Theor Appl Climatol (2013) 111:133–148
DOI 10.1007/s00704-012-0657-3

ORIGINAL PAPER

Trends of precipitation extremes during 1960–2008 in Xinjiang, the Northwest China

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Received: 28 June 2011 / Accepted: 9 April 2012 / Published online: 26 April 2012

Abstract The spatial–temporal variability of the precipitation extremes defined by eight precipitation indices based on daily precipitation dataset was analyzed using the linear regression method and the Mann–Kendall test. The results indicate that increasing trends in the precipitation amount, rainy days, and the intensity of the extreme precipitation were identified at above 70 % of the total rain stations considered in this study, with more than 30 % of them were significant, while most stations show notable decreasing trend in the annual maximum consecutive no-rain days. Significantly increasing trends of the precipitation extremes are observed mainly in the northern Xinjiang and the north of the southern Xinjiang. Most extreme precipitation indices show a potential regime shift starting from the middle of 1980s. The magnitude of the trends is compatible with their pattern of spatial stability. The generally increasing trends in precipitation extremes are found in this study.

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1 Introduction

Changes in the frequency or intensity of extreme weather and climate events can have severe consequences on the local environment and are accountable for a disproportionately large amount of climate-related risk (Wigley 1985). In addition to extensive physical damage, these extreme events can also have a significant negative impact on society and the economy (Easterling et al. 2000; Karl and Easterling 1999; IPCC 2007). These influences, however, are different in both space and time due to spatial and temporal variations of temperature changes (Houghton et al. 2001; Alexander et al. 2006). Therefore, assessing long-term characteristics of variations of extreme climate events, especially extreme precipitation events on regional scale is essential to evaluate climatic hazards and to contribute to development of drought and flood mitigation strategies such as supplementary irrigation, flood control structures, etc.

Over the past decades, trend in extreme precipitation has been examined extensively by different researchers from various parts of the world. Suppiah and Hennessy (1998) in Australia, Plummer et al. (1999) in the Australian Region and New Zealand, Manton et al. (2001) in Southeast Asia and the South Pacific, Brunetti et al. (2001, 2004) in Italy, Klein Tank and Konnen (2003) in Europe, Hundecha and Bardossy (2005) in western Germany, Kruger (2006) in South Africa, Rahimzadeh et al. (2009) in Iran, Costa and Soares (2009) in the South of Portugal, Zhang et al. (2008) in the Yangtze River basin, China, Lopez-Moreno et al. (2010) in the northeastern Iberian Peninsula, Caesar et al. (2011) in the Indo-Pacific region, Łupikasza (2010) and Łupikasza et al. (2011) in Poland and in southern

Poland and central-eastern German, Dravitzki and McGregor (2011) in the Waikato region of New Zealand, dos Santos et al. (2011) in Utah, USA, Toros (2012) in Turkey, Unkasevic and Tosic (2012) in Serbia, Shahid S (2011) in Bangladesh, and Zhang et al. (2011) over China are a few among such studies. These studies found observational evidence of increases in the frequency and intensity of various kinds of extreme precipitation over the last few decades.

As for extreme precipitation changes in China, a number of researches have been carried out in recent years. Sun et al. (1998) studied the change trends of extreme climate events in China. Zhai et al. (1999a, b) investigated the changes of precipitation extremes in China. They found that western northern China is the region that has experienced obvious increasing trends in precipitation, and the increasing trends in extreme annual precipitation is accompanied with an increase in daily precipitation exceeding 10 mm. Yan and Yang (2000) explored the geographic patterns of extreme climate changes in China during 1951–1997. Zhai et al. (2005) analyzed the trends in total precipitation and frequency of daily precipitation extremes over China. Zhang et al. (2008) analyzed the observed trends of precipitation extremes in the Yangtze River basin during 1960–2005. Zhai et al. (2007) reviewed the main progresses in study of change in precipitation extremes in China and concluded that during the recent 50 years, in most parts of China, the number of precipitation days has decreased significantly except in Northwest China, while the precipitation intensity has increased significantly. Ren and Yang (2007) studied the trends in extremely climate in arid land of northwest China. Yang et al. (2008a, b) analyzed the temporal and spatial characteristic of extreme precipitation event in China and the inner-annual heterogeneity characteristics of extreme precipitation events over Northwest China, and found remarkable regional differences in trend of extreme precipitation events. Min and Qian (2008) reported their study results on regionality and persistence of extreme precipitation events in China and concluded that there are obvious regional differences in persistence of extreme precipitation events in China. Ning and Qian (2008) researched the trends of annual and seasonal daily precipitation in China using a dataset of daily precipitation of 554 stations covering the landmass of China during 1961–2003. Wang and Qian (2009) analyzed the frequency and intensity of extreme precipitation events in China. Jiang et al. (2011) studied the variability of extreme summer precipitation over Circum-Bohai Sea region. Decreasing trends were identified in various measures of the precipitation regime, whereas non-significant increasing trends were found in the maximum consecutive dry days. Fan and Wang (2011) reported their research results on change trends of air temperature and precipitation over Shanxi Province, China. Hu et al. (2011) analyzed the trends of temperature and rainfall extremes in the Yellow River source region, China.

The Xinjiang is located in the inland and is featured by arid climate. Water is one of the key factors responsible for the sustainable ecological environment and social development in the region. Precipitation directly impacts the spatial and temporal distribution of water resources because of its important role in evaporation (Xu and Singh 2004). Recent 50 years increasing air temperature with a linear tendency of 0.2°C/decade in the region was observed (Zhang and Shi 2002; Dai et al. 2007; Zhang et al. 2009). Climate warming is suggested to be linked to the recent increase in extreme precipitation events due to the increasing atmospheric water vapor and warmer air (Houghton et al. 2001; IPCC 2007). While it is now widely recognized that regional temperature is increasing, changes in extreme precipitation are not yet well understood. Previous studies have focused on trends in the annual and the seasonal rainfall over the Xinjiang since 1961. These researches revealed that changes in the regional precipitation are complex and different from place to place (e.g., Xue et al. 2003; Su et al. 2007). A few researchers have focused their attention on variation of precipitation extremes in Xinjiang region in recent years (Yang 2003; Xin et al. 2008; Zhao et al. 2010a, b). Increasing trends were identified in various measures of the precipitation regimes. The upward tendency of damages caused by natural disasters supports the idea that precipitation extreme events, such as heavy precipitation, associated with the effects of climate change, occur with greater frequency (Jiang et al. 2004, 2005). Therefore, exploring changing characteristics of the extreme precipitations in the Xinjiang is a requisite for scientific assessment of impacts of climatic changes on regional ecological environment and agricultural development. However, previous studies about extreme precipitation in Xinjiang employed different precipitation indices and usually applied thresholds based on local precipitation volume to define extreme precipitation. For example, daily precipitation exceeding a threshold of 20 mm may be classified into extreme precipitation in a place, but in other place, only daily precipitation exceeding 40 mm may be defined as extreme precipitation. Obviously, such study results in different places were incomparable. What mentioned above is the main motivation of the present research. The objective of this paper was to estimate variations and trends of extreme precipitation in the Xinjiang based on the daily rainfall dataset covering 1960–2008. Eight extreme precipitation indices, which were based on precipitation percentile thresholds and suggested for general use by the ETCCDI, have been used in this study for the purpose of comparison to other studies (e.g., Rahimzadeh et al. 2009; Jiang et al. 2011). Definitions and implications of these indices can be referred to http://cccma.seos.uvic.ca/ETCCDI.

