Theor Appl Climatol (2013) 112:15–28
DOI 10.1007/s00704-012-0698-7

ORIGINAL PAPER

Changes in daily climate extremes in the arid area of northwestern China

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Received: 31 May 2011 / Accepted: 21 June 2012 / Published online: 17 July 2012

Abstract There has been a paucity of information on trends in daily climate and climate extremes, especially for the arid region. We analyzed the changes in the indices of climate extremes, on the basis of daily maximum and minimum air temperature and precipitation at 59 meteorological stations in the arid region of northwest China over the period 1960–2003. Twelve indices of extreme temperature and six indices of extreme precipitation are examined. Temperature extremes show a warming trend with a large proportion of stations having statistically significant trends for all temperature indices. The regional occurrence of extreme cool days and nights has decreased by −0.93 and −2.36 days/decade, respectively. Over the same period, the occurrence of extreme warm days and nights has increased by 1.25 and 2.10 days/decade, respectively. The number of frost days and ice days shows a statistically significant decrease at the rate of −3.24 and −2.75 days/decade, respectively. The extreme temperature indices also show the increasing trend, with larger values for the index describing variations in the lowest minimum temperature. The trends of Min Tmin (Tmax) and Max Tmin (Tmax) are 0.85 (0.61) and 0.32 (0.17)°C/decade. Most precipitation indices exhibit increasing trends across the region. On average, regional maximum 1-day precipitation, annual total wet-day precipitation, and number of heavy precipitation days and very wet days show insignificant increases. Insignificant decreasing trends are also found for consecutive dry days. The rank-sum statistic value of most temperature indices exhibits consistent or statistically significant trends across the region. The regional medians after 1986 of Min Tmin (Tmax), Max Tmin (Tmax), warm days (nights), and warm spell duration indicator show statistically more larger than medians before 1986, but the frost days, ice days, cool days (nights), and diurnal temperature range reversed. The medians of precipitation indices show insignificant change except for consecutive dry days before and after 1986.

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1 Introduction

The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007) stated that by the end of this century, the global mean temperature is expected to rise for about 0.74 °C. Within the context of global warming, variation and trends of extreme climate events, such as late spring frost, windstorm, extremely hot weather, severe drought, or prolonged soil wetness coinciding with hot weathers, have recently received much attention, as they are more sensitive to climate changes than mean values (Alexander et al. 2007; Tank and Konnen 2003; Williams et al. 2010). Changes in climatic extreme events impose serious challenges to society (Manton 2010), agriculture (Bencze et al. 2010; Peterson and Manton 2008), economy (Linnenluecke and Griffiths 2010), human health (Rocklov and Forsberg 2009), wildlife (Welbergen et al. 2008), and natural ecosystems (Mantua et al. 2010; Parker et al. 2008). There are two approaches to analyzing regional climate extremes. One is to use sophisticated models of the climate system, such as the regional climate models (RCMs).

Driven by general circulation models (GCMs) as the boundary conditions, RCMs provide simulated regional variability of climate variables at different temporal scales (Cooley and Sain 2010; Kysely et al. 2008; Marengo et al. 2009; Sylla et al. 2010). However, simulations in a finer resolution with RCMs forced by GCMs are subject to large uncertainties, which lead to a variance in the model-predicted changes in the extremes larger than natural variability (Kjellstrom et al. 2007). Boundary conditions from GCMs also often cause systematic biases in the regional simulation (Noguer et al. 1998). Some systematic biases can be amplified during the search of more extreme events like maximum and minimum temperatures (Moberg and Jones 2004). The other way to analyze regional climate extremes is to detect statistical trends in historical data, which has been proven to be effective. Alexander et al. (2007), using a standard set of annual and seasonal climate extreme indices derived from daily temperature and precipitation data, analyzed the relationships between mean and extreme trends across Australia and found that the trends in extremes of both temperature and precipitation are highly correlated with the mean trends. You et al. (2008) studied changes in daily climate extremes in the eastern and central Tibetan Plateau of China during 1961–2005. They found that temperature extremes and most precipitation indices exhibited increasing trends. Kioutsioukis et al. (2010) assessed statistical changes in climate extremes over Greece and found that a half of the examined climatic indices exhibited significant regional trends. For the arid region of China, most researches show detectable increases in precipitation, temperature, glacial melt water (Li et al. 2003), river runoff (Chen et al. 2006), water level rise and area expansion of the inland lakes (Wang et al. 2003), frequency of flood disasters (Xu et al. 2010), and vegetation cover (Ma et al. 2003), which state that the climate in Northwest China started to change in the year 1986 from warm-dry to warm-wet. Shi et al. (2007) also indicated there is an increase in the precipitation and runoff, which leads to hypothesis that climate in Northwest China, changed from warm-dry to warm-wet. And this change also took place around 1986

This paper presents a study of using the historical trend method to investigate the spatial and temporal variability of changes in temperature and precipitation extremes in the hyper-arid region located in the northwestern China. Literature reports that year 1980 seems to be a turning point of the climate in northwest China (Shi et al. 2007). Before that, the general climate characteristic of this area is warm and dry, and this general characteristic may have dominated the area ever since the Little Ice Age. After 1980, the regional climate seems to become increasingly warm and wet. It is not clear, however, whether the climatic extremes since 1980 have changed accordingly. So this study also assesses the differences of climatic extremes before and after 1986.

2 Materials and method

2.1 Study area

Our study area is the arid region located in the northwestern China, largely defined by 34–50°N and 73–108°E. This vast area includes the provinces of Xinjiang, Gansu, Qinghai, Ningxia, and the western part of Inner Mongolia (Fig. 1). The area has a typical inner-continental climate, featured by a wide range of temperature, low precipitation, and low humidity. The climate is dominated by continental arid conditions with lesser effects of the East Asian Monsoon. The high mountains, including the Tianshan Mountains, Kunlun Mountains, and Qilian Mountains, block atmospheric circulation and create vast desert basins in their rain shadows, including the Tarim Basin, Tsaidam Basin, Badanjilin Desert, Tengger Desert, and other endorheic drainage basins in Xinjiang, the Alashanqi desert in western Inner Mongolia, and the Hexi Corridor Gobi-desert in Gansu. The precipitation in most of the study area is below 200 mm/year. More than one third of the area has an annual precipitation less than 50 mm/year.

