Quaternary International 313-314 (2013) 118–129

Contents lists available at SciVerse ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Changes in precipitation extremes over Shaanxi Province, northwestern China, during 1960–2011

Wenli Liu, Mingjun Zhang*, Shengjie Wang, Baolong Wang, Fei Li, Yanjun Che

College of Geography and Environmental Science, Northwest Normal University, Lanzhou, 730030, China

ARTICLE INFO

Article history:
Available online 19 July 2013

ABSTRACT

Changes in indices of precipitation extremes were analyzed on the basis of daily precipitation observational data at 19 surface meteorological stations over Shaanxi Province during 1960–2011, originating from the China Meteorological Administration. Ten indices of extreme precipitation were studied. Maximum 1-day precipitation, very wet day precipitation, extremely wet day precipitation, simple daily intensity index, and consecutive dry days in the study area during 1960–2011 exhibit non-significant increasing trends. Decreasing trends are found for maximum 5-day precipitation, wet day precipitation, number of heavy precipitation days, number of very heavy precipitation days, and consecutive wet days, all statistically non-significant. For number of heavy precipitation days and consecutive wet days, stations in the study region have consistently negative trends. The variation trends for the other extreme precipitation indices have regional differences, and the change patterns of these indices are not spatially clustered. Very wet day precipitation experiences abrupt decreases in 1977 and 1985, while a significant abrupt increase change for extremely wet day precipitation is detected in 1983. There are multiple cycles in the changes for the very wet day precipitation and extremely wet day precipitation over Shaanxi Province during 1960–2011, showing variations of time and frequency. Except for consecutive dry days, the other extreme precipitation indices have high correlations with annual total precipitation. The elevation is positively correlated with consecutive dry days. There are negative correlations between the other extreme precipitation indices and elevation.

1. Introduction

With global warming (IPCC, 2007) and global hydrological cycle accelerating subsequently (Trenberth et al., 2003; Christensen and Christensen, 2004), the frequency of extreme precipitation events is increasing worldwide (Alexander et al., 2006). Similarly to the global trend, there is an increase in extreme precipitation events in the mid-latitude and high-latitude land areas of the Northern Hemisphere (Hore, 1981; IPCC, 2001; Frich et al., 2002; Haylock and Goodess, 2004; Groisman et al., 2005; IPCC, 2007). The increase in extreme precipitation events triggers the frequent occurrence of meteorological disasters such as droughts and floods, having catastrophic impacts on human socio-economic development (Changnon et al., 2000; McBean, 2004; Parry et al., 2007; Norbiato et al., 2007). Therefore, research regarding precipitation extremes has recently received much attention (Klein Tank and Konnen, 2003; Christensen and Christensen, 2004; Schmidli and Frei, 2005; Goswami et al., 2006; Michel, 2007; Su et al., 2008; Pal and Al-Tabbaa, 2009; Yang et al., 2010; Hidalgo-Muñoz et al., 2011; Li et al., 2012; Boccolari and Malmusi, 2013). Precipitation extremes have increased in the United States, Canada, Australia, Britain, Norway, Mexico, Poland, the former Soviet Union, and India (Karl et al., 1995, 1996; Nicholls, 1995; Dai et al., 1998; Karl and Knight, 1998; Groisman et al., 1999; Eastering et al., 2000; Frich et al., 2002; Kunkel, 2003; Klein Tank and Konnen, 2003; Groisman et al., 2004, 2005; Goswami et al., 2006). In China, the variation tendency in extreme precipitation events is basically consistent with that worldwide, namely, the occurrence of Chinese precipitation extremes is also increasing and has apparent regional characteristics (Yan and Yang, 2000; Qin et al., 2005; Zhai et al., 2007; Ren et al., 2010). Some studies suggest that the changes in precipitation extremes in different regions over China are distinct in recent decades. For example, a decrease in extreme precipitation events has been reported in northern China, central China, east-northeastern China, and southeast-northwestern China, while the extreme precipitation events have increased in west-northwestern China, southwestern China,

* Corresponding author.
E-mail address: mjzhang2004@163.com (M. Zhang).

1040-6182/$ – see front matter © 2013 Elsevier Ltd and INQUA. All rights reserved.
http://dx.doi.org/10.1016/j.quaint.2013.06.033

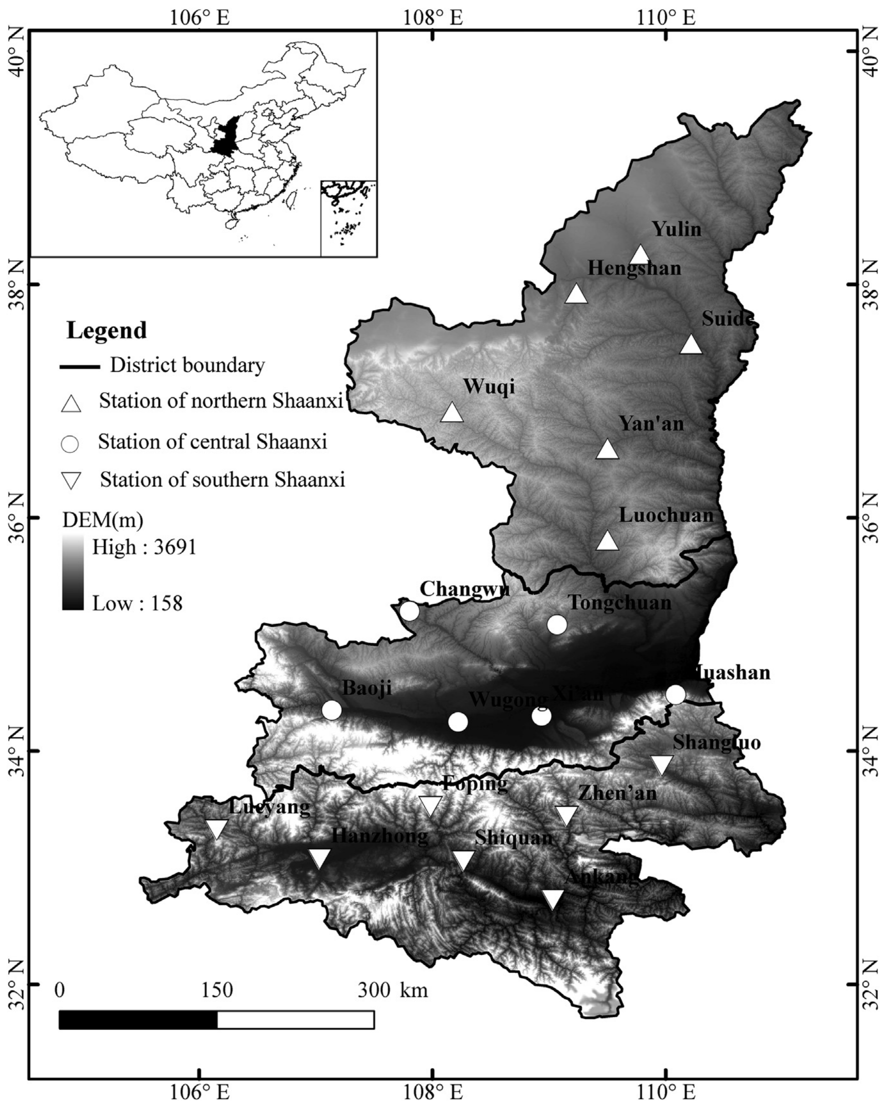

Fig. 1. Distribution of meteorological stations over Shaanxi Province.

coastal southern China, west-northeastern China, and middle and lower Yangtze River (Zhai et al., 1999a,b; Zhai and Pan, 2003; Qin et al., 2005; Wang and Zhou, 2005; Zhai et al., 2005, 2007; Jiang et al., 2007; Yang et al., 2008a,b).

Shaanxi Province is located at the transition zone between the coastal monsoon climate area in southeastern China and the continental climate area in northwestern China, a part of an ecological environmental vulnerable region (Yan et al., 2010). Being one of the provinces where natural disasters are frequent and serious in China, the province has many kinds of meteorological disasters, and drought-flood damage is severe (Li, 2004). With extreme climate events happening frequently, an increase in the frequency of drought-flood disasters appearing in Shaanxi Province has been found in recent years (Xiao and Zhao, 2006; Gao et al., 2012a,b), which has caused many adverse influences on the residents' life and property security, economic development, agricultural production, and ecological environment (Li, 2004; Sang and Zha, 2011; Gao et al., 2012a,b). In order to reduce disaster losses, it is necessary to discuss the causes to result in more serious drought-flood disasters. Precipitation extremes are one of the important causes (Xu et al., 2005; Zhang et al., 2009). Consequently, it is of practical importance to understand comprehensively and systematically the temporal and spatial variation characteristics in drought-flood disasters in the province, and to improve the ability for the prevention and mitigation of natural hazards to study the changes in precipitation extremes.