2 Data and methodology

2.1 Data description and quality control

The daily precipitation dataset at 55 meteorological stations in the Xinjiang was provided by the National Climatic Centre of China, China Meteorological Administration. Before using the weather data in trend analysis, it was necessary to do the preliminary controls on the choice of the length of the homogeneous record period and the missing data. Precipitation data are much more difficult to do the quality control than data for other climatic parameters, e.g., temperature, mainly because of the relatively poor spatial correlation of daily precipitation amounts (Kruger 2006). However, the quality control of the dataset has been conducted by above mentioned institution before its release, and homogeneous detection for the dataset has also been performed (e.g. Feng et al. 2004; Li and Yan 2009). Furthermore, in this study, the double mass curve method was used to check the data consistency (Su et al. 2006). The result showed that all the data series in this study were consistent. In total, the missing data accounts for 0.05 % of the data series. The station data used in this study were screened for missing values, and only those stations with data records that are at least 95 % complete for the range of 1959–2008 were included in our analysis. The missing data were completed using conventional statistical methods including: (1) if only one day has missing data, the missing data was replaced by the average value of its two neighboring stations; (2) if consecutive two or more days have missing data, the missing data would be processed by simple linear correlation between its neighboring stations (distance <100 km). As a result, 52 meteorological stations were selected for this study. The daily precipitation series cover mainly time interval of 1959–2008. Detailed information of the meteorological stations and dataset can be referred to Table 1. Locations of the meteorological stations can be referred to Fig. 1. Furthermore, the study area was divided into three subdivisions, i.e., Northern Xinjiang, Tianshan Mountains and Southern Xinjiang according to their natural geographic features. This division was commonly used in most studies about Xinjiang, so applying this division could enable results of this paper comparable with other studies. Distribution of selected stations in three subdivisions was shown in Table 1.

2.2 Selected indices and methodology

There are a variety of definitions for extreme precipitation. Nicholls and Murray (1999) represented a series of indices for precipitation extremes. In this study, the analysis of precipitation extremes was based on the precipitation indices, which were suggested for general use by the World Climate Research Program (WCRP) project on Climate Variability and Predictability (CLIVAR) Working Group on Climate Change Detection (GCOS/CLIVAR/WMO 1997; Easterling et al. 2003). These indices were initially used in an analysis by Frich et al. (2002) of the trends in the global climate, as well as in subsequent regions (e.g., Peterson et al. 2002; Kruger 2006; Jiang et al. 2011). Eight indices describing different aspects of the precipitation regime were defined and analyzed in this study (Table 2).

The long-term climatic trends of the eight extreme precipitation indices were studied for each of the 52 meteorological stations using the linear regressive method. The statistical significance of the trend is evaluated using the rank-based Mann–Kendall trend test (Mann 1945; Sneyers 1990), which is highly recommended for general use by the World Meteorological Organization (Sneyers 1990). The rank-based MK method is a nonparametric method, commonly used to assess the significance of monotonic trends in hydro-meteorological time series (Yue and Pilon 2004). The MK test has the advantage of not assuming any distribution form for the data and has the power similar to its parametric competitors (Serrano et al. 1999). The significance of the trend was tested at >95 % confidence level.

Serial correlation could affect the MK test by introduction of systematic errors (Yue and Pilon 2004; Hamed and Rao 1998; Serrano et al. 1999; Partal and Ercan 2006). It is suggested that the effect of series correlation on the MK test should be eliminated. The pre-whiten method was used to eliminate the effect of the serial correlation effects (Yue and Pilon 2004; Partal and Ercan 2006). Firstly, the lag-1 series correlation coefficient (r_1) was computed. If the calculated r_1 is significant at the 5 % level, prior to application of the MK test, the "pre-whitened" time series may be obtained as ($x_2-r_1x_1$, $x_3-r_1x_2$, …, $x_n-r_1x_{n-1}$), where x_i denotes the original series of the extreme precipitation indices. If the calculated r_1 is not significant, the MK test method can be applied directly to the original time series. According to this procedure, prior to MK test, the series correlation effects were tested for all indices series for 52 stations. The time series with significant ($p<0.05$) lag-1 series correlation coefficients were "pre-whitened" before applying the MK test.

3 Results

3.1 Annual total precipitation (PRCPTOT)

The linear tendencies of annual total precipitation (PRCPTOT) for 52 stations in the Xinjiang were analyzed using the linear regression method. Results show that in the past 50 years, linear tendencies of the PRCPTOT in the

Table 1 List of 52 meteorological stations selected for this study

No.	Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Data period	Mean annual precipitation	Subdivision belonged
1	Aheqi	40.93	78.45	1,984.9	1957.1.1–2008.12.31	214.3	T[a]
2	Akesu	41.17	80.23	1,103.8	1953.6.1–2008.12.31	75.7	S[b]
3	Alaer	40.55	81.27	1,012.2	1958.12.1–2008.12.31	51.0	S
4	Alashankou	45.18	82.57	336.1	1956.7.1–2008.12.31	113.9	N[c]
5	Aletai	47.73	88.08	735.3	1954.1.1–2008.12.31	194.2	N
6	Baicheng	41.78	81.90	1,229.2	1958.10.1–2008.12.31	121.0	S
7	Balikun	43.60	93.05	1,677.2	1956.12.1–2008.12.31	220.9	T
8	Baluntai	42.73	86.30	1,739.0	1957.11.1–2008.12.31	212.5	T
9	Bayinbuluke	43.03	84.15	2,458.0	1957.11.1–2008.12.31	277.6	T
10	Beitashan	45.37	90.53	1,653.7	1957-10.1–2008.12.31	177.2	N
11	Caijiahu	44.20	87.53	440.5	1958.10.1–2008.12.31	143.3	N
12	Dabancheng	43.35	88.32	1,103.5	1956.4.1–2008.12.31	74.9	T
13	Fuhai	47.12	87.47	500.9	1957.11.1–2008.12.31	123.9	N
14	Fuyun	46.59	89.31	807.5	1961.6.1–2008.12.31	185.7	N
15	Habahe	48.05	86.40	532.6	1957.11.1–2008.12.31	186.2	N
16	Hami	42.82	93.52	737.2	1951.1.1–2008.12.31	40.5	S
17	Hebukesaier	46.78	85.72	1,291.6	1953.7.1–2008.12.31	145.1	N
18	Hetian	37.13	79.93	1,375.0	1953.2.1–2008.12.31	39.5	S
19	Hongliuhe	41.53	94.67	1,573.8	1952.7.1–2008.12.31	49.1	S
20	Jimunai	47.43	85.93	984.1	1960.8.1–2008.12.31	205.8	N
21	Jinghe	44.62	82.90	320.1	1953.1.1–2008.12.31	106.3	N
22	Kashi	39.47	75.98	1,289.4	1951.2.1–2008.12.31	68.6	S
23	Keping	40.50	79.05	1,161.8	1959.1.1–2008.12.31	112.4	S
24	Kelamayi	45.62	84.85	449.5	1956.12.1–2008.12.31	95.5	N
25	Kuche	41.72	82.97	1,081.9	1951.1.1–2008.12.31	72.5	S
26	Kuerle	41.75	86.13	931.5	1958.7.1–2008.12.31	58.5	S
27	Kumishi	42.23	88.22	922.4	1958.11.1–2008.12.31	56.0	S
28	Luntai	41.78	84.25	976.1	1958.10.1–2008.12.31	68.4	S
29	Minfeng	37.07	82.72	1,409.5	1956.12.1–2008.12.31	39.3	S
30	Pishan	37.62	78.28	1,375.4	1959.1.1–2008.12.31	53.4	S
31	Qijiaojing	43.22	91.73	721.4	1952.7.1–2008.12.31	36.5	S
32	Qitai	44.02	89.57	793.5	1951.4.1–2008.12.31	188.1	N
33	Qiemo	38.15	85.55	1,247.2	1953.5.1–2008.12.31	26.6	S
34	Qinghe	46.67	90.38	1,218.2	1957.10.1–2008.12.31	172.3	N
35	Ruoqiang	39.03	88.17	887.7	1953.3.1–2008.12.31	31.1	S
36	Shache	38.43	77.27	1,231.2	1953.7.1–2008.12.31	55.2	S
37	Shihezi	44.32	86.05	442.9	1952.9.1–2008.12.31	210.9	N
38	Tacheng	46.73	83.00	534.9	1953.6.1–2008.12.31	281.0	N
39	Tasgkuergan	37.77	75.23	3,090.1	1957.1.1–2008.12.31	76.0	S
40	Tieganlike	40.63	87.70	846.0	1957.1.1–2008.12.31	37.1	S
41	Tuergate	40.52	75.40	3,504.4	1958.10.1–2008.12.31	248.7	T
42	Tulufan	42.93	89.20	34.5	1951.7.1–2008.12.31	17.3	S
43	Tuoli	45.93	83.60	1,077.8	1956.10.1–2008.12.31	241.5	N
44	Wenquan	44.97	81.02	1,357.8	1957.12.1–2008.12.31	233.1	N
45	Wulumuqi	43.78	87.65	935.0	1951.1.1–2008.12.31	263.7	N
46	Wuqia	39.72	75.25	2,175.7	1955.11.1–2008.12.31	180.5	S
47	Wusu	44.43	84.67	478.7	1953.3.1–2008.12.31	168.4	N
48	Yanqi	42.08	86.57	1,055.3	1951.5.1–2008.12.31	80.3	S