2.2 Data

We acquired data of daily minimum, maximum surface air temperature and precipitation observed at 59 meteorological stations in the study area (Table 1). The dataset was provided by the Climate Data Center (CDC) of the National Meteorological Center of the China Meteorological

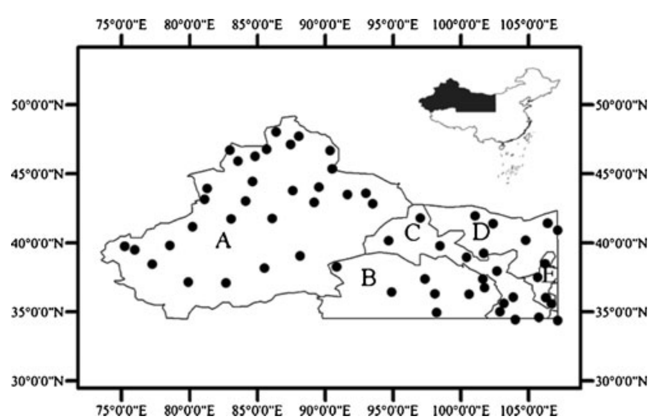

Fig. 1 Locations of meteorological stations available for this study. The regions are **a** Xinjiang; **b** Qinghai; **c** Gansu; **d** west Inner Mongolia; **e** Ningxia

Table 1 List of selected stations included in the analysis in arid lands northwestern China with World Meteorological Organization (WMO) number, station name, latitude, longitude, elevation, and ranges of the data

WMO number	Station name	North latitude	East longitude	Elevation (m)	Start year–end year
51053	Habahe	48.05	86.4	534	1957–2003
51068	Fuhai	47.12	87.47	502	1957–2003
51076	Altai	47.73	88.08	736.9	1954–2003
51133	Tacheng	46.73	83	536.6	1953–2003
51156	Hebukesair	46.78	85.72	1,294.2	1953–2003
51186	Qinghe	46.67	90.38	1,220	1957–2003
51241	Tuoli	45.93	83.6	1,077.7	1956–2003
51243	Kelamayi	46.28	84.85	445.6	1956–2003
51288	Beitashan	45.37	90.53	1,654.7	1957–2003
51346	Wusu	44.43	84.67	478.3	1953–2003
51379	Qitai	44.02	89.57	794.2	1951–2003
51431	Yining	43.95	81.33	664.3	1951–2003
51437	Zhaosu	43.15	81.13	1,854.6	1954–2003
51463	Wulumuqi	43.78	87.62	918.7	1951–2003
51495	Qijiaojing	43.48	91.63	874.4	1952–2003
51542	Bayinbuluke	43.03	84.15	2,458.9	1957–2003
51573	Tulufan	42.93	89.2	37.2	1951–2003
51628	Akesu	41.17	80.23	1,105.3	1953–2003
51644	Kuche	41.72	83.07	1,082.9	1951–2003
51656	Kurle	41.75	86.13	932.7	1958–2003
51705	Wuqia	39.72	75.25	2,177.5	1955–2003
51709	Kashi	39.47	75.98	1,290.7	1951–2003
51716	Bachu	39.8	78.57	1,117.4	1953–2003
51777	Ruoqiang	39.03	88.17	889.3	1953–2003
51811	Shache	38.43	77.27	1232	1953–2003
51828	Hetian	37.13	79.93	1,374.7	1953–2003
51839	Minfeng	37.07	82.72	1,409.7	1956–2003
51855	Qiemo	38.15	85.55	1,248.4	1957–2003
51886	Mangya	38.25	90.85	2,944.8	1958–2003
52101	Balikun	43.6	93	1,650.9	1956–2003
52203	Hami	42.82	93.52	737.9	1951–2003
52267	Ejinaqi	41.95	101.07	941.3	1959–2003
52323	Mazongshan	41.8	97.03	1,770.1	1957–2003
52378	Guaizihu	41.37	102.37	960	1959–2003
52418	Dunhuang	40.15	94.68	1,139.6	1951–2003
52495	Bayinmaodao	40.17	104.8	1,325.9	1957–2003
52533	Jiuquan	39.77	98.48	1,478.2	1951–2003
52576	Alashanyouqi	39.22	101.68	1,511.5	1959–2003
52652	Zhangye	38.93	100.43	1,483.7	1951–2003
52679	Wuwei	37.92	102.67	1,531.9	1951–2003
52737	Delingha	37.37	97.37	2,982.4	1955–2003
52765	Menyuan	37.38	101.62	2,851	1956–2003
52818	Germu	36.42	94.9	2,809.2	1955–2003
52836	Dulan	36.3	98.1	3,192.1	1954–2003
52856	Qiapuqia	36.27	100.62	2,836	1953–2003
52866	Xining	36.72	101.75	2,295.2	1954–2003
52889	Lanzhou	36.05	103.88	1,518.3	1951–2003
52984	Linxia	35.58	103.18	1,918.5	1951–2003
53231	Hailisu	41.4	106.4	1,510.2	1970–2003

Table 1 (continued)

WMO number	Station name	North latitude	East longitude	Elevation (m)	Start year–end year
53420	Hangjinhouqi	40.9	107.13	1,057.9	1954–1990
53614	Yinchuan	38.48	106.22	1,112.7	1951–2003
53705	Zhongning	37.48	105.67	1,184.9	1953–2003
53817	Guyuan	36	106.27	1,752.8	1956–2003
53915	Pingliang	35.55	106.67	1,348.2	1951–2003
56033	Maduo	34.92	98.22	4,273.3	1953–2003
56080	Hezuo	35	102.9	2,910.5	1957–2003
56093	Minxian	34.43	104.02	2,315.8	1951–2003
57006	Tianshui	34.58	105.75	1,142.6	1951–2003
57016	Baoji	34.35	107.13	610.3	1951–2003

Administration, and has gone through the quality control procedures of the CDC. CDC also provided the annual mean temperature, precipitation, and elevation data for our study area.

We first used the RclimDex software package (http://cccma.seos.uvic.ca/ETCCDMI), to "clean up" the data, including: (1) identifying errors in the temperature and precipitation data, such as precipitation value below 0 mm or days with Tmax<Tmin; (2) searching for outliers, where we choose three standard deviations as the threshold for a finer quality control of the data; (3) using the generalized data plot in RclimDex to visually inspect the data to further identify outliers and a variety of other problems that may cause error or bias in analyzing changes in the seasonal cycle or variance of the data; (4) using the Rhtest program (http://cccma.seos.uvic.ca/ETCCDMI) to perform the two-phase regression to detect multiple step change points that could exist in a time series (Wang 2003), which is a way to assess data homogeneity.