In the context of the decrease in precipitation extremes in southeast northwestern China, the changes in precipitation extremes in Shaanxi Province have attracted some scholars' attention in recent years. Li (2008) discussed the changes in extreme precipitation events in Shaanxi Province by using the number of precipitation days and heavy rain days. Xu (2009) employed maximum daily precipitation to study the temporal and spatial distribution characteristics in precipitation extremes in Shaanxi Province. Jiang et al. (2011a,b) analyzed the spatiotemporal evolution characteristics of extreme heavy precipitation in Shaanxi Province during 1961–2009 by defining the threshold of extreme heavy precipitation events. Cai et al. (2012) investigated the temporal and spatial variability in precipitation extremes over Shaanxi Province during 1961–2010 by applying the number of heavy rain days, threshold of extreme precipitation, severe dry events, and serious wet events. However, less extreme precipitation indices were used in these previous investigations. There are few studies applying multiple indices. Therefore, 19 meteorological stations where the sequences of observed data are complete in Shaanxi Province were selected, together with ten extreme precipitation indices generated by the joint CCl/CLIVAR/JCOMM ETCCDI, to investigate more comprehensively the changes in precipitation extremes over Shaanxi Province during 1960–2011. Analyzing the changes in precipitation extremes will hopefully provide a scientific basis for the studies in natural hazards in the province and regional responses to global climate change.

2. Data and methods

2.1. Study area and data

Shaanxi Province, situated in the east of northwestern China, ranges from 31°42′ to 39°35′N and from 105°29′ to 111°15′E, and is surrounded by eight provinces (regions or municipality): Inner Mongolia Autonomous Region, Shanxi Province, Henan Province, Hubei Province, Chongqing Municipality, Sichuan Province, Gansu Province, and Ningxia Hui Autonomous Region. According to administrative zoning, the province is divided into three districts: northern, central, and southern Shaanxi (Fig. 1).

According to the standards whereby observed data are continuous and data series are as long as possible, 19 meteorological stations in Shaanxi Province were selected (Fig. 1). All the selected meteorological stations are identified by their World Meteorological Organization (WMO) numbers, station names, latitudes, longitudes, and elevations (Table 1. These stations spread comparatively uniformly over Shaanxi Province. The daily precipitation observational data during 1960–2011 are provided by the National Meteorological Information Center of China Meteorological Administration. All the observed daily precipitation data have been subject to strict quality control (including extreme value test and time consistency test) using the software RClimDex V1 obtained from http://etccdi.pacificclimate.org.

Table 1
List of the selected meteorological stations in Shaanxi Province, including the World Meteorological Organization (WMO) Number, Station Name, Latitude, Longitude and Elevation.

WMO number	Station name	North latitude	East longitude	Elevation(m)
53646	Yulin	38°16′	109°47′	1157
53738	Wuqi	36°55′	108°10′	1331.4
53740	Hengshan	37°56′	109°14′	1111
53754	Suide	37°30′	110°13′	929.7
53845	Yan'an	36°36′	109°30′	958.5
53942	Luochuan	35°49′	109°30′	1159.8
53929	Changwu	35°12′	107°48′	1206.5
53947	Tongchuan	35°5′	109°4′	978.9
57016	Baoji	34°21′	107°8′	612.4
57034	Wugong	34°15′	108°13′	447.8
57036	Xi'an	34°18′	108°56′	397.5
57046	Huashan	34°29′	110°5′	2064.9
57106	Lueyang	33°19′	106°9′	794.2
57127	Hanzhong	33°4′	107°2′	509.5
57134	Foping	33°31′	107°59′	827.2
57143	Shangluo	33°52′	109°58′	742.2
57144	Zhen'an	33°26′	109°9′	693.7
57232	Shiquan	33°3′	108°16′	484.9
57245	Ankang	32°43′	109°2′	290.8

2.2. Methods

Ten extreme precipitation indices used in this study were selected from the core indices list recommended by the joint CCl/CLIVAR/JCOMM ETCCDI (http://etccdi.pacificclimate.org) (Table 2). These indices were calculated by the software RClimDex V1. They can reflect the change of extreme precipitation in different aspects with relatively weak extremes, low noise, and strong significance (Frich, 1999), and they have been widely used to assess the changes in daily precipitation extremes (Klein Tank et al., 2006; Caesar et al., 2011; Vincent et al., 2011; You et al., 2011). The ten selected extreme precipitation indices were classified into two types (Wang et al., 2013a) in this study. One type is indices in precipitation (RX1day, RX5day, PRCPTOT, R95p and R99p) and SDII. The other type is indices in the number of precipitation days (R10 mm, R20 mm, CDD and CWD).

Table 2
Definitions of ten extreme precipitation indices used in this study. [a]

Index	Descriptive name	Definition	Units
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm
PRCPTOT	Wet day precipitation	Annual total precipitation from wet days	mm
SDII	Simple daily intensity index	Average precipitation on wet days	mm/d
R95p	Very wet day precipitation	Annual total precipitation when RR > 95th percentile of 1960–2011 daily precipitation	mm
R99p	Extremely wet day precipitation	Annual total precipitation when RR > 99th percentile of 1960–2011 daily precipitation	mm
R10 mm	Number of heavy precipitation days	Annual count of days when RR ≥ 10 mm	d
R20 mm	Number of very heavy precipitation days	Annual count of days when RR ≥ 20 mm	d
CDD	Consecutive dry days	Maximum number of consecutive dry days	d
CWD	Consecutive wet days	Maximum number of consecutive wet days	d

[a] All indices were calculated by RClimDex. Abbreviation is as follows: RR, daily precipitation. A wet day is defined when RR ≥ 1 mm and a dry day when RR < 1 mm.

In addition, the methods of linear tendency estimate, probability distribution functions, sequential Mann–Kendall test, Morlet wavelet analysis were employed to analyze the temporal variations in precipitation extremes. The ArcGIS was applied to plot the spatial distributions of the variation trends in these extreme precipitation indices. The method of correlation analysis was utilized to analyze the relationship between extreme precipitation indices and annual total precipitation, and the relationship between extreme precipitation indices and elevation (Fig. 1).

3. Results

3.1. Indices in precipitation and SDII

During the period of 1960–2011, the RX1day in Shaanxi Province shows a slight increasing trend (Fig. 2a), while there is a statistically non-significant decreasing tendency for RX5day (Fig. 2b). The regional trends for these two indices are 0.35 and −0.77 mm/decade, respectively (Table 3). For RX1day, about 58% of the meteorological stations have positive trends (Table 3), and these stations are mainly in southern Shaanxi, with some in central and northern Shaanxi (Fig. 3a). The stations where RX5day exhibits negative trends account for 58% (Table 3), primarily in northern and southern Shaanxi (Fig. 3b). The other stations have positive tendencies (Table 3), and they are spread relatively evenly in northern, central, and southern Shaanxi (Fig. 3b).

Table 3
Trends per decade and percentage of stations with positive or negative trends for regional indices of precipitation extremes over Shaanxi Province during 1960–2011.

Index	Regional trends	Range	Percentage of stations showing positive trend	Percentage of stations showing significant positive trend	Percentage of stations showing negative trend	Percentage of stations showing significant negative trend
RX1day	0.35	−3.16 to 2.82	58%	0%	42%	0%
RX5day	−0.77	−4.09 to 3.51	42%	0%	58%	0%
PRCPTOT	−10.24	−38.30 to 14.80	16%	0%	84%	13%
SDII	0.06	−0.29 to 0.31	68%	15%	32%	17%
R95p	1.95	−15.12 to 27.44	53%	10%	47%	0%
R99p	1.93	−9.00 to 13.10	58%	9%	42%	0%
R10 mm	−0.53	−1.36 to −0.11	0%	0%	100%	11%
R20 mm	−0.07	−0.44 to 0.55	37%	0%	63%	0%
CDD	0.66	−2.32 to 2.45	79%	0%	21%	0%
CWD	−0.20	−0.40 to −0.02	0%	0%	100%	11%

As Fig. 2c and d show, the PRCPTOT over Shaanxi Province during 1960–2011 has decreased at a rate of 10.24 mm/decade, while SDII has increased by 0.06 mm/d/decade. As for PRCPTOT, 84% of meteorological stations show negative trends, and 13% have statistically significant negative trends (Table 3). The stations displaying decreasing trends for PRCPTOT appear throughout the whole research region, and Suide in northern Shaanxi and Huashan in central Shaanxi are statistically significant at the 0.05 level (Fig. 3c). The stations with increasing trends for PRCPTOT are scattered sporadically in central and southern Shaanxi (Fig. 3c). The percentages of stations with positive trends and stations with negative trends for SDII are 68% (15% statistically significant) and 32% (17% statistically significant), respectively (Table 3). A consistent increasing trend for SDII is observed in southern Shaanxi, and