Table 1 (continued)

No.	Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Data period	Mean annual precipitation	Subdivision belonged
49	Yining	43.95	81.33	662.5	1951.8.1–2008.12.31	274.2	N
50	Yiwu	43.27	94.70	1,728.6	1958.11.1–2008.12.31	92.6	T
51	Yutian	36.85	81.65	1,422.0	1955.11.1–2008.12.31	50.5	S
52	Zhaosu	43.15	81.13	1,815.0	1954.3.1–2008.12.31	505.9	T

[a] Tianshan Mountains

[b] Southern Xinjiang

[c] Northern Xinjiang

Xinjiang ranged from −1.95 to 25.37 mm/decade, with a regional average of 6.96 mm/decade. Upward trends were observed at 50 out of 52 stations, while two stations, the Tuoli in the northern Xinjiang and the Qijiaojing in the southern Xinjiang exhibited downward trends (Table 3). The highest upward trend occurred at the Wulumuqi station in the northern Xinjiang, while the highest downward trend was observed at the Qijiaojing station.

Figure 2a illustrates the spatial pattern of linear tendencies of the time series of the PRCPTOT over the Xinjiang for the period of 1959–2008. It can be found from this figure that the most of stations was characterized by positive tendency in the PRCPTOT, and generally, northern and central parts experienced a larger increasing rate of the PRCPTOT than southern part of the Xinjiang. Several regions, including the southwest and the north of the northern Xinjiang, and the north of the southern Xinjiang were dominated by relatively higher positive tendencies, while lower positive tendencies were observed in the west of the northern Xinjiang, and the southwest and the south of the southern Xinjiang (Fig. 2a).

MK significance testing for the trends in the time series of the PRCPTOT showed that 30 out of 52 stations have significant upward trends (at $p<0.05$), accounting for 57.7 % of the total stations (Table 4). Figure 2a illustrates also the spatial pattern of MK trends in the PRCPTOT in the Xinjiang over the period of 1959–2008. From the spatial perspective, the distribution pattern of stations with obvious MK upward trend is similar to that of stations with higher positive tendencies, and the most stations with significant upward trends were located in the middle and the north of the Xinjiang.

Above-mentioned upward trends in the PRCPTOT can also be observed from Fig. 3. Five-year moving average line

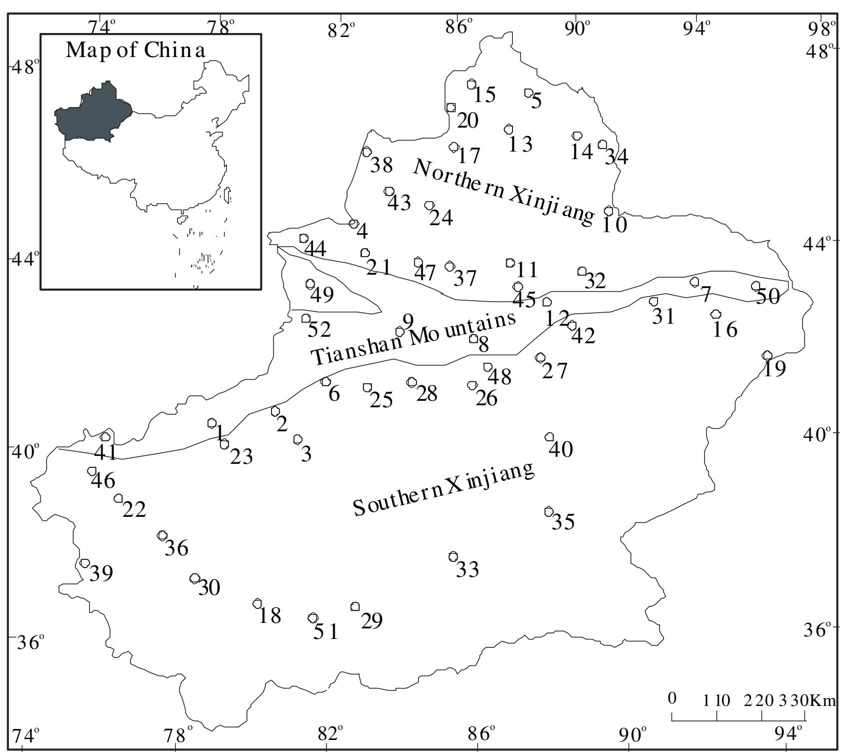

Fig. 1 Location of the study region and meteorological stations

Table 2 Acronyms and descriptions of the eight selected precipitation indices

Acronym	Description	Unit
PRCPTOT	Annual total precipitation(≥0.1 mm)	mm
R95	Annual total precipitation exceeding the 1959–2008 mean 95th percentiles	mm
WD	Number of wet days (precipitation ≥0.1 mm)	Days
Ds95	Number of days with precipitation greater than the 1959–2008 mean 95th percentiles	days
SDII	Simple daily intensity index (average precipitation on wet days)	mm/day
CWD	Maximum number of consecutive wet days (precipitation ≥0.1 mm)	days
CDD	Maximum number of consecutive dry days (precipitation <0.1 mm)	days
RX1day	Maximum 1-day total precipitation	mm

in Fig. 3a indicates a slightly long-term variation from the 1960s to the early period of 1980s and a roughly persistent increasing trends of the PRCPTOT in the Xinjiang from the middle of 1980s to the middle of 2000s. This might be a regime shift of precipitation, which was also found by Shi et al. (2003). In addition, three sub-regions, i.e., the southern Xinjiang and the Tianshan Mountains and the northern Xinjiang (see Table 1 and Fig. 1), also exhibited significant upward trends and potential changes in the PRCPTOT started from the mid-1980s (Fig. 3b–d).

3.2 Annual extreme precipitation (R95)

The linear tendencies of annual extreme precipitation (R95) in the Xinjiang varied between −1.66 and 25.92 mm/decade, with a regional average of 6.53 mm/decade. Upward trends were observed at 51 out of 52 stations, only one station, the Qijiaojing in the southern Xinjiang exhibited downward trend (Table 3). From the spatial perspective, positive tendencies in the R95 dominated the most of stations, and generally, the northern and the central parts experienced a larger increasing rate of annual extreme precipitation than the southern parts of the Xinjiang. Several regions, including the south and the north of the northern Xinjiang, and the north of the southern Xinjiang, were dominated by relatively higher positive tendencies, while lower positive tendencies were observed in the northwest of the northern Xinjiang, the southwest and the south of the southern Xinjiang. Only one station, the Qijiaojing station, shows lower negative tendency (Fig. 2b).

Table 3 Numbers and percentages of stations with upward and downward linear trends

	Upward		Downward	
	Number of stations	Percentage	Number of stations	Percentage
PRCPTOT	50	96.2	2	3.8
R95	51	98.1	1	1.9
RX1day	43	82.7	9	17.3
WD	42	80.8	10	19.2
Ds95	49	94.2	3	5.8
SDII	37	71.2	15	28.8
CWD	39	75.0	13	25.0
CDD	11	21.2	41	78.8

Figure 2b also represents statistically significant increasing (positive) and decreasing (negative) trends in addition to no trend. Spatially, a similar distribution pattern of the R95 with significant increasing trends to that of the PRCPTOT can be found. A total of 98.1 % out of the stations showed positive trends, with 53.8 % of them were significant, and scattered throughout the Xinjiang. Another 46.2 % of the stations indicated no significant trend (Table 4).

Figure 4 shows the long-term variation regime of the R95 for the entire Xinjiang and its three sub-regions, from which above-mentioned upward trends can be also observed. Five-year moving average line in Fig. 4a indicates a slightly long-term variation of the R95 in the entire Xinjiang from the 1960s to the mid-1980s and a roughly persistent increasing trends from the mid-1980s to the mid-2000's. In addition, three sub-regions, i.e., the southern Xinjiang and the Tianshan Mountains and the northern Xinjiang (see Table 1 and Fig. 1) also exhibited upward trends and potential changes in the P95 from the mid-1980s (Fig. 4b–d). These results were similar to those of the PRCPTOT, demonstrating that R95 may be one of the most contributors to the PRCPTOT. Relatively higher Pearson's correlation coefficients between two extreme precipitation indices for the entire Xinjiang, the southern Xinjiang, the northern Xinjiang, and the Tianshan Mountains indicated also that they were closely related (Table 5).