We then used RclimDex to calculate climate indices from the cleaned data. We selected 12 temperature indices and six precipitation indices for further analysis (Table 2).

Table 2 Definitions of 12 temperature indices and 6 precipitation indices used in this study

Index	Descriptive name	Definition	Units
Temperature			
FD0	Frost days	Annual count when TN(daily minimum)<0 °C	Days
ID0	Ice days	Annual count when TX(daily minimum)<0 °C	Days
TNn	Min Tmin	Monthly minimum value of daily minimum temp	°C
TXn	Min Tmax	Monthly minimum value of daily maximum temp	°C
TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
TX10p	Cool days	Percentage of days when TX<10th percentile	Days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C
TNx	Max Tmin	Monthly maximum value of daily minimum temp	°C
TXx	Max Tmax	Monthly maximum value of daily maximum tem	°C
TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
TX90p	Warm days	Percentage of days when TX>90th percentile	Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX<90th percentile	Days
Precipitation			
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days(defined as PRCP>= 1.0 mm)	mm/day
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1 mm	Days
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR≥1 mm)	mm
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10 mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm

2.3 Methods

As we know, both parametric and nonparametric tests may be employed for trend detection. However, some of the indices data do not have a Gaussian distribution, and for these cases, a simple linear least squares estimation would not be appropriate. Therefore we used a nonparametric trend statistic, Mann–Kendall test (Van and Hughes 1984), which has no assumption on the distribution of the residuals and is robust to the effect of outliers in the series, to detect monotonic trend in a time series. In the Mann–Kendall test, the elements of a time series $n(X_1, X_2, \cdots\cdots, X_n)$ are replaced by their ranks $(R_1, R_2, \cdots\cdots, R_n)$. The test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1}\left[\sum_{j=i+1}^{n} \operatorname{sgn}(R_j - R_i)\right] \quad (1)$$

where

$$\begin{cases} \operatorname{sgn}(X) = 1 \text{ for } X > 0 \\ \operatorname{sgn}(X) = 0 \text{ for } X = 0 \\ \operatorname{sgn}(X) = -1 \text{ for } X < 0 \end{cases} \quad (2)$$

A positive S indicates an increasing trend in the time series and a negative S indicates the opposite. If the null hypothesis H_0 (there is no trend in the data) is true, then S can be assumed to be approximately normally distributed with:

$$\begin{cases} \mu = 0 \\ \sigma = n(n-1)(2n+5)/18 \end{cases} \quad (3)$$

The z score of S is calculated as

$$z = |s|/\sigma^{0.5} \quad (4)$$

The corresponding p value of a z score can be obtained from the normal probability table. In this study, we used $\alpha = 0.05$ to determine if a trend was statistically significant. Since the Mann–Kendall test does not give an indication of the magnitude of the trend, we also calculated the trends with the linear least square method, about at individual stations, and for regional average anomaly series for each index. The regional average series are calculated as an arithmetic mean of values at all stations in the study (the time series of World Meteorological Organization (WMO) number of 53231 and 53420 being short, so do not need to be calculated).

We used the rank-sum test (Grayson et al. 1996; Kundzewicz and Ronson 2000) to compare the medians of the time series before and after 1986. The process is as follows: Rank all data, from 1(smallest) to N (largest); in the case of ties (equal data values), use the average of ranks; compute a statistic S as the sum of ranks of the observations in the smaller group (the number of observations in the smaller group is denoted as n, and the number of observational in the larger group is denoted as m); and compute the theoretical mean and standard deviation of S under H_0 for the entire sample

$$\begin{cases} \mu = n(N+1)/2 \\ \sigma = [nm(N+1)/12]^{0.5} \end{cases} \quad (5)$$

The standardized form of the test statistic Z_{rc} is computed as:

$$\begin{cases} Z_{rc} = (S - 0.5 - \mu)/\sigma & \text{if } s > \mu \\ Z_{rc} = 0 & \text{if } s = \mu \\ Z_{rc} = |(S - 0.5 - \mu)|/\sigma & \text{if } s < \mu \end{cases} \quad (6)$$

Z_{rc} is approximately normally distributed, and the critical test statistical values for various significance levels can be obtained from the normal probability tables. A positive Z_{rc} indicates the median after 1986 is larger than median before 1986 and a negative Z_{rc} indicates the opposite.

3 Results

When being averaged for the entire arid region of northwest China, almost all temperature indices show significant changes over the study period. Trends in temperature indices at individual stations also exhibit statistically significant changes. The magnitudes of the changes of minimum temperature related extremes are generally greater than those of maximum temperature related extremes. Precipitation extreme indices have more variability, with trends less significant than those of temperature extreme indices.

3.1 Temperature

3.1.1 Cold extremes (FD0, ID0, TNn, TXn, TN10p, and TX10p)

Figure 2 shows the spatial distribution of trends in cold extremes in the study area. Figure 3 shows the regional annual anomaly series of the indices of cold extremes in the study area. Figure 4 shows the frequencies of trend magnitudes per decade of the indices of cold extremes at the 59 meteorological stations. For frost days (FD0) and ice days (ID0), 81 and 63 %, respectively, of the stations had statistically significant decreasing trends. For FD0, 83 % of the stations had change magnitudes ranging from −6 to 0 days/decade (Fig. 4). For ID0, 72 % of the stations had change magnitudes ranging from −4 to −1 days/decade. The stations in the eastern had greater magnitudes for both indices. At the regional level, FD0 and ID0 kept decreasing since 1987, and the magnitudes were −3.24 and −2.75 days/decade, respectively.