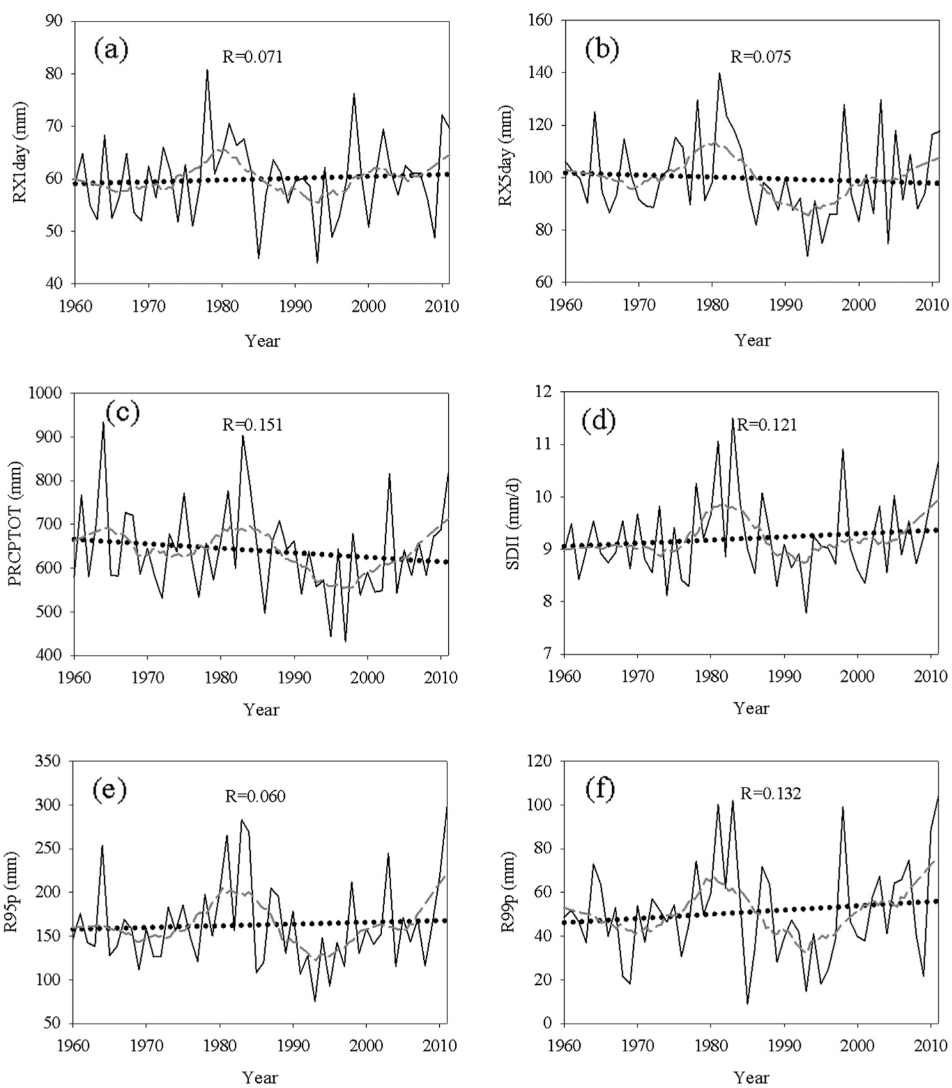

Fig. 2. Regional annual series for the indices in precipitation and SDII over Shaanxi Province during 1960–2011. (The dotted line is the linear trend and R is its correlation coefficient. The dashed line is the 10-year smoothing average.)

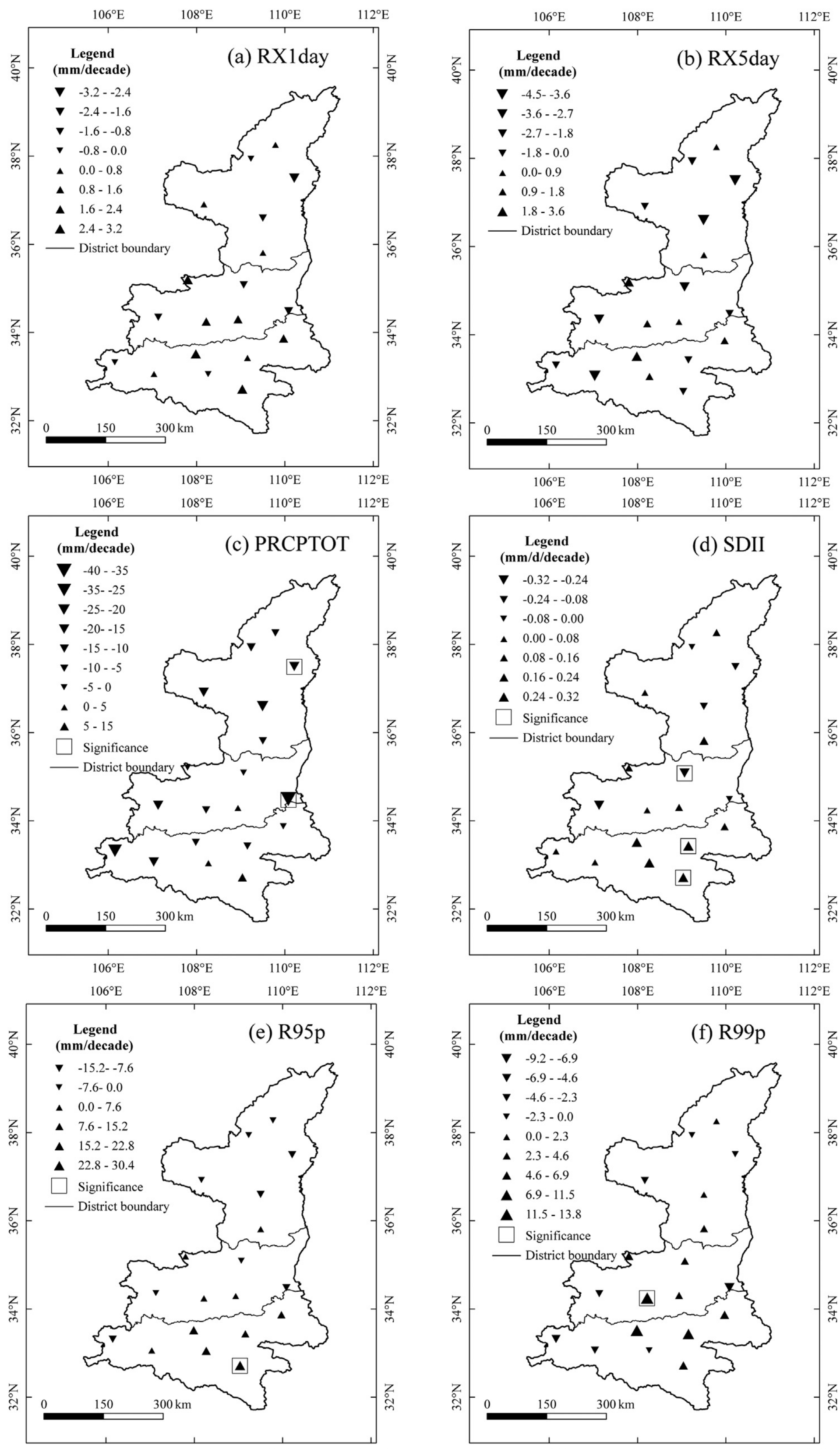

Fig. 3. Spatial patterns of trends per decade for the indices in precipitation and SDII over Shaanxi Province during 1960–2011.

the Zhen'an and Ankang stations in this district reach 95% confidence level (Fig. 3d). Half of the stations in northern and central Shaanxi show decreasing trends, and that for Tongchuan in central Shaanxi is statistically significant at the 0.05 level (Fig. 3d).

Both the R95p and R99p in Shaanxi Province over the analysis period show increasing trends with fluctuations (Fig. 2e and f). The regional trends in R95p and R99p are 1.95 and 1.93 mm/decade, respectively (Table 3). The trend rate for R95p ranges from −15.12 to 27.44 mm/decade (Table 3). In the research area, 53% of meteorological stations for R95p have positive trends and the proportion of stations with statistically significant positive trends is 10% (Table 3). Most of the stations situated in southern Shaanxi have increasing trends for R95p, and Ankang in this district is significant at 95% confidence level (Fig. 3e). The stations showing decreasing trends for R95p are centered on northern Shaanxi, and there are the same number of stations with increasing and decreasing trends in central Shaanxi (Fig. 3e). For R99p, 58% of the stations have positive trends, and 9% of them present statistically significant positive trends (Table 3). The stations experiencing increases and undergoing decreases for R99p are distributed relatively homogeneously in northern, central, and southern Shaanxi (Fig. 3f). The station where the increasing trend for R99p is statistically significant at the 0.05 level is Wugong in central Shaanxi (Fig. 3f).

In order to further investigate the temporal variation characteristics in extreme precipitation over Shaanxi Province in the past 52 years, R95p and R99p were chosen to analyze their interdecadal change trends, abrupt step change years, and change cycles. As the Probability Distribution Function of R95p (Fig. 4a) shows, R95p represents a decreasing trend from the 1960s to the 1970s, then increases rapidly in the 1980s, decreases in the 1990s, and displays an increasing trend again the 1990s to the period of 2000–2011, which is identical with previous study results (Jiang et al., 2011a,b). R99p (Fig. 4b) exhibits a continuous positive tendency from the 1960s to the 1980s, and shows a persistent negative trend subsequently.