3.3 Maximum 1-day precipitation (RX1day)

The linear tendencies of the maximum 1-day precipitation (RX1day) in the Xinjiang varied between −10.32 and 31.80 mm/decade, with a regional average of 7.03 mm/decade. Upward trends were observed at 43 out of 52 stations, and 9 stations exhibited downward trend (Table 3). The highest upward trend occurred in Wulumuqi station, while the highest downward trend was observed at the Tacheng station in the northern Xinjiang with changing rate of 31.80 and −10.32 mm/decade, respectively.

The spatial distribution of linear tendencies of the RX1day series is illustrated in Fig. 2c. Generally, the northern and the central parts experienced a larger increasing rate of the RX1day than the southwestern parts of the Xinjiang. Several regions, including the northeast and the south of the

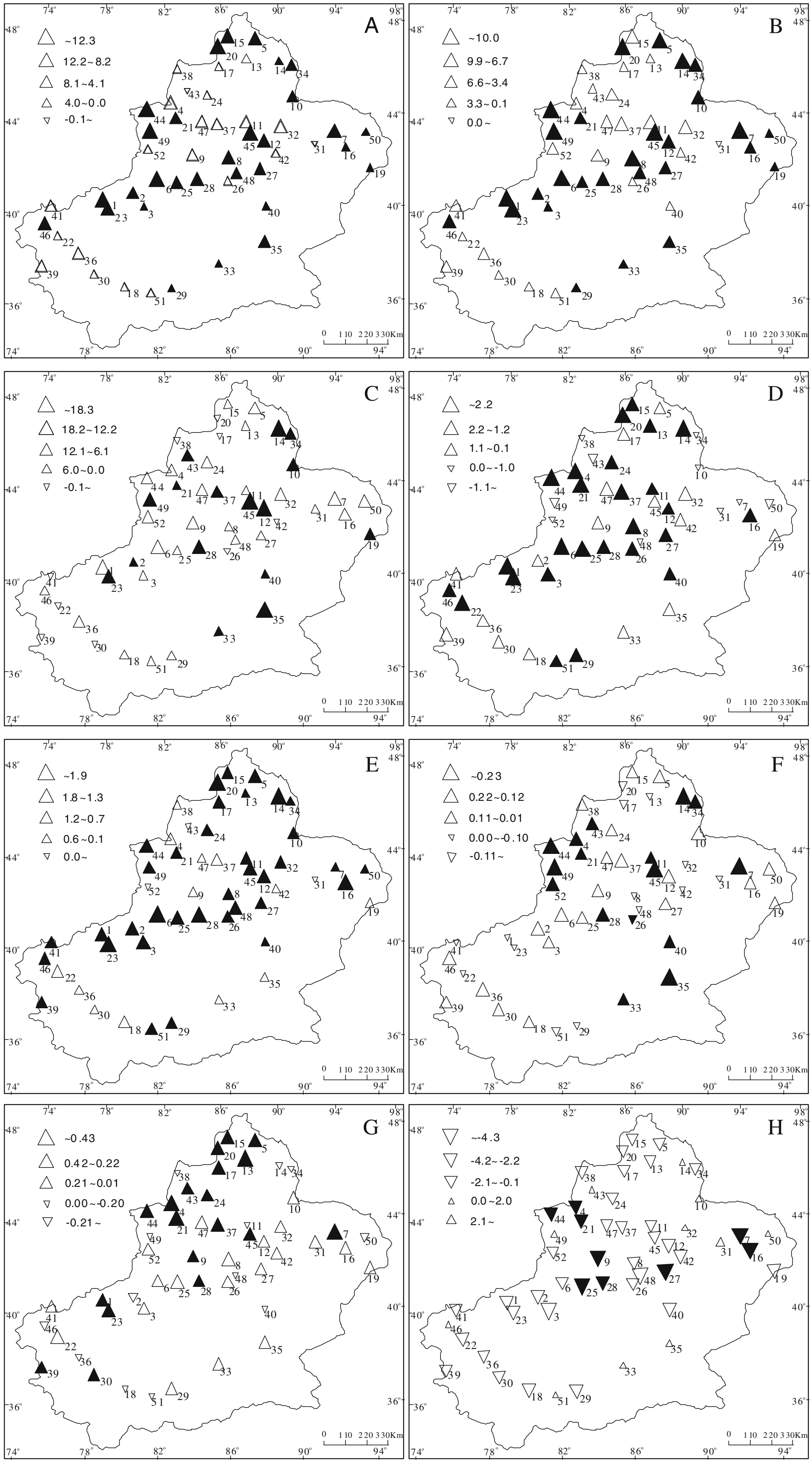

Fig. 2 Spatial distribution of trends and tendencies: significant positive (*filled triangle*) and negative (*filled inverted triangle*) and not significant positive (*empty triangle*) and negative (*empty inverted triangle*) MK trends of the extreme precipitation indices (**a** PRCPTOT, **b** R95, **c** RX1day, **d** WD, **e** Ds95, **f** SDII, **g** CWD, **h** CDD). Significance of the trend is identified by 95 % confidence level

Table 4 Results of MK significance test

	Upward		Downward		No trend	
	Number of stations	Percentage	Number of stations	Percentage	Number of stations	Percentage
PRCPTOT	30	57.7	0	0.0	22	42.3
R95	28	53.8	0	0.0	24	46.2
RX1day	16	30.8	0	0.0	36	69.2
WD	26	50.0	0	0.0	26	50.0
Ds95	36	69.2	0	0.0	16	30.8
SDII	15	28.8	1	1.9	36	69.2
CWD	19	36.5	0	0.0	33	63.5
CDD	0	0.0	9	17.3	43	82.7

northern Xinjiang and the north and the east of the southern Xinjiang, were dominated by relatively higher positive tendencies, while lower positive tendencies were observed in the southwest of the northern Xinjiang and the southwest of the southern Xinjiang (Fig. 2c).

Statistically significant increasing (positive) and decreasing (negative) trends in addition to no trend are also represented in Fig. 2c. A total of 82.7 % out of the total stations showed positive trends, with 30.8 % of the total stations were significant, while another 69.2 % indicate no trends (Table 3, 4). Spatially, the stations with notable upward trends scattered in the northern and the southern Xinjiang.

Above-mentioned upward trends in the RX1day can be also observed from Fig. 5. Five-year moving average line in Fig. 5a indicates a slightly long-term variation from the 1960s to the early period of 1980s and a roughly persistent increasing trends of the RX1day in the Xinjiang starting from the mid-1980s. In addition, two sub-regions, the Tianshan Mountains and the southern Xinjiang (see Table 1 and Fig. 1), also exhibited significant upward trends and potential changes in the RX1day starting from the mid-1980s, while the northern Xinjiang exhibited a slightly long-term variation during 1959–2008 (Fig. 5b–d). The temporal trend was similar to that of the PRCPTOT, indicating a higher contribution of the RX1day to the PRCPTOT. The higher Pearson's correlation coefficients between two extreme precipitation indices for the entire, the southern, and the northern Xinjiang and the Tianshan Mountains indicate also that they were closely related (Table 5).