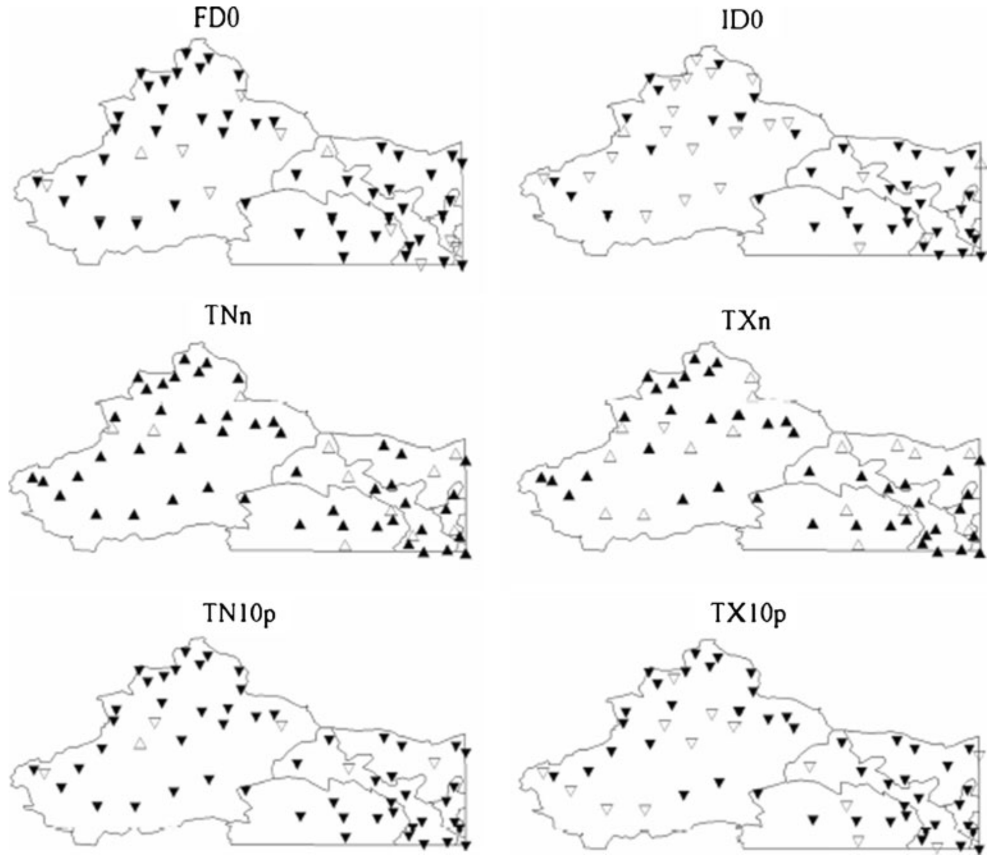

Fig. 2 Spatial pattern of trends of the cold extremes (Mann–Kendall statistic) (*black down-pointing triangle*: negative and statistically significant trend; *white down-pointing triangle*: negative trend but not statistically significant; *black up-pointing triangle*: positive trend but not statistically significant; *white up-pointing triangle*: positive and statistically significant trend)

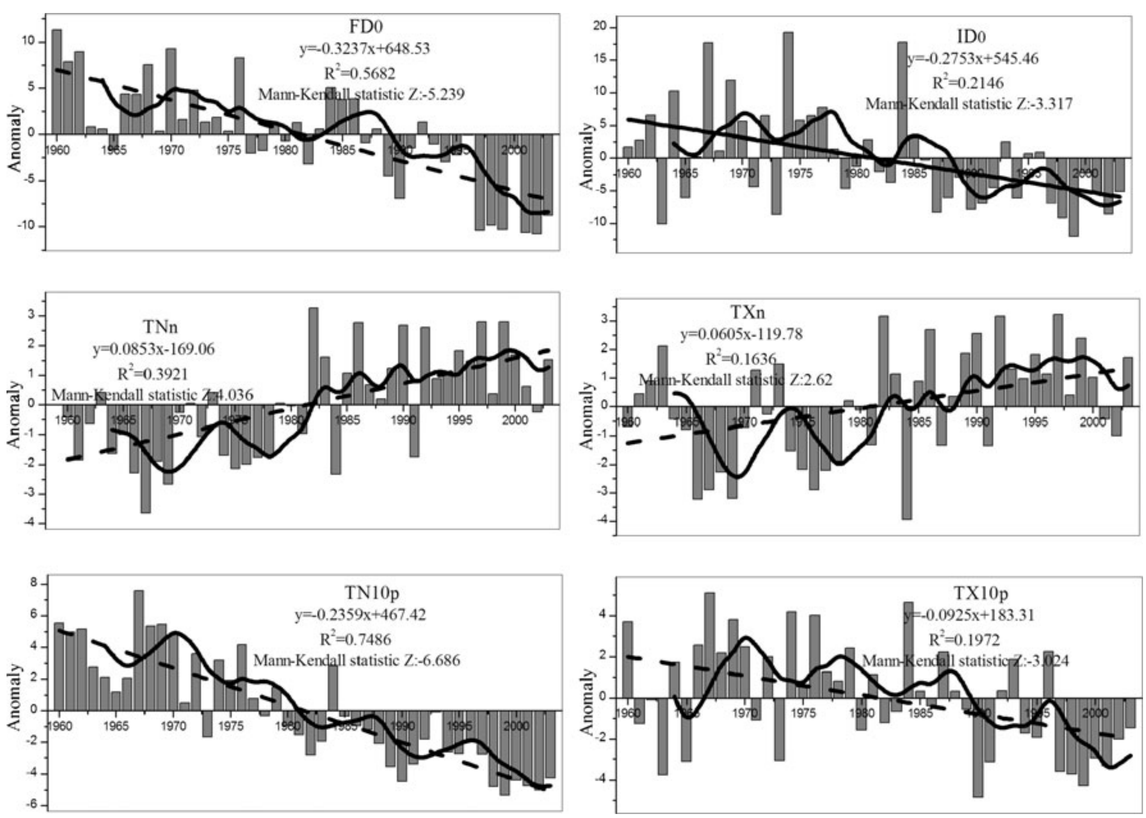

Fig. 3 Regional annual anomaly series of the cold extremes (the *column* is the annual anomaly series; the *solid line* is the 5-year smoothing average; the *dash line* is the linear regression)