Fig. 5 demonstrates the sequential Mann–Kendall analysis results for the R95p and R99p over Shaanxi Province during the study period. Several abrupt step changes are detected during 1960–2011, with only the abrupt decreasing step changes happening in 1977 and 1985 being statistically significant (Fig. 5a). There are four abrupt change years in the whole change process of time sequence for R99p: 1961, 1980, 1983, and 2010 (Fig. 5b). A significant abrupt increase step change for R99p is found in 1983, while R99p experiences statistically non-significant abrupt changes in the other years (Fig. 5b).

Fig. 6a and c show the time-frequency distributions in the real part of the Morlet wavelet analysis for the R95p and R99p in Shaanxi Province during 1960–2011. For R95p, there are three scales of change cycles: 5-year, 10-year, and 25-year cycles (Fig. 6a). The 5-year cycle appears mainly before the 1970s, during 1976–1992 and in the 21st century (Fig. 6a). The interdecadal variation cycles of 10-year and 25-year scales exist almost throughout the whole change process of time sequence (Fig. 6a). Four variation periods for R99p are found: 5-year cycle, 7-year cycle, 8–15-year cycle and 27-year cycle (Fig. 6c). The 7-year cycle is relatively obvious during 1980–1997 only, while the change periods of 5-year, 8–15-year and 27-year scales emerge during the whole study period with good continuity (Fig. 6c). Owing to the false oscillation existing in the real part of Morlet wavelet analysis, it is necessary to analyze the time-frequency distributions in the modulus square of the Morlet wavelet analysis for R95p and R99p (Fig. 6b and d) to verify further the stability of their periodic changes. The oscillating energy of the 5-year cycle during 1976–1992 for R95p is comparatively strong, while the oscillating energies of the other variation periods are relatively weak and exist in the whole time domain (Fig. 6b). For R99p, strong oscillating energies for change periods are detected except for the 27-year cycle (Fig. 6d). The oscillation energies of 5-year cycle and 8–15-year cycle are through the whole time domain, whereas the oscillating energy of 7-year cycle is mainly observed during 1980–1997 (Fig. 6d). On the whole, the time-frequency distribution characteristics of period changes found for the real part of Morlet wavelet analysis agree basically with those found for the modulus square of Morlet wavelet analysis in the period analysis for the R95p and R99p over Shaanxi Province, which guarantees the periodic stability of R95p and R99p. Without a fixed cycle, but multiple cycles, such as small-scale cycle, middle–scale cycle and large-scale cycle, are detected for the changes in the R95p and R99p over Shaanxi Province in the past 52 years, showing strong variable characteristics of time and frequency.

3.2. *Indices in the number of precipitation days*

Both the R10 mm and R20 mm over Shaanxi Province during the research period have decreased at the rates of 0.53 and 0.07 d/decade, respectively (Table 3). The decreasing trend for R10 mm is more significant than that for R20 mm (Fig. 7a and b). A uniform decreasing trend for R10 mm is detected in the whole study region (Fig. 8a). The trend rate for R10 mm varies from −1.36 to −0.11 d/decade (Table 3). The meteorological stations undergoing statistically significant decreases are Baoji and Huashan located in central Shaanxi, passing the statistically significant test at the 0.05 level (Fig. 8a). For R20 mm, more than half (63%) of stations have negative trends (Table 3) mainly in northern Shaanxi and central Shaanxi (Fig. 8b). There are only seven stations exhibiting increasing trends for R20 mm and they are mainly situated in southern Shaanxi (Fig. 8b).

The CDD in study area during 1960–2011 exhibits an increasing trend with statistical non-significance, whereas a clear decreasing

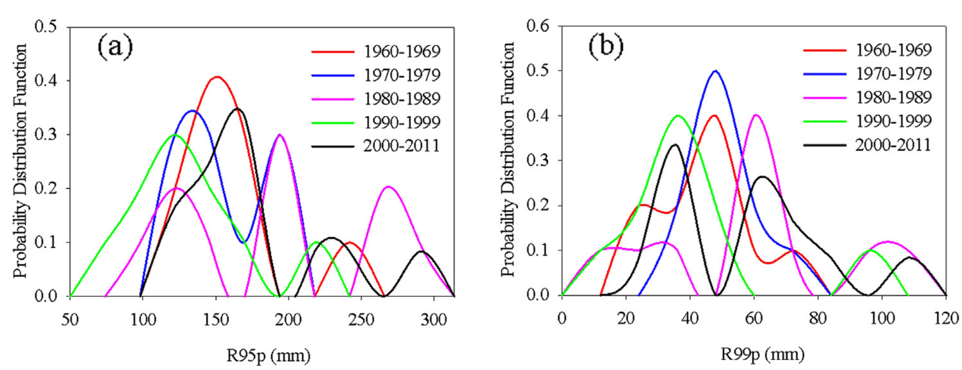

Fig. 4. Probability distribution functions of R95p (a) and R99p (b) over Shaanxi Province during 1960–2011.

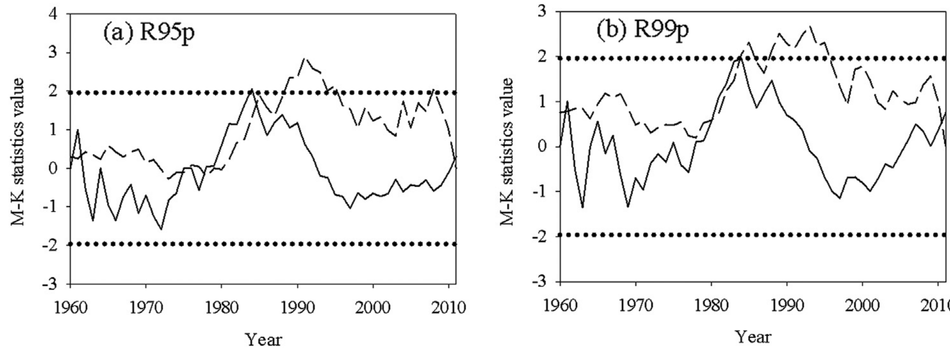

Fig. 5. Sequential Mann–Kendall analysis results for the R95p (a) and R99p (b) over Shaanxi Province during 1960–2011. (The solid and dashed lines are forward and backward series, respectively, and horizontal dotted lines are the 0.05 confidence level.)

trend is found for CWD (Fig. 7c and d). The regional trends for these two indices are 0.66 and −0.20 d/decade, respectively (Table 3). The meteorological stations with increasing trends for CDD are located throughout southern Shaanxi, most parts of northern Shaanxi and parts of central Shaanxi (Fig. 8c), accounting for 79% of the stations in Shaanxi Province (Table 3). The stations having decreasing trends appear sporadically in the research area (Fig. 8c). The change in CWD shows apparent spatial consistency in the study area and all the stations display decreasing trends (Fig. 8d). For CWD, about 11% of stations have negative trends that are statistically significant at 95% confidence level (Table 3), Luochuan in northern Shaanxi and Lueyang in southern Shaanxi, respectively (Fig. 8d).

3.3. *Precipitation extremes correlated with annual total precipitation*

In order to validate whether the extreme precipitation indices used in this study have indicative functions for the change of annual total precipitation or not, the correlation coefficients between annual total precipitation and selected extreme precipitation indices were acquired (Table 4). Except for CDD, the other extreme precipitation indices have positive correlations with annual total precipitation and their correlation coefficients are statistically significant at the 0.01 level, which is consistent with previous results (Wang et al., 2013b). The correlation coefficients between selected extreme precipitation indices with annual total precipitation exceed 0.30, other than CDD. The research result implies that these extreme precipitation indices have significant correlations with annual total precipitation, especially the PRCPTOT, R10 mm and R20 mm whose correlation coefficients are more than 0.90. Therefore, the extreme precipitation indices used in this study have indicative functions for the change of annual total precipitation over Shaanxi Province apart from CDD. In other words, the increases or decreases in precipitation extremes will reflect the increase or decrease in annual total precipitation.

The ratio between extreme precipitation and annual total precipitation can reflect the contribution of extreme precipitation to annual total precipitation, and can also reveal the contribution of precipitation extremes to floods to some degree (Bao and Huang, 2006). The contribution rate of R95p to annual total precipitation over Shaanxi Province during the study period shows a slight increasing trend at a rate of 0.59%/decade (Fig. 9a), and ranges from 13.20% to 35.73% with the mean contribution rate of 24.61%. Similarly, a non-significant increasing tendency for the contribution rate of R99p to annual total precipitation is observed (Fig. 9b). The regional trend in this ratio, average contribution rate and the variation range of the contribution rate are 0.36%/decade, 7.74% and between 1.37% and 14.35%, respectively. The results above indicate that the contribution of extreme precipitation to annual total precipitation has increased, and reveal that the contribution of precipitation extremes to floods has increased as well.