3.4 Number of wet days

The linear tendencies of the number of wet days (WD) in the Xinjiang vary between −2.13 and 6.94 days/decade, with a regional average of 1.32 days/decade. The upward trends

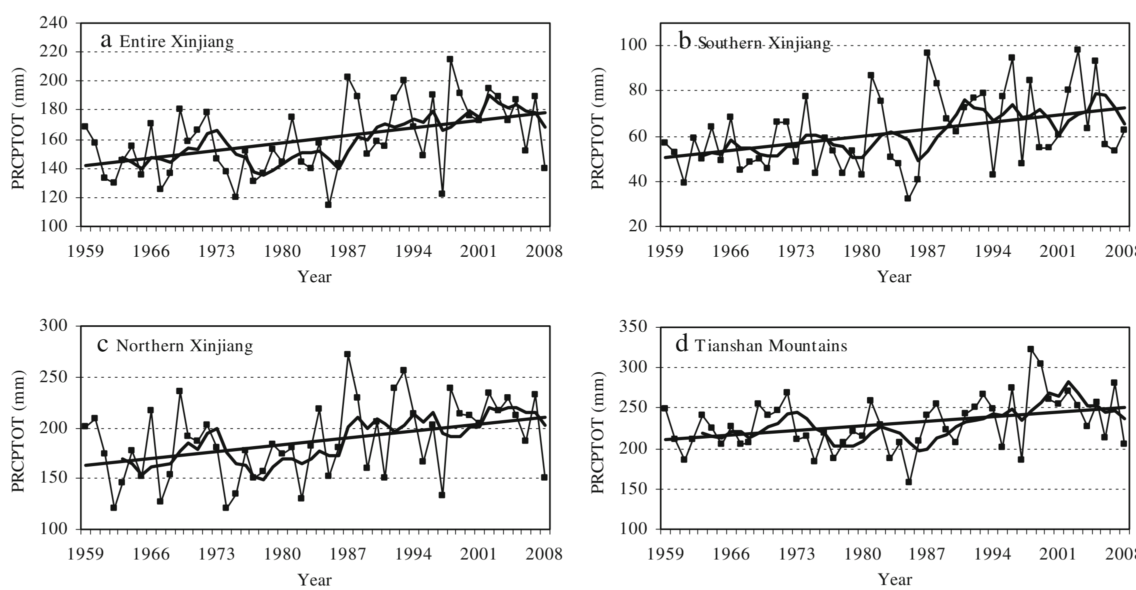

Fig. 3 Annual total precipitation (PRCPTOT) time series of entire Xinjiang, southern Xinjiang, northern Xinjiang, and the Tianshan Mountains (*dotted lines*). *Straight lines* mark the linear trend

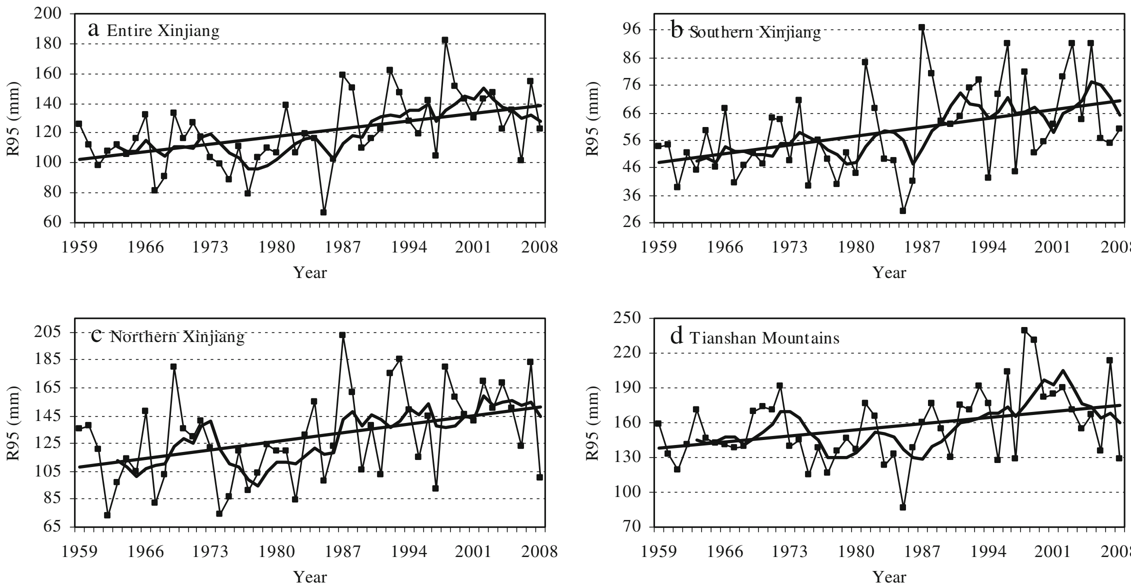

Fig. 4 The same as Fig. 3, but for annual extreme precipitation (R95)

are observed at 42 out of 52 stations, while 10 stations exhibit downward trend (Table 3). The highest upward trend occurs at the Jimunai station in the northern Xinjiang, while the highest downward trend is observed at the Yiwu station in the eastern Xinjiang.

Figure 2d depicts spatial distribution of increasing (positive) and decreasing (negative) trends in addition to no trend in the WD. From this figure, it can seen that most stations are characterized by positive tendency in the WD, and generally, the northern and the central parts experience a larger increasing rate of the WD than the southern part of the Xinjiang. Several regions, including the southwest and the north of the northern Xinjiang and the north of the southern Xinjiang, are dominated by relatively higher positive tendencies, while lower positive tendencies are observed in the southwest of the southern Xinjiang. In addition, stations characterized by negative tendencies are mostly distributed in the east part of the Xinjiang and the northwest and the west of the northern Xinjiang (Fig. 2d).

MK significance testing for the trends in the WD series showed that 26 out of 52 stations are dominated by significant upward trends (at $p<0.05$), accounting for 50.0 % of the total stations (Table 4). Figure 2d illustrates also the spatial pattern of MK trends in the WD in the Xinjiang over the period of 1959–2008. It can be seen from Fig. 2d that the spatial distribution of stations with obvious MK upward trend is similar to that of the PRCPTOT and the R95, and the most stations with significant upward trends are located in the middle and the north of the Xinjiang.

Figure 6 shows also above mentioned upward trends in the WDs in the entire Xinjiang and three sub-regions. Five-year moving average line in Fig. 6a indicates that the WD has a slightly long-term variation from the 1960s to the mid-1980s and a roughly persistent increasing trends from the mid-1980s to the mid-2000s in the entire Xinjiang. In addition, three sub-regions, i.e., the southern Xinjiang and the Tianshan Mountains and the northern Xinjiang (see Table 1 and Fig. 1) also exhibit obvious upward trends and potential changes in the WDs started from the mid-1980's (Fig. 6b–d).

3.5 Very wet days (Ds95)

The linear tendencies of annual very wet days (Ds95) in the Xinjiang vary between −0.84 and 2.6 days/decade, with a regional average of 0.88 days/decade. The upward trends are observed at 49 out of 52 stations, while three stations, the Tuoli and the Zhaosu in the northern Xinjiang and the Qijiaojing in the southern Xinjiang, exhibit downward trends (Table 3). The highest upward trend occurs at the Keping station, while the lowest downward trend is observed at the Qijiaojing station in the southern Xinjiang.

Spatially, positive tendencies in the Ds95 dominate the most of stations, and generally, northern and central parts experience a larger increasing rate of annual extreme precipitation than southern part of the Xinjiang. Several regions, including the south and the north parts of the northern Xinjiang and the north of the southern Xinjiang, are dominated by relatively higher positive tendencies (Fig. 2e).

Figure 2e also represents statistically significant increasing (positive) and decreasing (negative) trends in addition to no trend existence. A total of 94.2 % out of the stations show positive trends, with 69.2 % of the total stations are significant, while another 30.8 % indicate no trend (Table 4).