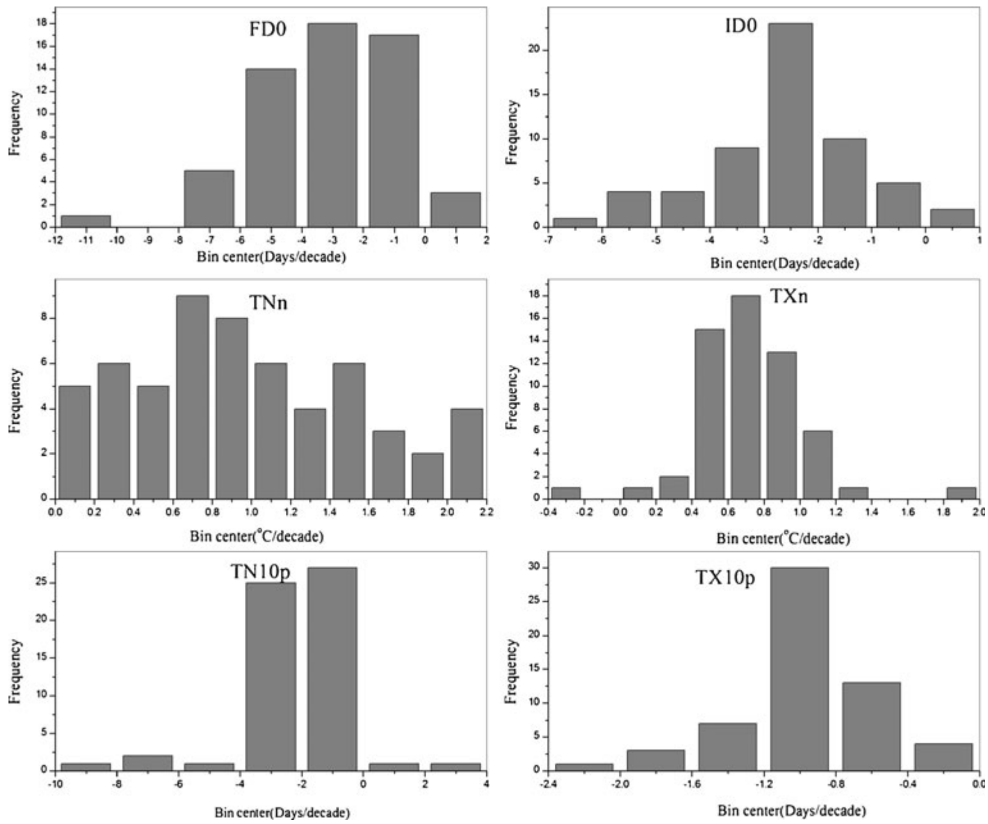

Fig. 4 Frequency of trend magnitude per decade for the indices of cold extremes

Similarly, the number of cool night (TN10p) and cool day (TX10p) had decreasing trends at almost all stations. For TN10p, 90 % of the stations, and for TX10p, 76 % of the stations had statistically significant trends, and about 88 % and 73 % of stations for magnitudes range from −4 to 0 and from −1.2 to −0.4 days/decade (Fig. 4). At the regional level, TN10p had a decreasing magnitude of −2.36 days/decade with a dramatic rise after 1985. TX10p had fluctuation before 1990, but had been continuously decreasing after that. The regional change magnitude of TX10p was −0.93 days/decade.

The temperature of Min Tmin (TNn) had increased at the rate of 0.85 °C/decade, and about 80 % of the stations had statistically significant increasing trends. Min Tmax (TXn) had also generally increased over the analysis period at the regional rate of 0.61 °C/decade, and about 70 % of the stations show statistically significant increasing trends. The stations with larger change magnitudes are located in the eastern and northern parts of the study area. TXn of 78 % stations ranges from 0.4 to 1 °C/decade, while the frequency of trend magnitudes for TNn is evenly distributed from 0 to 2.2 °C/decade. The values of these two indices had dramatic rises since mid-1990s.

3.1.2 Diurnal temperature range

For diurnal temperature range (DTR), about 90 % of the stations exhibit decreasing trends, and at nearly 60 % of the stations the trends are statistically significant. The areas with the largest DTR decrease are in the northern arid area (Fig. 5). The regional change rate was −0.24 °C/decade at the 0.05 significant level for the whole time series, which drastically declines after 1980. The trends of about 80 % stations are ranging from −0.6 to 0 days/decade (not shown). The decrease in DTR might be mainly caused by a faster increase in minimum temperature than maximum temperature, which indicates a warming trend in the climate (Liu et al. 2009). The decrease in DTR might be mainly due to the increase in vapor and aerosol in the air, which reduces the daytime incoming solar radiation and also the nighttime

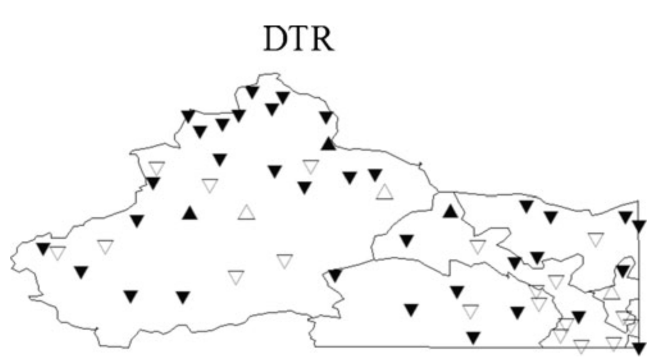

Fig. 5 Same as Fig. 2, but for trends in diurnal temperature range

outgoing longwave radiation from the land surface, resulting in a high minimum temperature (Shen et al. 2010).

3.1.3 Warm extremes (TNx, TXx, TN90p, TX90p, and WSDI)

For warm extremes, the spatial distribution of stations with different trends (significant negative, insignificant, and significant positive) is shown in Fig. 6. About 80 % of the stations had increasing trends for Max Tmin (TNx) and Max Tmax (TXx), but only at about 30 and 20 % of the stations, respectively, the trends were statistically significant. The regional trend for TNx is statistically significant and had a rate of 0.32 °C/decade, while the trend of TXx is not statistically significant. About 56 and 59 % of stations for TNx and TXx range from 0 to 0.4 and from 0 to 0.3 °C/decade, respectively.

For the percentage of days exceeding the 90th percentiles (TN90p and TX90p), about 80 and 50 % of the stations had statistically significant increasing trends, respectively, and about 78 and 90 % stations are ranging from 0 to 3 days/decade and from 0 to 2 days/decade. The regional trends for these two indices were statistically significant with the rates of 2.11 and 1.25 days/decade, respectively. For the warm spell duration indicator (WSDI), about 90 % of the stations had increasing trends, but only 20 % were statistically significant; the regional change rate was 1.08 days/decade. All the warm extremes had been above their long-term averages since 1995.