3.4. *Relationship between precipitation extremes and elevation*

As Fig. 10 shows, CDD is positively correlated with elevation, whereas the other extreme precipitation indices are negatively correlated with elevation over Shaanxi Province during 1960–2011. There are trends towards decreases for these extreme precipitation indices with elevation except CDD (Fig. 10). The decreasing trends for RX5day, SDII and R20 mm are statistically significant at the 0.05 level. As is shown in Table 5, with elevation increase, CDD exhibits a decrease-increase-decrease tendency, while all the other extreme precipitation indices display increase-decrease-increase trends. CDD decreases when the other indices increase from the elevation of 200–400 m to 400–600 m. At the elevation rank of 400–600 m, RX1day, RX5day, SDII and CWD reach maximum values, CDD presents a relatively small value, and the other indices have comparatively large values. Above 600 m asl, CDD increases continuously, whereas the other indices reduce persistently with elevation. At the elevation of 1000–1200 m, CDD attains a maximum value, while the other indices have minimum values except RX1day and SDII. The minimum values for RX1day and SDII emerge at 1200–1400 m elevation. After the maxima and minima values, CDD decreases, while the other indices increase with elevation. CDD is minimum, whereas PRCPTOT, R95p, R99p, R10 mm, R20 mm and CWD are maximum when elevation is 1400–2200 m. In short, maximum value and minimum values for CDD appear at the elevation of 1000–1200 m and 1400–2200 m, respectively. For the other extreme precipitation indices, the maximum values center mainly at 400–600 m and 1400–2200 m elevations, while the minimum values exist mainly at elevations of 1000–1200 m and 1200–1400 m.

Table 4
Correlation coefficients between annual total precipitation and selected extreme precipitation indices over Shaanxi Province during 1960–2011.

	RX1day	RX5day	PRCPTOT	SDII	R95p	R99p	R10 mm	R20 mm	CDD	CWD
Annual total precipitation	0.370**	0.682**	1.000**	0.655**	0.838**	0.528**	0.966**	0.936**	−0.147	0.454**

**Significant at the 0.01 level.

Table 5
Variation of selected extreme precipitation indices in categorized elevation ranks. [a]

Elevation rank(m)	RX1day(mm)	RX5day(mm)	PRCPTOT(mm)	SDII(mm/d)	R95p(mm)	R99p(mm)	R10 mm(d)	R20 mm(d)	CDD(d)	CWD(d)
200−400	59.61	99.84	682.44	9.64	166.73	52.54	21.34	9.40	49.40	5.88
400−600	**68.05**	**118.63**	768.75	**10.02**	203.83	62.57	23.34	10.49	45.25	**6.29**
600−800	61.86	108.08	719.57	9.32	181.28	56.85	22.66	9.48	47.91	6.13
800−1000	59.12	98.49	607.07	9.06	156.55	49.23	18.93	7.77	58.39	5.70
1000−1200	52.92	**80.49**	**448.93**	8.52	**113.49**	**36.46**	**13.87**	**5.65**	**69.81**	**4.80**
1200−1400	**52.69**	81.56	511.26	**8.39**	126.16	39.44	16.17	6.09	60.02	5.47
1400−2200	67.69	109.37	**801.83**	9.73	**203.98**	**63.93**	**24.79**	**10.90**	**35.42**	**6.29**

[a] Maximum and minimum values of extreme precipitation indices were set in bold.

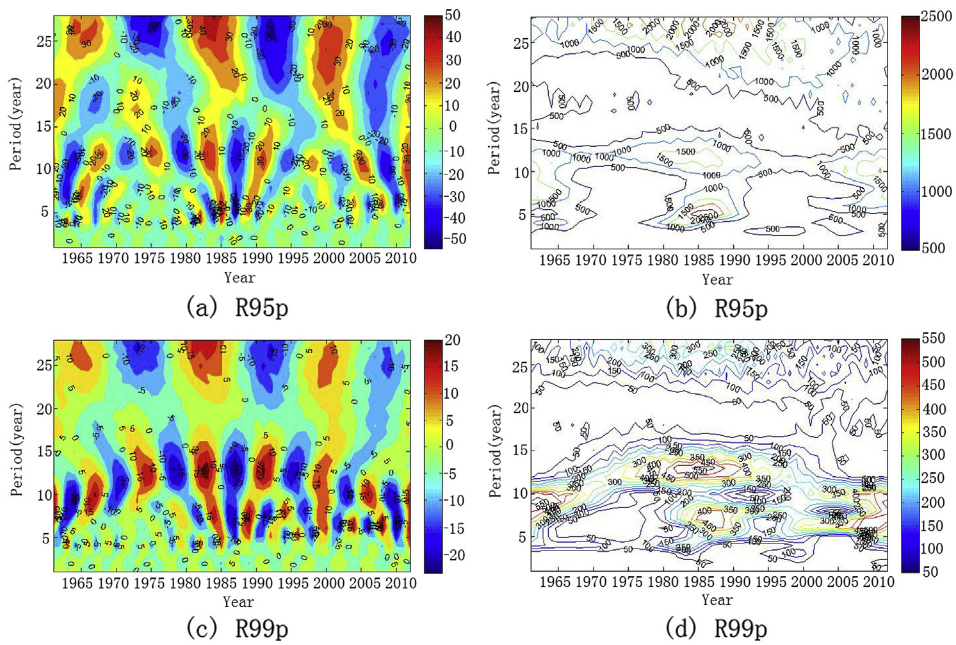

Fig. 6. Time-frequency distributions of the real part (a, c) and the modulus square (b, d) of the Morlet wavelet analysis of the R95p and R99p over Shaanxi Province during 1960−2011.

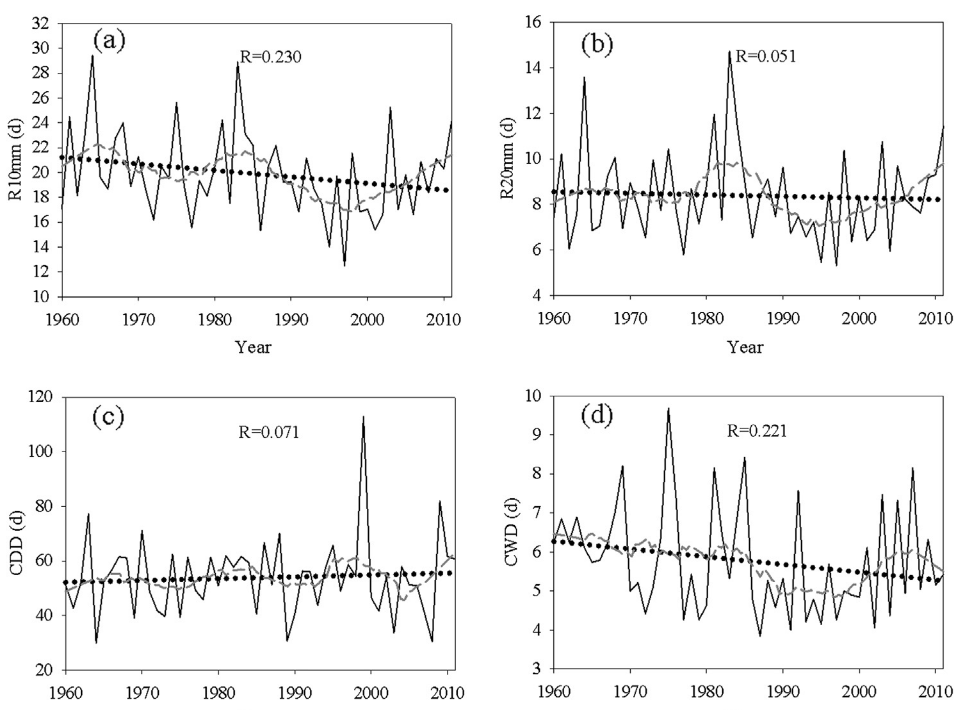

Fig. 7. Regional annual series for the indices in the number of precipitation days over Shaanxi Province during 1960−2011. (The dotted line is the linear trend and *R* is its correlation coefficient. The gray dashed line is the 10-year smoothing average.)