Table 5 Pearson's correlation coefficients between eight extreme precipitation indices for Entire Xinjiang, Southern Xinjiang, Northern Xinjiang, and the Tianshan Mountains

	Entire Xinjiang							Southern Xinjiang						
	WD	R95	Ds95	SDII	CWD	CDD	RX1day	WD	R95	Ds95	SDII	CWD	CDD	RX1day
PRCPTOT	0.673	0.918	0.841	0.631	0.592	−0.503	0.761	0.829	0.988	0.920	0.662	0.430	−0.718	0.823
WD		0.594	0.680	0.140	0.636	−0.480	0.357		0.816	0.948	0.229	0.622	−0.714	0.532
R95			0.784	0.635	0.546	−0.390	0.761			0.907	0.668	0.429	−0.705	0.820
Ds95				0.357	0.576	−0.607	0.585				0.372	0.573	−0.729	0.664
SDII					0.347	−0.193	0.861					0.087	−0.340	0.860
CWD						−0.409	0.484						−0.464	0.248
CDD							−0.338							−0.490

	Northern Xinjiang							Tianshan Mountains						
	WD	R95	Ds95	SDII	CWD	CDD	RX1day	WD	R95	Ds95	SDII	CWD	CDD	RX1day
PRCPTOT	0.890	0.985	0.982	0.670	0.644	−0.600	0.723	0.611	0.978	0.887	0.586	0.390	−0.318	0.657
WD		0.826	0.871	0.409	0.654	−0.701	0.470		0.467	0.658	0.074	0.474	−0.465	0.188
R95			0.974	0.713	0.621	−0.549	0.769			0.844	0.648	0.326	−0.238	0.705
Ds95				0.563	0.651	−0.622	0.646				0.226	0.369	−0.319	0.429
SDII					0.336	−0.106	0.884					0.197	−0.116	0.762
CWD						−0.445	0.435						−0.224	0.256
CDD							−0.147							−0.202

Italicized numbers indicate correlation is significant at 0.01 level (two-tailed)

The long-term variations of the Ds95 for the entire Xinjiang and its three sub-regions are depicted in Fig. 7, in which above-mentioned upward trends in the Ds95 can be also observed. Five-year moving average line in Fig. 7a indicates a slightly long-term variation from the 1960s to the mid-1980s and a roughly persistent increasing trends of the Ds95 since the mid-1980s. Apart from the northern Xinjiang, other two regions, the southern Xinjiang and the Tianshan Mountains (see Table 1 and Fig. 1), also exhibit significant upward trends and potential changes in the Ds95 starting from the mid-1980s (Fig. 7b–d).

3.6 Simple daily intensity index

The linear tendencies of precipitation intensity (SDII) in the Xinjiang vary between −0.19 and 0.52 mm/decade, with a regional average of 0.08 mm/decade. Upward trends are detected at 37 out of 52 stations, while other 15 stations exhibit downward trend (Table 3). The highest upward trend occurs in Wulumuqi station in the northern Xinjiang, while the lowest downward trend is observed at the Yutian station in the southern Xinjiang.

Trends for the SDII are shown in Fig. 2f. From the spatial respective, stations characterized by increasing trends are mostly located in the northern Xinjiang, while stations with lower negative tendencies are observed in the northwest of the northern Xinjiang, the central part of the Xinjiang, and the southern Xinjiang.

MK significance testing for the trends in the time series of the SDII shows that 15 out of 52 stations have significant upward trends (at $p<0.05$), and 36 stations show no trend, while one station, Kuerle, shows significant downward trend, accounting for 28.8, 69.2, and 1.9 % of the total stations, respectively(Table 4). Figure 2f illustrates also the spatial pattern of MK trends in the SDII. It can be seen from Fig. 2f that the most stations with significant upward trends are located in northern Xinjiang. Two regions, the west of northern Xinjiang and the southeast of southern Xinjiang, are dominated by notable increasing trends.

Figure 8 shows the long-term variation of the SDII for the entire Xinjiang and its three sub-regions. Five-year moving average line in Fig. 8a indicates that there is a roughly persistent increasing trend of the SDII in the Xinjiang since the middle of 1970s. Meanwhile, three sub-regions, i.e., the Southern Xinjiang, the Tianshan Mountains, and the northern Xinjiang (Table 1 and Fig. 1) also exhibit significant upward trends and potential changes in the SDII started from the middle of the 1970's (Fig. 8b–d).

3.7 Maximum number of consecutive wet days

The linear tendencies of the maximum number of consecutive wet days (CWD) in the Xinjiang vary between −0.42

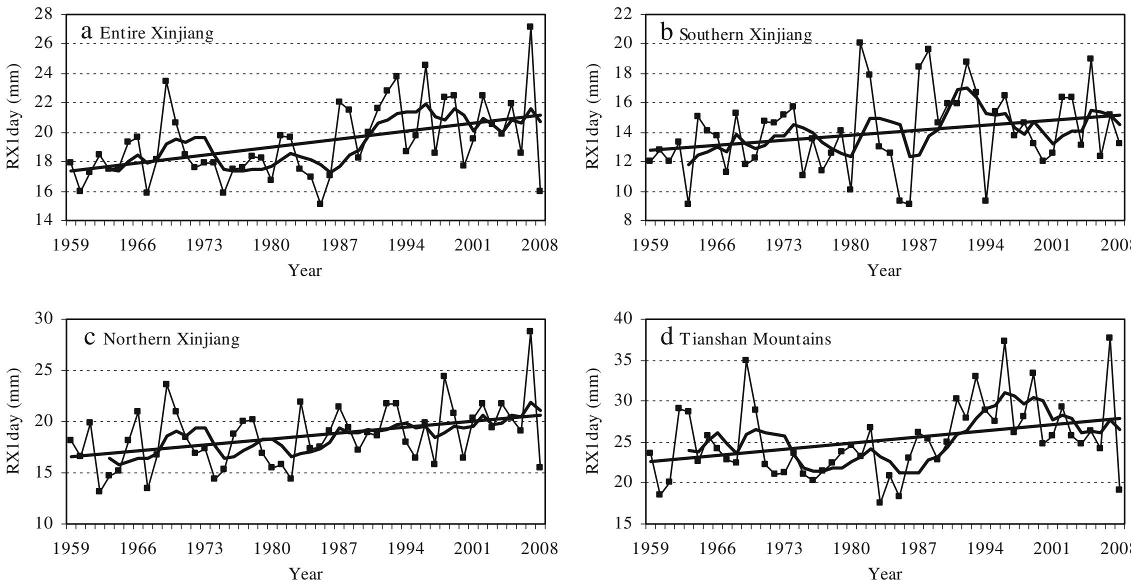

Fig. 5 The same as Fig. 3, but for the maximum 1-day precipitation (RX1day)

and 0.97 days/decade, with a regional average of 0.13 days/decade. Upward trends are observed at 39 out of 52 stations, while 13 stations exhibit downward trend (Table 3). The highest upward trend occurs in Alashankou station in northern Xinjiang, while the lowest downward trend is observed at the Akesu station in the southern Xinjiang.

Figure 2g illustrates the spatial pattern of linear tendencies in the CWD/CWDs over the Xinjiang for period 1959–2008. It can be found from this figure that the most of stations is characterized by positive tendency in the CWDs, and generally, northern and central parts experience a larger increasing rate of the CWD than southern part of the Xinjiang. Lower positive tendencies are observed in the east of northern Xinjiang and the southwest of southern Xinjiang (Fig. 2g).

MK significance testing for the trends in the CWD indicates that 19 out of 52 stations have significant upward trends (at $p<0.05$), accounting for 36.5 % of the total stations (Table 4). Figure 2g illustrates also the spatial pattern of MK trends in the CWD, showing that stations

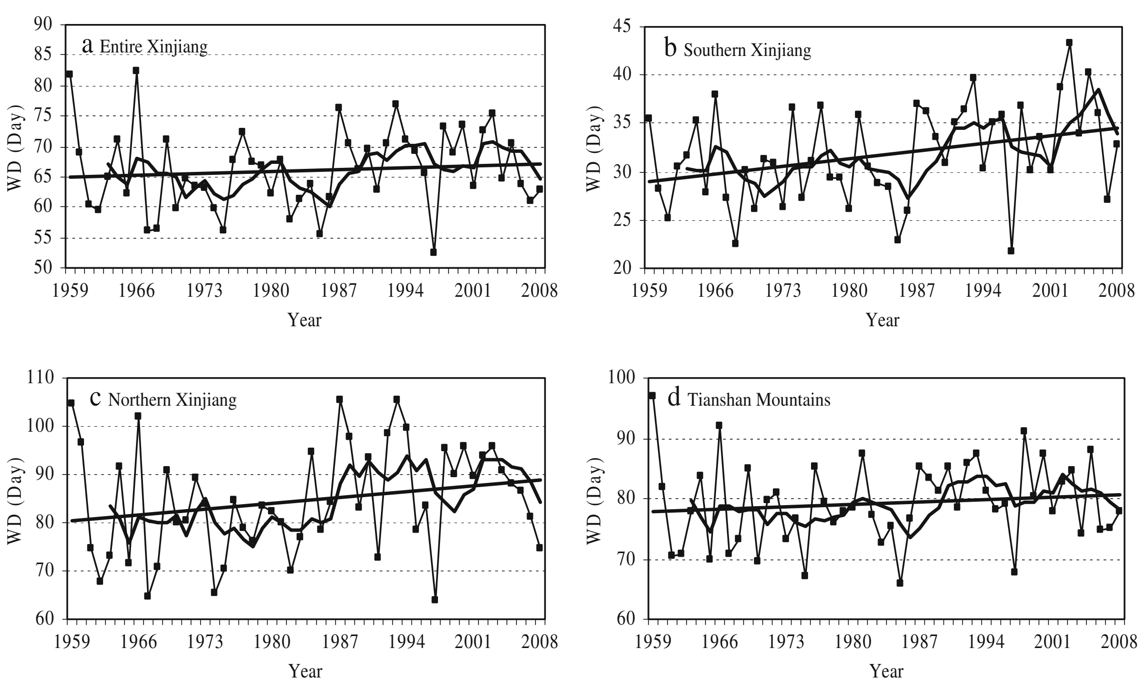

Fig. 6 The same as Fig. 3, but for number of wet days (WD)

