoon on Summer Rainfall over the Yangtze River Basin. *Chin. J. Atmos. Sci.* **33** (6), 1226–1236.

Liu, X. R., Cheng, B. Y., Yang, X., Zhang, T. Y. & Deng, B. S. H. 2009 Changing characteristics of high temperature and drought of Sichuan–Chongqing regions in summer and its analysis of circulation patterns in anomalous years. *Plateau Meteorol.* **28** (2), 306–312.

Mann, H. B. 1945 Nonparametric tests again trend. *Econometrica* **13**, 245–259.

Maniak, U. 1997 *Hydrologie und Wasserwirtschaft*. Springer, Berlin (in German).

Mathieu, R. & Richard, Y. 2003 Intensity and spatial extension of drought in South Africa at different time scales. *Water SA* **29** (4), 489–500.

McKee, T. B., Doesken, N. J. & Kleist, J. 1995 Drought monitoring with multiple time scales. In *Ninth Conference on Applied Climatology*. American Meteorological Society, Dallas, Texas, pp. 233–236.

Min, S. K., Kwon, W. T., Park, E. H. & Choi, Y. 2003 Spatial and temporal comparisons of droughts over Korea with East Asia. *Int. J. Climate* **23** (2), 223–233.

Morid, S., Smakhtin, S. & Moghaddasi, M. 2006 Comparison of seven meteorological indices for drought monitoring in Iran. *Int. J. Climatol.* **26**, 971–985.

Nalbantis, I. & Tsakiris, G. 2009 Assessment of hydrological drought revisited. *Water Resour. Manag.* **23**, 881–897.

Pandey, R. P., Mishra, S. K., Singh, R. & Ramasastri, K. S. 2008 Streamflow drought severity analysis of Betwa river system (India). *Water Resour. Manag.* **22**, 1127–1141.

Pang, X. Y., Bao, W. K. & Wu, N. 2008 Reasons of dry valley climate characteristic and its formation reason in upstream of MinJiang river. *Resources and Environment in the Yangtze Basin* **17** (1), 46–52.

Paulo, A. & Pereira, L. 2006 Drought concepts and characterization: comparing drought indices applied at local and regional scales. *Water Int.* **31** (1), 37–49.

Raziei, T., Sagfahian, B., Paulo, A. A., Pereira, L. S. & Bordi, I. 2009 Spatial patterns and temporal variability of drought in Western Iran. *Water Resour. Manag.* **23**, 439–455.

Seiler, R., Hayes, M. & Bressan, L. 2002 Using the standardized precipitation index for flood risk monitoring. *Int. J. Climate* **22**, 1365–1376.

Shen, H. Y. 1996 Background analysis of droughty weather for the Yangtze River Basin. *Yangtze River* **27** (12), 36–38.

Shiau, J. T. 2006 Fitting drought duration and severity with two dimensional copulas. *Water Resour. Manag.* **20**, 795–815.

Silva, V. 2005 On climate variability in Northeast of Brazil. *J. Arid Environ.* **58** (4), 575–596.

Sneyers, R. 1990 *On the Statistical Analysis of Series of Observation.* Technical Note No. 143, WMO, Geneva.

Tallaksen, L. M. & van Lanen, H. A. J. (eds) 2004 *Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater.* Developments in Water Sciences, Vol. 48, Elsevier, Dordrecht, The Netherlands.

Thom, H. C. S. 1966 *Some Methods of Climatological Analysis.* Technical Note No. 81, WMO, Geneva.

Tsakiris, G. & Vangelis, H. 2004 Towards a drought watch system based on spatial SPI. *Water Resour. Manag.* **18**, 1–12.

Tsakiris, G., Pangalou, D. & Vangelis, H. 2007 Regional drought assessment based on the Reconnaissance Drought Index (RDI). *Water Resour. Manag.* **21**, 821–833.

Türkeş, M. & Tatlı, H. 2009 Use of the standardized precipitation index (SPI) and a modified SPI for shaping the drought probabilities over Turkey. *Int. J. Climatol.* **29**, 2270–2281.

Vermes, L. 1998 *How to Work Out a Drought Mitigation Strategy.* ICID Guide 309/1998, DVWK, Bonn, Germany.

Wang, J. & Wang, S. X. 2002 *Flood and Drought Hazards in Yangtze River Basin.* CWRC Publication, BeiJing, China, pp. 203–324.

Wilks, D. S. 1995 *Statistical Methods in the Atmospheric Sciences: An Introduction.* Academic, San Diego.

Wilhite, D. A. & Glantz, M. H. 1985 Understanding the drought phenomenon: the role of definitions. *Water Int.* **10** (3), 111–120.

Wu, H., Svoboda, M., Hayes, M., Wilhite, D. & Wen, F. 2007 Appropriate application of the Standardized Precipitation Index in arid locations and dry seasons. *Int. J. Climatol.* **27**, 65–79.

Wu, H., Hayes, M., Wilhite, D. & Svoboda, M. 2005 The effect of the length of record on the standardized precipitation index calculation. *Int. J. Climatol.* **25**, 505–520.

Xu, J. J., Yang, D. W., Lei, Z. D. & Huang, W. 2008 Study of drought evaluation method in the upper basin of Yangtze river. *Yangtze River* **39** (11), 1–5.

Yu, Y., Zou, S. & Whittemore, D. 1993 Non-parametric trend analysis of water quality data of rivers in Kansas. *J. Hydrol.* **150**, 61–80.

Zhai, L. X. & Qi, F. 2009 Spatial and temporal pattern of precipitation and drought in Gansu Province, Northwest China. *Nat Hazards* **49**, 2–22.

Zhang, Q., Gemmer, M. & Chen, J. Q. 2008 Climate changes and flood/drought risk in the Yangtze Delta, China, during the past millennium. *Quatern. Int.* **176–177**, 62–69.

Zeng, X. F., Zhai, H. Q., Jiang, T. & Su, B. D. 2008 Spatial characteristics and evolutional trends of annual precipitation in the Yangtze River basin. *J. Hohai University (Nat. Sci.)* **36** (6), 727–73.