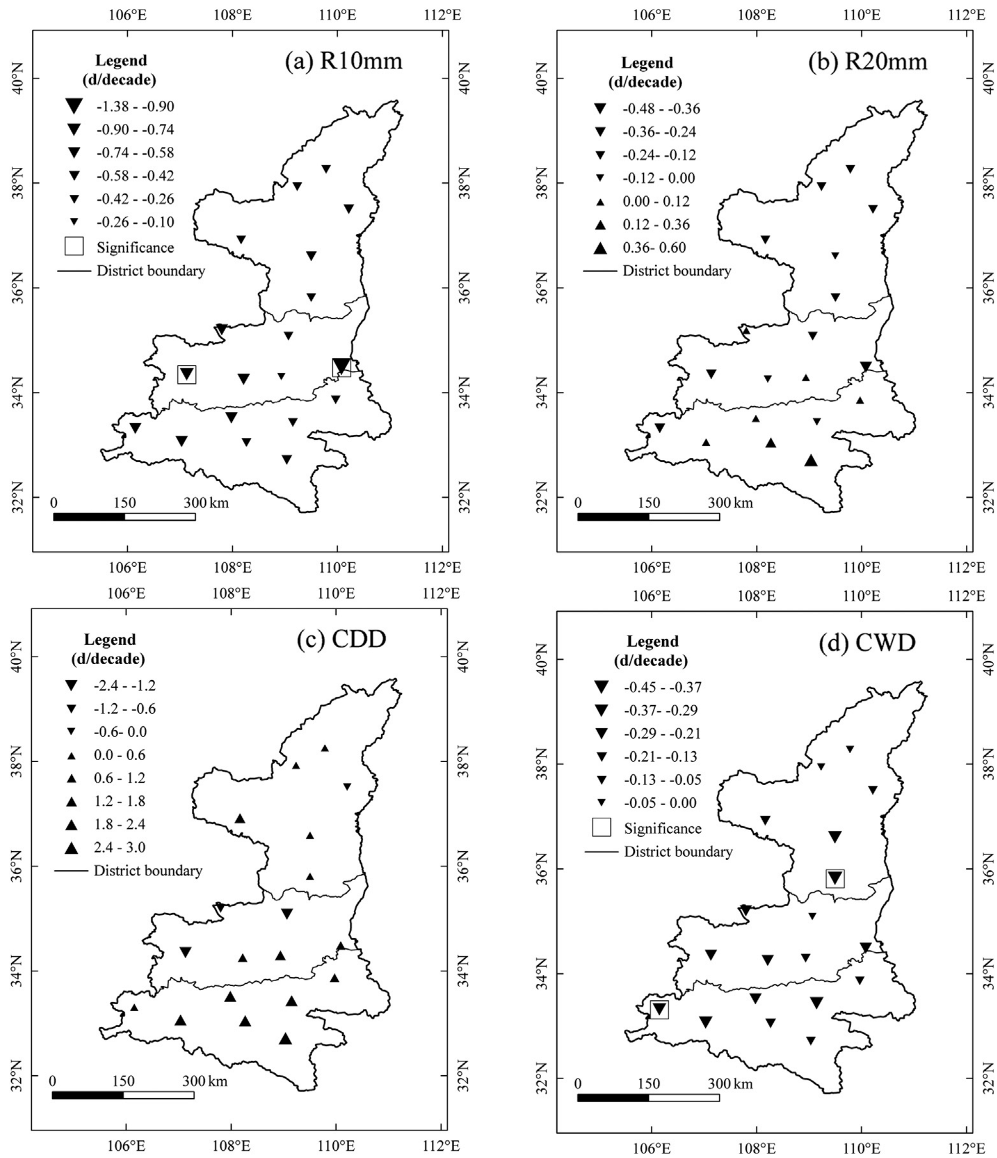

Fig. 8. Spatial patterns of trends per decade for the indices in the number of precipitation days over Shaanxi Province during 1960–2011.

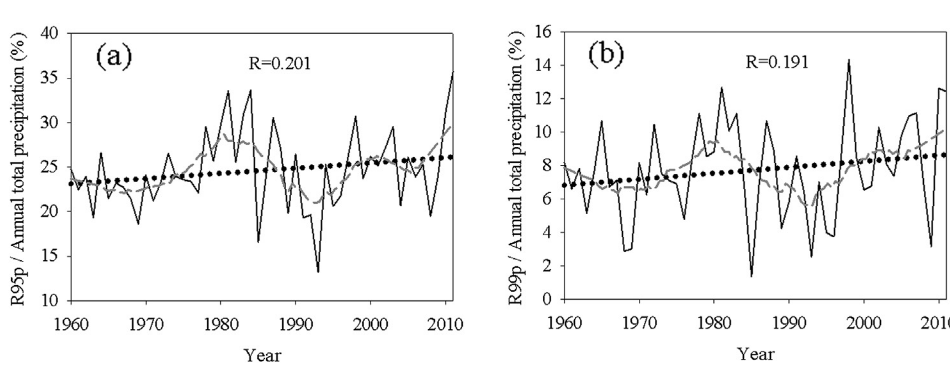

Fig. 9. Regional annual series (a) for the ratio between R95p and annual total precipitation and (b) for the ratio between R99p and annual total precipitation over Shaanxi Province during 1960–2011. (The dotted line is the linear trend and *R* is its correlation coefficient. The gray dashed line is the 10-year smoothing average.)

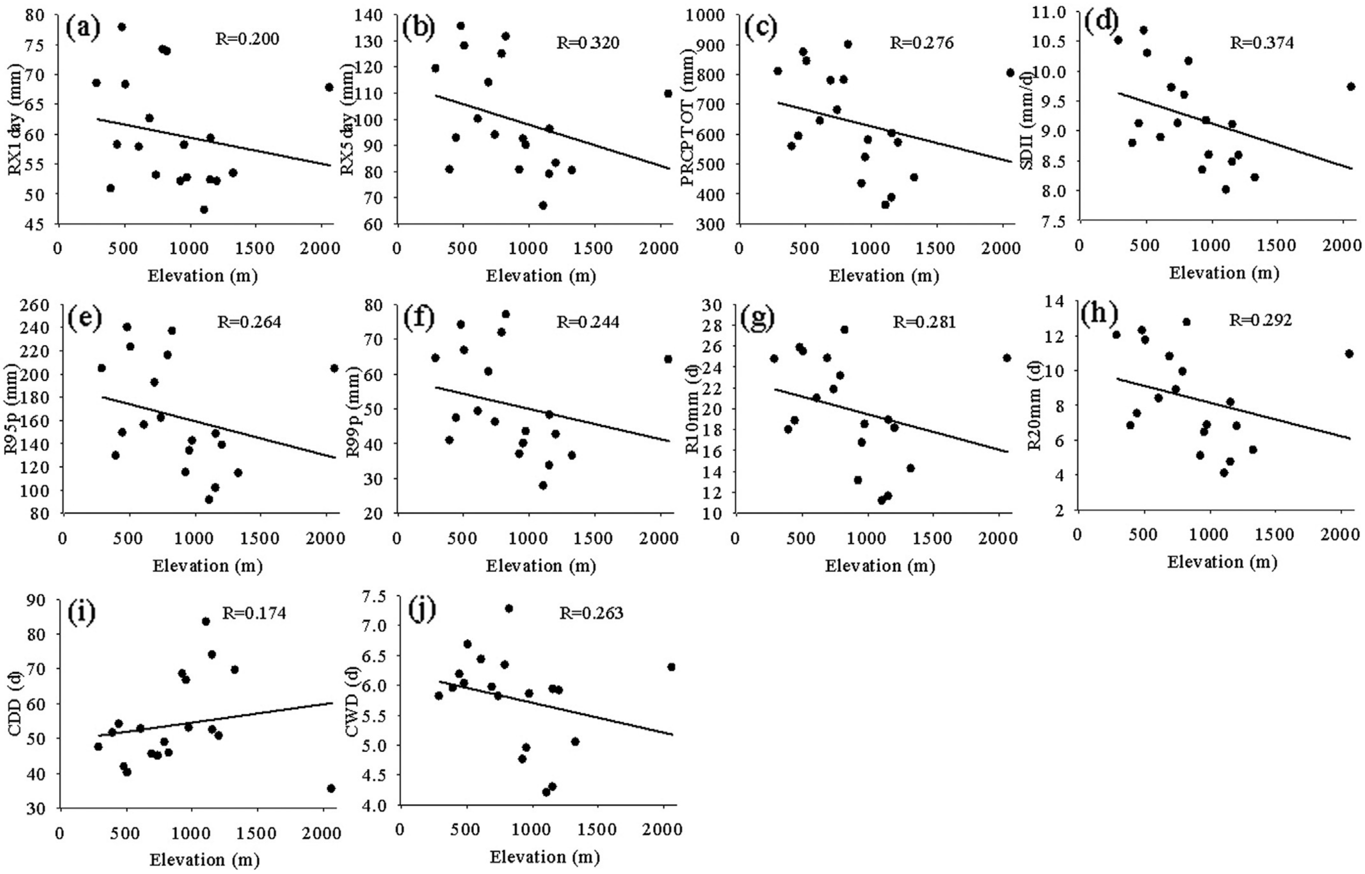

Fig. 10. Correlation between selected extreme precipitation indices and elevation. (The solid line is the linear trend and *R* is its correlation coefficient.)

4. Discussion and conclusions

According to the daily precipitation observed data over Shaanxi Province during 1960–2011 and ten selected extreme precipitation indices, the temporal and spatial distribution characteristics in precipitation extremes were analyzed. For the temporal variation characteristics in precipitation extremes over Shaanxi Province during 1960–2011, RX1day, R95p, R99p, SDII and CDD have increasing trends at the rates of 0.35, 1.95, 1.93 mm/decade, 0.06 mm/d/decade and 0.66 d/decade, respectively. A decreasing tendency is found for RX5day, PRCPTOT, R10 mm, R20 mm and CWD, and the regional trends for these indices are −0.77, −10.24 mm/decade, −0.53, −0.07, and −0.20 d/decade, respectively. All the change trends of these extreme precipitation indices used in this study are statistically non-significant. Except for CDD as a dry index, the other selected extreme precipitation indices in this research are wet indices. Based on the results above, the general variation tendency for wet indices over Shaanxi Province during 1960–2011 is decreasing, whereas the dry index shows an increasing trend. The result agrees with the research result of Cai et al. (2012) and suggests that the regional climate of Shaanxi Province has tended to get drier in the last 52 years, in accordance with the study result (He and Zhang, 2011). The interdecadal variation characteristic for R95p is not significant, while R99p increases continuously from the 1960s to the 1980s and decreases persistently afterwards. Abrupt step changes in significant decrease for R95p are observed in 1977 and 1985, while R99p undergoes an abrupt step change with a significant increase in 1983. Multiple cycles, such as small-scale cycle, middle–scale cycle, and large-scale cycle, exist together in the change processes for R95p and R99p, showing strong varying characteristics of time and frequency.