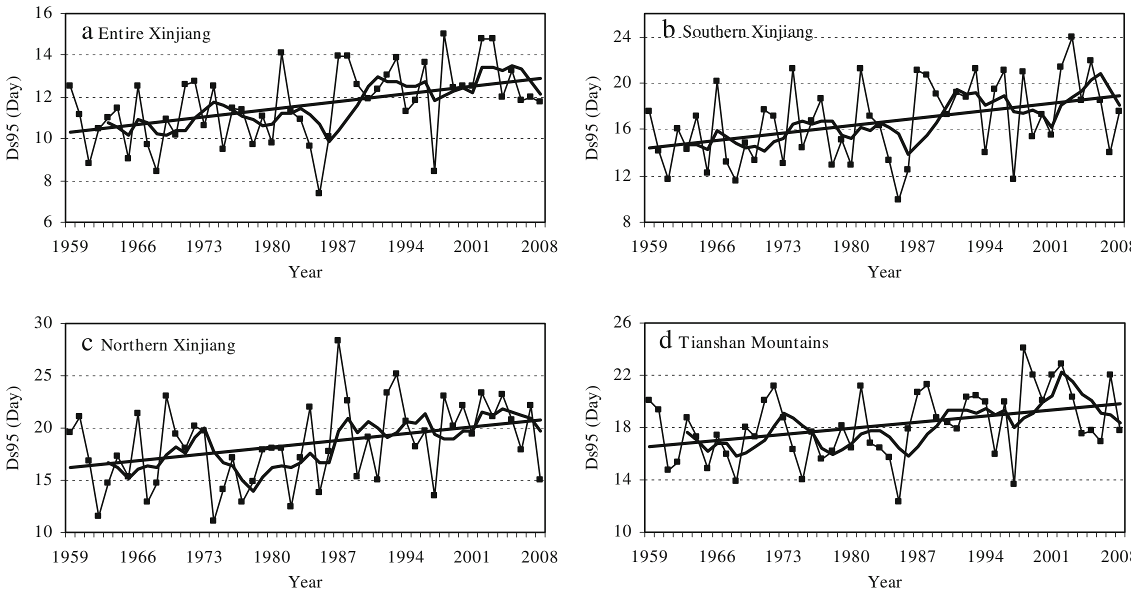

Fig. 7 The same as Fig. 3, but for very wet days (Ds95)

characterized by obvious MK upward trends are mostly located in northern Xinjiang.

Figure 9 depicts the long-term variation of the CWD. From this figure, it can be seen that a general upward trend occurs. Five-year moving average line in Fig. 9a indicates that the CWD has a slightly decrease trend from the 1960s to the mid-1980s and a rapidly persistent increasing trend of the CWD since the mid-1980s, which shows a similar temporal pattern to that of the PRCPTOT. In addition, three subregions, i.e., the southern Xinjiang, the Tianshan Mountains and the northern Xinjiang (Table 1 and Fig. 1) also exhibit significant upward trends and potential changes in the CWD starting from the mid-1980s (Fig. 9b–d). Notable upward trend in the CWD means that drought severity is decreasing in the Xinjiang. Except PI, other five indices, PRCPTOT, R95, WD, Ds95, and RX1day, are positively correlated with the CWD at $p<0.05$(Table 5), indicating that increase in the CWD is mostly derived from increase in the five indices other than the SDII.

3.8 Maximum number of consecutive dry days

In order to identify linear tendencies in the maximum number of consecutive dry days (CDD/CDDs) for 52 stations in

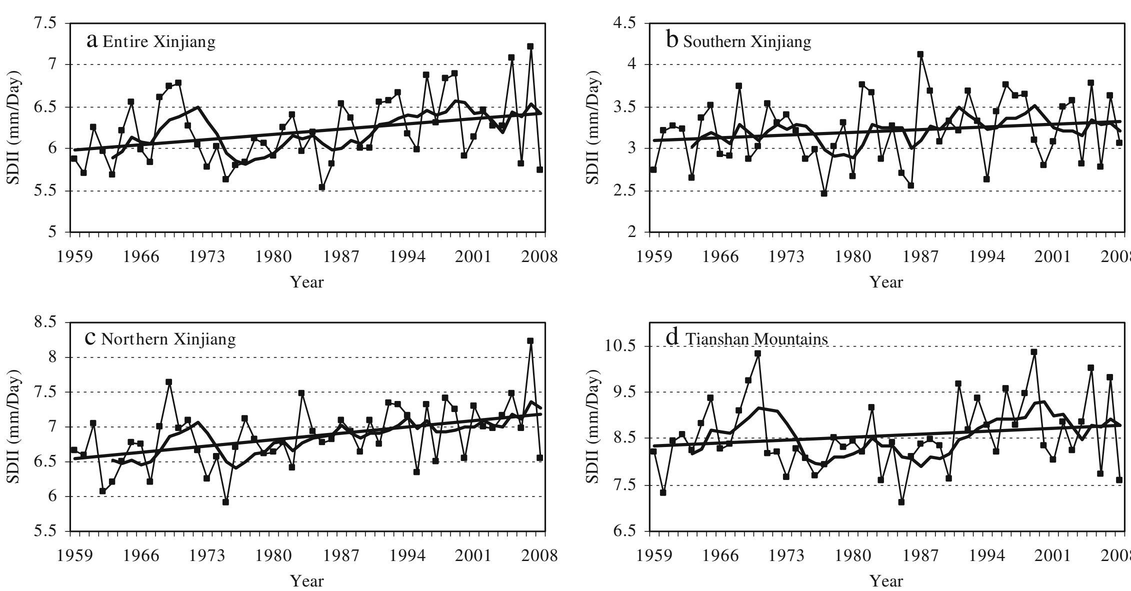

Fig. 8 The same as Fig. 3, but for simple daily intensity index (SDII)

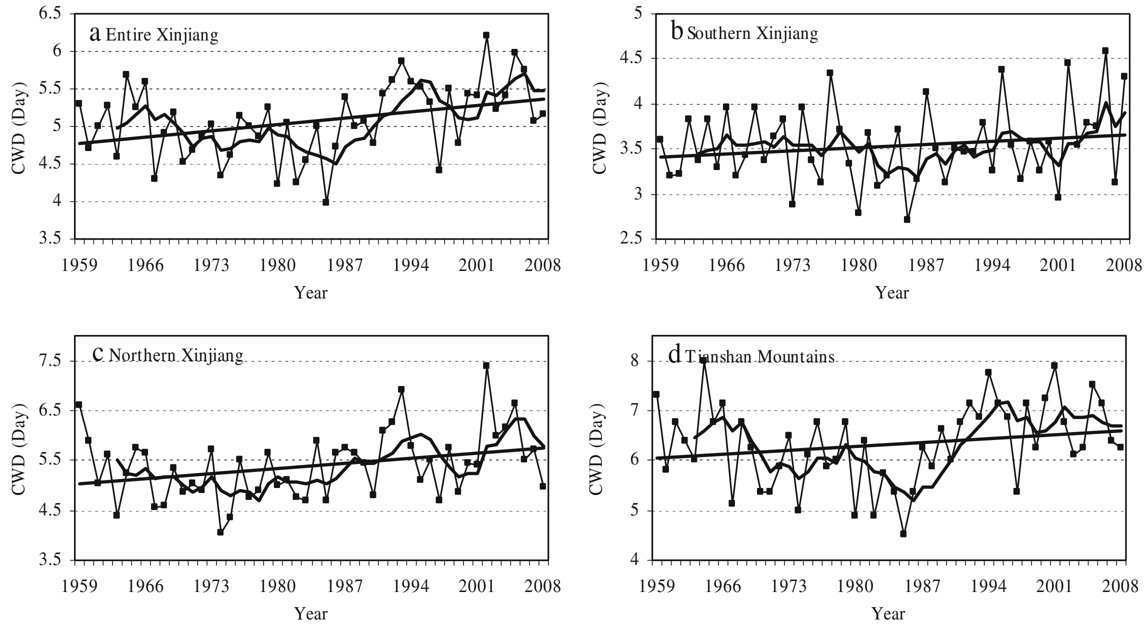

Fig. 9 The same as Fig. 3, but for the maximum number of consecutive wet days (CWD)