3.1.4 Comparison of the temperature extreme indices

Comparing trends in warm and cold indices may provide information about changes in the tails of the daily temperature distributions. For minimum temperature, the regional average trend in TN10p (−2.36 days/decade) is of greater magnitude than that of TN90p (2.10 days/decade). More stations have trends in TN10p that are greater than TN90p. Similarly, the regional average trend of TNn is greater than that of TNx. At about 90 % of the stations (Table 3), the trends of TNn had larger magnitudes than those of TNx. The regional trend in TX90p was higher than that in TX10p (1.25 vs. −0.93 days/decade), and about a half of the stations show greater trends in TX90p. Averagely, the magnitude of the change of TXn is 3.5 times that of TXx. At about 90 % of the stations, the magnitude of the change of TXn is greater than that of TXx. The above findings indicate that most warm extremes (TN90p, TNx, and TXx) seem to have smaller magnitude of change than that of their corresponding cold extremes (TN10p, TNn, and TXn). The only exception is that TX90p has a greater change magnitude TX10p.

In terms of minimum and maximum values of the same index, in 86 % of the stations, TN10p had greater change magnitude than TX10; in 66 % of the stations, TNn had greater change magnitude than TXn; in 90 % of the stations, TNx had greater change magnitude than TXx; in 84 % of the stations, TN90 had greater magnitude than TX90; and in 55 % of the stations FD0 had greater magnitude than ID0 (Table 3).

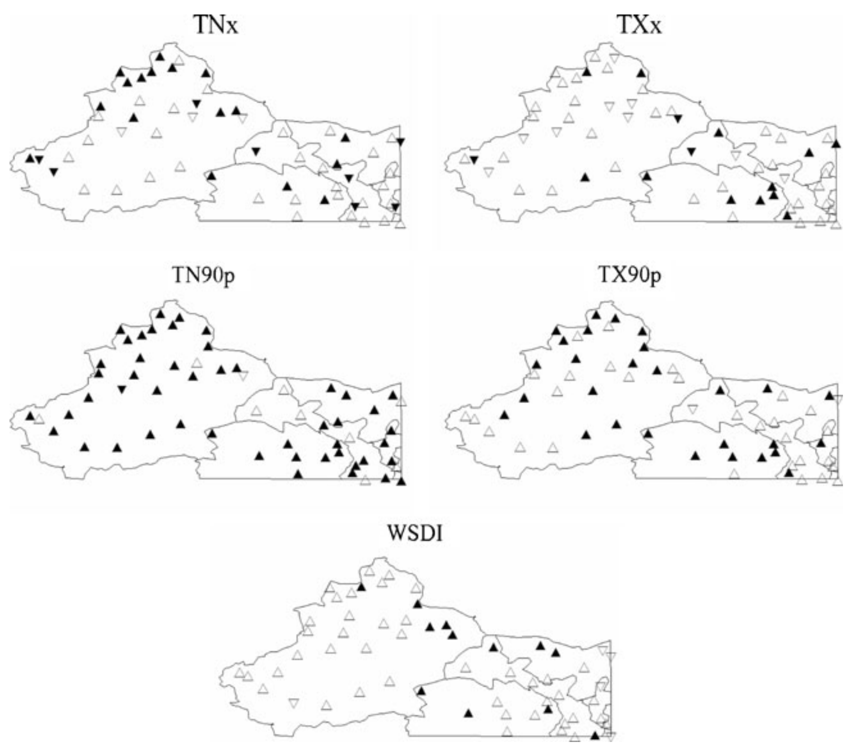

Fig. 6 Same as Fig. 2, but for warm extreme indices

In terms of regional average, all minimum values (TN90p, TN10p, FD0, TNx, and TNn) had greater change magnitudes than their corresponding maximum values (TX90p, TX10p, ID0, TXx, and TXn).

3.2 Precipitation

Figure 7 shows the frequency of change magnitudes of precipitation extremes at the 59 stations. Most precipitation indices had increasing trends for the whole region, but only at a small number of the stations such one can find a statistically significant trend for whatever index (not shown). In terms of regional average, Max 1-day precipitation amount (RX1day), simple daily intensity index (SDII), annual total wet-day precipitation (PRCPTOT), number of heavy precipitation days (R10), and very wet days (R95p) show insignificant increases by 0.41 mm/decade, 0.04 mm/decade, 2.85 mm/decade, 0.07 days/decade, and 1.64 mm/decade, respectively. The proportion of stations with positive trends (statistically significant trend) for those five indices are 59 % (8 %), 59 % (12 %), 68 % (12 %), 59 % (8 %), and 56 % (8 %), and approximately 88, 83, 80, 76 and 73 % of stations for trend magnitudes are −1–2 days/decade, −0.2–0.2 mm/decade, −5–10 mm/decade, −0.2–0.4 days/decade, and −2–4 mm/decade, respectively. In addition, about 61 % of stations (7 % statistically significant) for consecutive dry days (CDD) have decreasing trends with the regional trends of −2.52 days/decade. These results indicated that although the precipitation extremes have increased for the arid region of China in recent years, these changes are seem to be insignificant.

3.3 Changes before and after 1986

In this study, we used rank-sum test to examine whether the medians are different for periods before and after 1986 in our study area and the results are shown in Figs. 8 and 9. Figure 8 is for cold extremes and Fig. 9 is for precipitation extremes and warm extremes, and DTR are not shown. Over 90 % of the stations show decreasing trends of median after 1986 for FD0, ID0, TN10p, and TX10p, and approximately 64, 69, 86, and 66 % stations are statistically significant, respectively. The temperature medians for TNn, TXn after 1986 are much higher than that before 1986 with 81 and 83 % stations showing statistically significant increasing trends. About 74 % (52 % statistically significant) of stations show a decrease of medians after 1986 in DTR. The medians after 1986 related to warm extremes all show at least 75 % of stations with positive trends, especially for the indices of TN90p, TX90p, and WSDI, which are over 95 % with the statistically significant increasing stations of 90, 64, and 88 %, respectively. The regional medians of temperature extremes after 1986 (not show) all exhibit a statistical change except for TXx. FD0, ID0, TN10p, TX10p, and DTR show a significant decreasing trend, while TNn, TXn, TNx, TN90p, TX90p, and WSDI a increasing trend. The stations of medians after 1986 of precipitation indices mostly exhibit an increasing trend. The PRCPTOT, R10,