For the spatial variation characteristics in precipitation extremes over Shaanxi Province during 1960–2011, generally speaking, the variation trends for R10 mm and CWD present spatially uniform patterns in the study area, whereas the change trends of the other extreme precipitation indices have apparent regional differences. The number of meteorological stations with increasing trends for extreme precipitation events in southern Shaanxi is more than those in northern Shaanxi and central Shaanxi. The result reveals extreme precipitation events happen more frequently in southern Shaanxi than in northern and central Shaanxi. Consequently, there are more drought-flood disasters in southern Shaanxi, and relevant departments should strengthen work in disaster prevention and reduction in this region.

The extreme precipitation indices used in this study have high correlations with annual total precipitation, except CDD, especially PRCPTOT, R10 mm and R20 mm. The result indicates these indices have very good indicative functions for annual total precipitation over Shaanxi Province with the exception of CDD. The increasing trends detected for the contribution of R95p to annual total precipitation and the contribution of R99p to annual total precipitation suggest a shift to extreme precipitation. The elevation is positively correlated with CDD, while it is negatively correlated with the other extreme precipitation indices. The result indicates that dry extreme precipitation events happen frequently in high-elevation regions, whereas wet extreme precipitation events appear easily in the low-elevation districts.

The temporal variation characteristics in precipitation extremes over Shaanxi Province during 1960–2011 may be the results of joint action between climate warming and atmospheric circulation abnormities. One the one hand, in the context of global climate change, the mean temperature over Shaanxi Province is also increasing in recent years (Jiang et al., 2011a,b), which may induce hydrological cycle acceleration and possible increase in precipitation variability subsequently. On the other hand, anomalous general circulation may influence the changes in precipitation extremes (You et al., 2011). Being a result of atmospheric circulation abnormity, more severe typhoons lead to frequent occurrence in extreme rainstorms (Hou et al., 2006). Compared with climate warming and atmospheric circulation abnormities, landform and climate differences may be the main reasons resulting in the spatial variation characteristics in precipitation extremes over Shaanxi Province. The territory of Shaanxi Province is long and narrow with a span of 870 km from south to north, and its climate differences from south to north are obvious. In addition, surface vegetation cover changes (Zhao and Pitman, 2002; Suh and Lee, 2004) and urbanization level (Yin et al., 2007) may be important causes that lead to the spatial variation characteristics in precipitation extremes over Shaanxi Province. However, more detailed studies are still needed to fully understand the underlying mechanisms of the temporal and spatial changes in precipitation extremes over Shaanxi Province in the future.

Acknowledgments

This study was supported by the National Basic Research Program of China (973 Program) (No. 2013CBA01801), the National Natural Science Foundation of China (No. 41161012, 41240001), and the Basic Scientific Research Foundation in University of Gansu Province. Thanks also to the editorial staff.

References

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P.M., Rusticucci, M., Vazquez-Aguirre, J.L., 2006. Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research 111, D05109. http://dx.doi.org/10.1029/2005JD006290.

Bao, M., Huang, R.H., 2006. Characteristics of the interdecadal variations of heavy rain over China in the last 40 years. Chinese Journal of Atmospheric Sciences 30, 1057–1067.

Boccolari, M., Malmusi, S., 2013. Changes in temperature and precipitation extremes observed in Modena, Italy. Atmospheric Research 122, 16–31.

Caesar, J., Alexander, L.V., Trewin, B., Tse-ring, K., Sorany, L., Vuniyayawa, V., Keosavang, N., Shimana, A., Htay, M.M., Karmacharya, J., Jayasinghearachchi, D.A., Sakkamart, J., Soares, E., Hung, L.T., Thuong, L.T., Hue, C.T., Dung, N.T.T., Hung, P.V., Cuong, H.D., Cuong, N.M., Sirabaha, S., 2011. Changes in temperature and precipitation extremes over the Indo–Pacific region from 1971 to 2005. International Journal of Climatology 31, 791–801.

Cai, X.L., Wu, S.L., He, H., Jiang, C.Y., Sun, X., Gao, H.Y., Zheng, G.F., 2012. Change of extreme climate events in Shaaxi Province under global warming background. Journal of Desert Research 32, 1095–1101.

Changnon, S.A., Pielke Jr., R.A., Changnon, D., Sylves, R.T., Pulwarty, R., 2000. Human factors explain the increased losses from weather and climate extremes. Bulletin of the American Meteorological Society 81, 437–442.

Christensen, O.B., Christensen, J.H., 2004. Intensification of extreme European summer precipitation in a warmer climate. Global and Planetary Change 44, 107–117.

Dai, A., Trenberth, K.E., Karl, T.R., 1998. Global variations in droughts and wet spells: 1900–1995. Geophysical Research Letters 25, 3367–3370.

Eastering, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E., Ambenje, P., 2000. Observed variability and trends in extreme climate events: a brief review. Bulletin of the American Meteorological Society 81, 417–425.

Frich, P., 1999. REWARD: a nordic collaborative project. Annex of "Meeting of the joint CCl/CLIVAR task group on climate indices, Bracknell, UK, 2–4 September 1998". In: Folland, C.K., Horton, E.B., Scholefield, P.R. (Eds.), World Climate Data and Monitoring Programme. World Meteorological Organization, Geneva. WCDMP-No.37, WMO-TD No.930.

Frich, P., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A.M.G., Peterson, T., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate Research 19, 193–212.

Gao, M.S., Fan, J.Z., Wu, Q.L., 2012a. Influence of drought and flood disasters on grain production in Shaanxi Province. Journal of China Agricultural University 17, 149–153.

Gao, M.S., Fan, J.Z., Wu, Q.L., 2012b. Analysis on the characteristics of natural disasters and the disaster loss in Shaanxi Province. Acta Agriculture Boreali-occidentalis Sinica 21, 202–206.

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. Science 314, 1442–1445.

Groisman, P.Y., Karl, T.R., Easterling, D.R., Knight, R.W., Jamason, P.F., Hennessy, K.J., Suppiah, R., Page, C.M., Wibig, J., Fortuniak, K., Razuvaev, V.N., Douglas, A., Forland, E., Zhai, P.M., 1999. Changes in the probability of heavy precipitation: important indicators of climate change. Climatic Change 42, 243–283.

Groisman, P.Y., Knight, R.W., Karl, T.R., Easterling, D.R., Sun, B., Lawrimore, J.H., 2004. Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in situ observations. Journal of Hydrometeor 5, 64–85.

Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. Journal of Climate 18, 1326–1350.

Haylock, M.R., Goodess, C.M., 2004. Interannual variability of European extreme winter rainfall and links with mean large-scale circulation. International Journal of Climatology 24, 759–776.

He, Y.F., Zhang, L., 2011. Temporal and spatial characteristics of climatic change from 1980 to 2006 in Shaanxi Province. Journal of Arid Land Resources and Environment 25, 59–63.

Hidalgo-Muñoz, J.M., Argüeso, D., Gámiz-Fortis, S.R., Esteban-Parra, M.J., Castro-Díez, Y., 2011. Trends of extreme precipitation and associated synoptic patterns over the southern Iberian Peninsula. Journal of Hydrology 409, 497–511.

Hore, D.J., 1981. A rotated principal component analysis of the inter-annual variability of the northern hemisphere 500 mb height field. Monthly Weather Review 109, 2080–2092.

Hou, J.Z., Wang, C., Lu, Y.P., Ning, Z.Q., Du, J.W., 2006. Activity of typhoons and extreme rainstorms in Shaanxi Province. Journal of Tropical Meteorology 22, 203–208.

IPCC, 2001. Climate change 2001. The scientific basis. In: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007. Summary for policymakers of climate change. The physical science basis. In: Contribution of Working Group I to the Forth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jiang, Z.H., Ding, Y.G., Chen, W.S., 2007. Projection of precipitation extremes for the 21th century over China. Advances in Climate Change Research 3, 202–207.

Jiang, C.Y., Cai, X.L., Wu, S.L., Kang, L., Hui, Y., 2011a. Spatiotemporal evolution of extreme precipitation events in Shaanxi Province during the period 1961–2009. Arid Zone Research 28, 151–157.

Jiang, C.Y., Wei, N., Cheng, X.X., Fang, J.G., Sun, X., 2011b. Analysis of inter-annual temperature and precipitation regional change during 1961–2008 in Shaanxi Province. Research of Soil and Water Conservation 18, 197–200.