the Xinjiang, the linear regression method is applied. Results show that in the past 50 years, linear tendencies of the CDDs in the Xinjiang range between −9.90 and 5.28 days/decade, with a regional average of −1.72 days/decade. Downward trends are observed at 41 out of 52 stations, while other 11 stations exhibit upward trend (Table 3). The highest downward trend occurs at the Kumishi station in the southern Xinjiang, while the highest upward trend is observed at the Qijiaojing station.

Figure 2h depicts the spatial pattern of linear tendencies in the CDDs over the Xinjiang for period 1959–2008. From this figure, it can be seen that the most of stations is characterized by negative tendency, and generally, the northern, the southwestern, and the central parts experience a larger decreasing rate of CDDs than other parts of the Xinjiang (Fig. 2h).

MK significance testing for the trends in the time series of CDDs shows that 9 out of 52 stations have significant downward trends (at $p<0.05$), accounting for 17.3 % of the

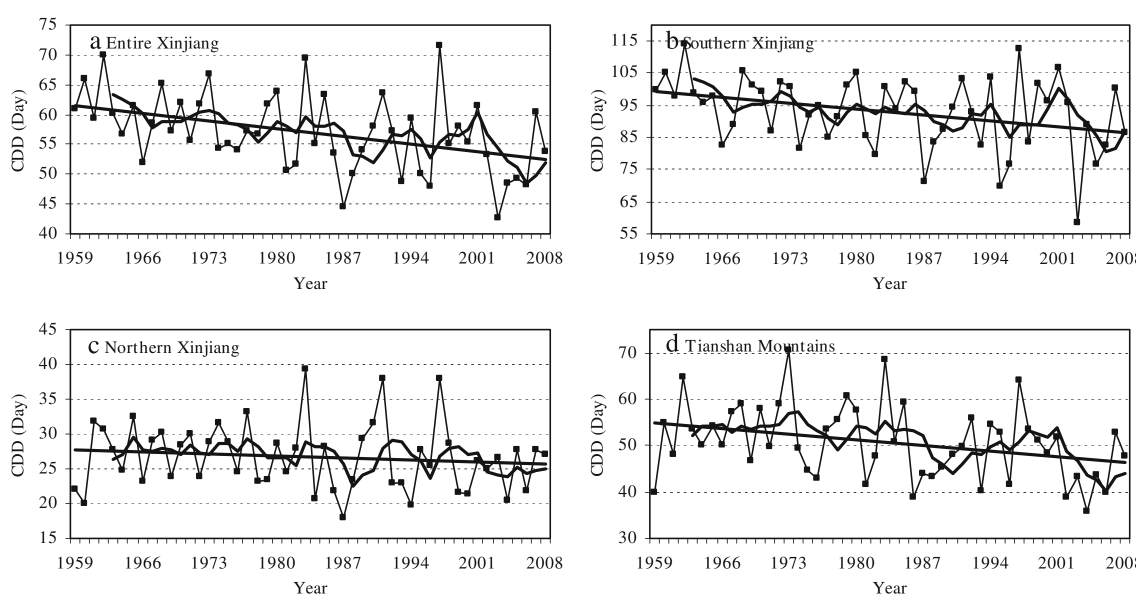

Fig. 10 The same as Fig. 3, but for the maximum number of consecutive dry days (CDD)

total stations (Table 4). Figure 2h illustrates also the spatial pattern of MK trends in CDDs in the Xinjiang over the period 1959–2008. Spatially, stations with obvious MK upward trends distribute in the central parts of the Xinjiang.

Above-mentioned downward trends in the CDDs can be also observed from Fig. 10. Five-year moving average line in Fig. 10a indicates a slightly long-term variation from the 1960s to the middle of the 1980s, and thereafter, in addition to downward trends, a higher variation range of the CDDs occurs. In addition, three sub-regions, i.e., the southern Xinjiang, the Tianshan Mountains, and the northern Xinjiang (see Table 1 and Fig. 1), also exhibit significant downward trends (Fig. 10b–d). Significant downward trend in the CDD means that drought severity is decreasing. Table 5 shows that the CDD is negatively correlated with other indices demonstrating that the CDD has a reverse variation trend when compare it with other seven extreme precipitation indices.

4 Discussions

Positive trends were dominated in all indices representing extreme heavy precipitation, while negative trends were detected in CDD, the only one index representing extreme weak precipitation. The increasing of extreme heavy precipitation and decreasing of extreme weak precipitation indicated that extreme precipitation became heavier and stronger. Consistently increasing trends in extreme precipitation were also detected by several authors, e.g., Yang (2003), Xue et al. (2003), and Zhao et al. (2010b), although these studies might use different definitions of extreme precipitation.

These trends of extreme precipitation were in good agreement with the variations of precipitation (Zhang et al. 2011). Many studies concluded that wet tendency was identified in Xinjiang during the most recent decades (e.g., Hu et al. 2002; Shi et al. 2003). Water vapor flux in Xinjiang was increasing may be mainly contributor of this wet trend. Moreover, the proportion of extreme precipitation to annual precipitation in Xinjiang was relatively high, and extreme precipitation and annual precipitation changed synchronously (Yang 2003). As the precipitation increased, the possibilities of extreme strong precipitation would increase correspondently. Higher correlations among the R95, RX1day, and the PRCPTOT revealed in this study (Table 5) could support above viewpoint.

Xinjiang is a typical arid region in China; the increase in extreme precipitation could help to alleviate the drought severity and losses generated by drought disasters. The harmful aspects of these trends, however, should also be considered. Heavy precipitation events may result in damaging floods (Kunkel et al. 1999). Furthermore, due to the special geological structure formed by arid climate in Xinjiang, even small magnitude floods may trigger landslides.

5 Conclusions

Extreme precipitation events can have serious impacts on our environment and society. This paper represents an updated revision of extreme precipitation trends in the Xinjiang, an arid land locating in the northwestern China. The following important and interesting conclusions are obtained.

- Increasing trends in the precipitation amount, rainy days, and the intensity of the extreme precipitation were identified at above 70 % of the total rain stations considered in this study, while most stations show decreasing trend in the annual maximum consecutive dry days. These tendencies indicate that extreme precipitation in Xinjiang became heavier.
- Significantly increasing trends of the precipitation extremes were observed mainly in the northern Xinjiang and the north of the southern Xinjiang. Hence, northern Xinjiang and the north of the southern Xinjiang suffered more tremendous aggravations of extreme precipitation than other parts in Xinjiang.
- Most extreme precipitation indices show a potential regime shift starting from the middle of 1980s. Although slightly changing of most indices was detected from the 1960s, the variations came to be more violent since the middle of 1980s.
- The magnitude of the trends is compatible with their pattern of spatial stability. The strongest trends are normally recorded at the stations characterized by stable trends. The slightly decreasing trends are observed at a fewer stations, mainly at the Qijiaojing stations in the southern Xinjiang and the Tuoli station in the northern Xinjiang.

Acknowledgments This work was financially supported by the Chinese National Basic Research Key Project (grant no. 2010cb951001), the National Scientific and Technological Support Program (grant no. 2007BAC03A0604), the Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, CAS (grant no. 05710401), and by Xinjiang Technology Innovative Program (grant no. 201001066 and 200931105). The authors would like to thank the reviewers for their invaluable suggestions.

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