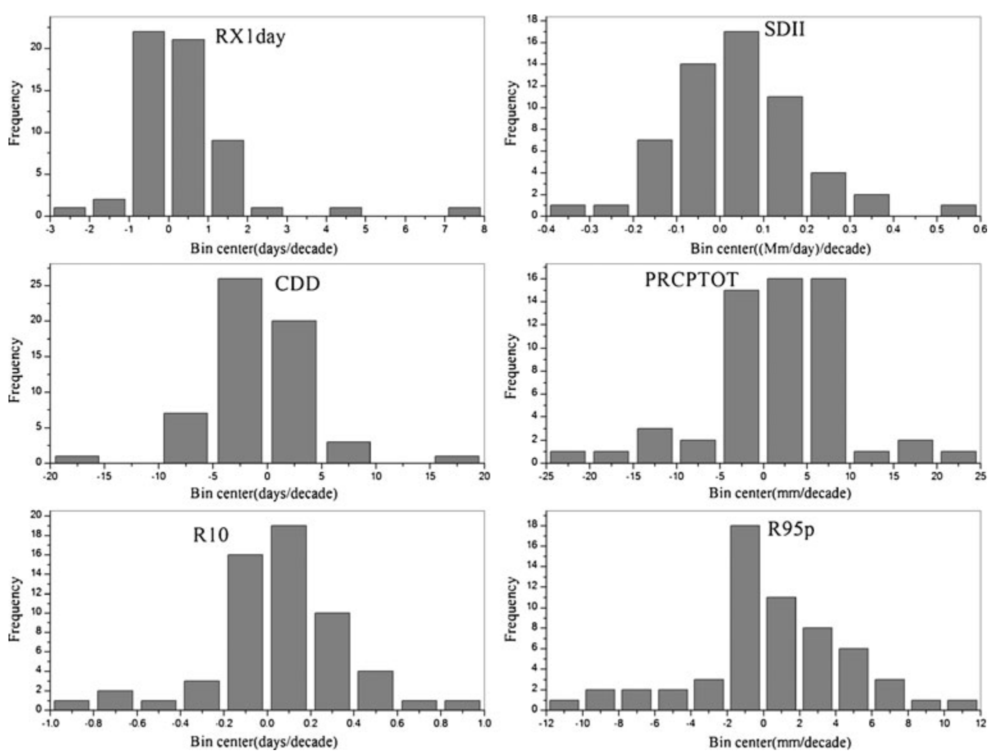

Fig. 7 Same as Fig. 4, but for precipitation indices

Table 3 Number and proportion of individual stations where the trend in one index is of greater magnitude than the trend in the other

Index	Comparison	Number	Proportion, %
TN10p>TN90p	abs	40	69
TNn>TNx	rel	52	90
TX10p>TX90p	abs	27	47
TXn>TXx	rel	52	90
TN90p>TX90p	abs	49	84
TN10p>TX10p	abs	52	90
FD0>ID0	abs	32	55
TNx>TXx	abs	37	64
TNn>TXn	abs	38	66
TN10p>TX90p	abs	50	86
TX10p>TN90p	abs	49	16

abs absolute magnitudes of trends are compared, *rel* signs of trends are retained during comparison

and R95p show 79 % (22 % statistically significant), 84 % (43 % statistically significant), and 78 % (40 % statistically significant) of stations a increasing trend. The RX1day and SDII of increasing trend are both over 70 %; however, only 5 and 14 % of stations are statistically significant. The regional trend of CDD (not shown) is the only index showing a statistically significant decreasing trend. When looking at individual stations, we can see 69 % of stations showing a decreasing trend with 9 % of stations statistically significant. Therefore, we can clearly indicate that the cold extreme events have decreased after period of 1986, while warm extreme events increased. The arid region of China is becoming wetter, but this change is insignificant.

4 Discussion and conclusion

Relationship between climate extreme trends (also trend magnitudes) at individual surface stations and elevation in the arid region of China are analyzed (Table 4). There are slight correlations between trend and elevation, but they are not significant. The only strong positive relationship occurs in TXx. It is very interesting that relationship between elevation and cold extremes show negative, and in warm extremes, this relationship is positive. The relationship between precipitation extreme trends and elevation show mix pattern, with positive relations in the indices of PRCPTOT, R10, and RX1day, but the opposite relationship in CDD, R95p, and SDII. So the relationships between climate extremes and elevation are not clear. Whether high elevations around the global have been warming faster or slower than nearby lower elevations or global averages is an inconclusive question (Beniston et al. 1997; Seidel and Free 2003; Pepin and Lundquist 2008). Liu and Chen (2000) revealed a more enhanced warming at high-elevation stations and when compared with surrounding regions in the Tibetan Plateau. This elevation dependency also has been reported by many other regional studies (Chen et al. 2003). However, many studies fail to find an elevation dependency in the trends of climate or a decreasing warming rate at high elevation (You et al. 2010; Pepin and Lundquist 2008). Our