Karl, T.R., Knight, R.W., 1998. Secular trends of precipitation amount, frequency and intensity in the United States. Bulletin of the American Meteordogical Society 79, 231–241.

Karl, T.R., Knight, R.W., Plummer, N., 1995. Trends in high-frequency climate variability in the twentieth century. Nature 377, 217–220.

Karl, T.R., Knight, R.W., Easterling, D.R., Qualye, R.G., 1996. Indices of climate change for the United States. Bulletin of the American Meteorological Society 77, 279–292.

Klein Tank, A.M.G., Konnen, G.P., 2003. Trends in indices of daily temperature and precipitation extremes in Europe, 1946–1999. Journal of Climate 16, 3665–3680.

Klein Tank, A.M.G., Peterson, T.C., Quadir, D.A., Dorji, S., Zou, X., Tang, H., Santhosh, K., Joshi, U.R., Jaswal, A.K., Kolli, R.K., Sikder, A.B., Deshpande, N.R., Revadekar, J.V., Yeleuova, K., Vandasheva, S., Faleyeva, M., Gomboluudev, P., Budhathoki, K.P., Hussain, A., Afzaal, M., Chandrapala, L., Anvar, H., Amanmurad, D., Asanova, V.S., Jones, P.D., New, M.G., Spektorman, T., 2006. Changes in daily temperature and precipitation extremes in central and south Asia. Journal of Geophysical Research 111, D16105. http://dx.doi.org/10.1029/2005JD006316.

Kunkel, K.E., 2003. North American trends in extreme precipitation. Natural Hazards 29, 291–305.

Li, H.R., 2004. Discussion of drought and flood damage in Shaanxi Province. Journal of Water Resources & Water Engineering 15, 65–67.

Li, M.J., 2008. Scenario Analysis of Future Extreme Climate Events in Shaanxi (Master dissertation). Lanzhou University.

Li, Z.X., He, Y.Q., Wang, P.Y., Theakstone, W.H., An, W.L., Wang, X.F., Lu, A.G., Zhang, W., Cao, W.H., 2012. Changes of daily climate extremes in southwestern China during 1961–2008. Global and Planetary Change 80–81, 255–272.

McBean, G., 2004. Climate change and extreme weather: a basis for action. Natural Hazards 31, 177–190.

Michel, D., 2007. Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Global and Planetary Change 57, 16–26.

Nicholls, N., 1995. Long-term climate monitoring and extreme events. Climatic Change 31, 231–245.

Norbiato, D., Borga, M., Sangati, M., Zanon, F., 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. Journal of Hydrology 345, 149–166.
Pal, I., Al-Tabbaa, A., 2009. Trends in seasonal precipitation extremes-an indicator of 'climate change' in Kerala, India. Journal of Hydrology 367, 62–69.
Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p. 982.
Qin, D.H., Ding, Y.H., Su, J.L., Ren, J.W., Wang, S.W., Wu, R.S., Yang, X.Q., Wang, S.M., Liu, S.Y., Dong, G.R., Lu, Q., Huang, Z.G., Du, B.L., Luo, Y., 2005. Assessment of climate and environment changes in China(I): climate and environment changes in China and their projection. Advances in Climate Change Research 1, 4–9.
Ren, G.Y., Feng, G.L., Yan, Z.W., 2010. Progresses in observation studies of climate extremes and changes in mainland China. Climatic and Environmental Research 15, 337–353.
Sang, J.J., Zha, X.C., 2011. Effect of flood disasters on economic and social development in nearly 60 years in Shaanxi Province. Journal of Arid Land Resources and Environment 25, 140–145.
Schmidli, J., Frei, C., 2005. Trends of heavy precipitation and wet and dry spells in Switzerland during the 20th century. International Journal of Climatology 25, 753–771.
Su, B.D., Gemmer, M., Jiang, T., 2008. Spatial and temporal variation of extreme precipitation over the Yangtze River Basin. Quaternary International 186, 22–31.
Suh, M.S., Lee, D.K., 2004. Impacts of land use/cover changes on surface climate over East Asia for extreme climate cases using RegCM2. Journal of Geophysical Research 109, D02108. http://dx.doi.org/10.1029/2003JD003681.
Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bulletin of the American Meteorological Society 84, 1205–1217.
Vincent, L.A., Aguilar, E., Saindou, M., Hassane, A.F., Jumaux, G., Roy, D., Booneeady, P., Virasami, R., Randriamarolaza, L.Y.A., Faniriantsoa, F.R., Amelie, V., Seeward, H., Montfraix, B., 2011. Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008. Journal of Geophysical Research 116, D10108. http://dx.doi.org/10.1029/2010JD015303.
Wang, Y.Q., Zhou, L., 2005. Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large-scale circulation. Geophysical Research Letters 32, L09707. http://dx.doi.org/10.1029/2005GL022574.
Wang, B.L., Zhang, M.J., Wei, J.L., Wang, S.J., Li, S.S., Ma, Q., Li, X.F., Pan, S.K., 2013a. Change in extreme events of temperature and precipitation over Xinjiang, Northwest China, during 1960–2009. Quaternary International 298, 141–151.
Wang, B.L., Zhang, M.J., Wei, J.L., Wang, S.J., Li, X.F., Li, S.S., Zhao, A.F., Li, X.S., Fan, J.P., 2013b. Changes in extreme precipitation over Northeast China, 1960–2011. Quaternary International 298, 177–186.
Xiao, J., Zhao, J.B., 2006. The study on the characteristics of agricultural drought disasters in recent 54a in Shaanxi Province. Journal of Arid Land Resources and Environment 20, 201–204.
Xu, J.C., 2009. Study of Temporal and Spatial Distribution of Weather and Climate Extreme Value and Its Return Period in Shaanxi Province Based on ArcGIS (Master dissertation). Shaanxi Normal University.
Xu, C.Y., Widden, E., Halldin, S., 2005. Modeling hydrological consequences of climate change-progress and challenge. Advances in Atmospheric Sciences 22, 789–797.
Yan, Z.W., Yang, C., 2000. Geographic patterns of extreme climate changes in China during 1951–1997. Climate and Environmental Research 5, 267–272.
Yan, N., Li, D.K., Du, J.W., Yan, J.P., 2010. Monitoring of drought situation in Shaanxi Province based on MODIS land product LST, NDVI and EVI. Journal of Natural Disasters 19, 178–182.
Yang, J.H., Jiang, Z.H., Bai, H.Z., 2008a. Teleconnection between summer extreme precipitation event of east part of Northwest China and Pacific SSTA. Plateau Meteorology 27, 331–338.
Yang, J.H., Jiang, Z.H., Wang, P.X., Chen, Y.S., 2008b. Temporal and spatial characteristic of extreme precipitation event in China. Climatic and Environmental Research 13, 75–83.
Yang, T., Shao, Q.X., Hao, Z.C., Zhang, Z.X., Xu, C.Y., Sun, L.M., 2010. Regional frequency analysis and spatio-temporal pattern characterization of rainfall extremes in the Pearl River Basin, China. Journal of Hydrology 380, 386–405.
Yin, S.Y., Huang, C.C., Qiu, L.H., Jia, Y.F., 2007. Study on the historical drought and flood disasters in the Guanzhong Plain and the urban development. Arid Zone Research 24, 77–82.
You, Q.L., Kang, S.C., Aguilar, E., Pepin, N., Flügel, W.A., Yan, Y.P., Xu, Y.W., Zhang, Y.J., Huang, J., 2011. Changes in daily climate extremes in China and its connection to the large scale atmospheric circulation during 1961–2003. Climate Dynamics 36, 2399–2417.
Zhai, P.M., Pan, X.H., 2003. Change in extreme temperature and precipitation over Northern China during the second half of the 20th century. Acta Geographica Sinica 58, 1–10.
Zhai, P.M., Ren, F.M., Zhang, Q., 1999a. Detection of trends in China's precipitation extremes. Acta Meteorological Sinica 57, 208–216.
Zhai, P.M., Sun, A.J., Ren, F.M., Liu, X.N., Gao, B., Zhang, Q., 1999b. Changes of climate extremes in China. Climatic Change 42, 203–218.
Zhai, P.M., Zhang, X.B., Wan, H., Pan, X.H., 2005. Trends in total precipitation and frequency of daily precipitation extremes over China. Journal of Climate 18, 1096–1108.
Zhai, P.M., Wang, C.C., Li, W., 2007. A review on study of change in precipitation extremes. Advances in Climate Change Research 3, 144–148.
Zhang, Q., Xu, C.Y., Chen, Y.Q., Yang, T., 2009. Spatial assessment of hydrologic alteration across the Pearl River Delta, China, and possible underlying causes. Hydrological Processes 23, 1565–1574.
Zhao, M., Pitman, A.J., 2002. The impact of land cover change and increasing carbon dioxide on the extreme and frequency of maximum temperature and convective precipitation. Geophysical Research Letters 29 (1078). http://dx.doi.org/10.1029/2001GL013476.