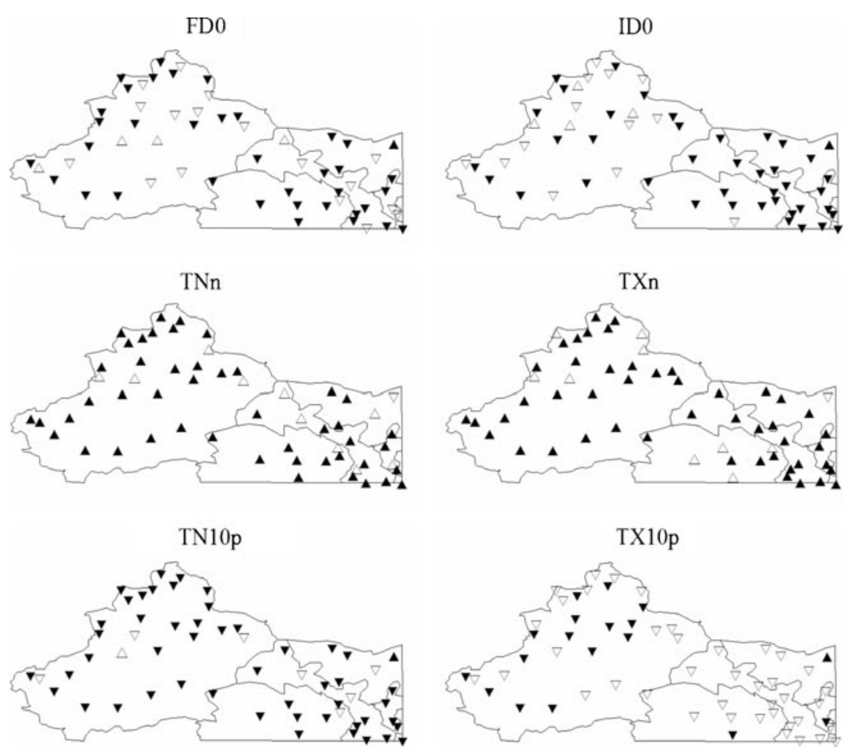

Fig. 8 Spatial pattern of the difference in medians for cold extremes (rank-sum statistic) (*black down-pointing triangle*: the median after 1986 is statistically significant decreasing than median before 1986; *white down-pointing triangle*: the median after 1986 is statistically insignificant decreasing than median before 1986 *black up-pointing triangle*: the median after 1986 is statistically significant increasing than median before 1986; *white up-pointing triangle*: the median after 1986 is statistically insignificant increasing than median before 1986)

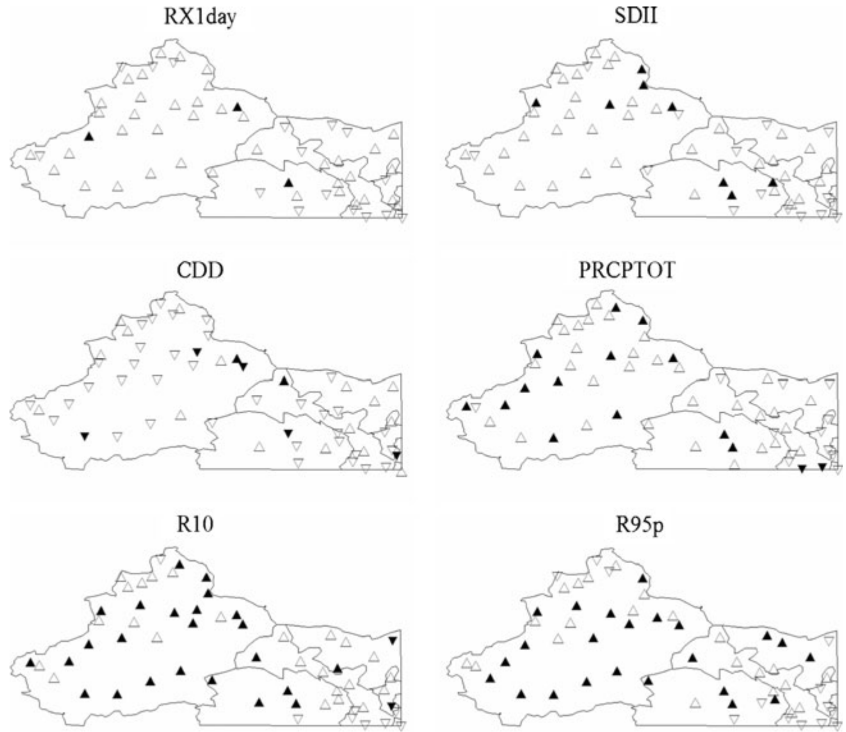

Fig. 9 Same as Fig. 8, but for precipitation extremes

study also shows that there are no simple linear relationship between climate extreme trends and elevation, and therefore a suggestion of elevation dependency could be misleading in the arid region of China for the climate extremes.

Relationships between trends (trend magnitudes) and mean climate are also shown in Table 4. There are strong negative correlations between warm extremes and mean temperature ($p<0.05$). Faster warming trends occur at lower temperature, which is in accordance with the study of Tibetan Plateau (You et al. 2010). For cold extremes, the positive relationships can be found in most indices, but this relationship is insignificant. Precipitation extremes show

Table 4 Relationship between climate extremes (unit/decade), elevation (meters), and mean climate (unit/decade)

Indices		Elevation		Mean	
		Trend	Magnitude	Trend	Magnitude
Cold extremes	FD0	−0.0003	−0.0005	0.08792	**0.01813**
	ID0	−0.0002	−0.0002	−0.04497	−0.02799
	TN10p	−0.0003	−0.0006	−0.00851	0.06286
	TNn	−0.00008	−0.0002	0.08781	0.01134
	Tx10p	0.00006	0.00008	0.01477	0.0037
	TXn	−0.0003	−0.0002	0.07136	0.02223
DTR	DTR	0.0003	−0.00005	0.03866	0.00879
Warm extremes	TN90p	0.0004	0.0002	**−0.13789**	−0.05536
	TNx	0.0003	0.00003	**−0.19313**	**−0.03201**
	TX90p	0.0002	0.00003	**−0.07756**	0.039381
	TXx	**0.0006**	**0.0001**	**−0.12585**	**−0.02323**
	CSDI	0.0002	0.0004	**−0.06113**	**−0.05603**
Precipitation extremes	CDD	0.00007	0.0036	−0.0008	−0.000017
	PRCPTOT	0.00007	0.0002	**−0.00346**	**−0.02212**
	R10	0.00006	0.00005	**−0.00184**	**−0.00076**
	R95p	0.00002	−0.001	0.0009	**−0.008**
	RX1day	0.00002	−0.0002	−0.00103	−0.00065
	SDII	−0.00001	0.0004	−0.00116	−0.00012

The coefficient is the linear slope between two variables; slope significant are marked in bold

Table 5 Trends of temperature and precipitation extremes form this study and other works

Index	This study	China	Global	Eastern and central Tibetan Plateau	Middle East	Central and south Asia	Southern and west Africa
Temperature							
FD0 (days/decade)	**3.24**	**−3.73**	–	**−4.32**	−0.6	–	–
ID0 (days/decade)	**2.75**	–	–	**−2.46**	–	–	–
TNn (°C/decade)	**0.85**	**0.63**	**0.71**	**0.69**	**0.28**	**0.73**	**0.27**
TXn (°C/decade)	**0.61**	**0.35**	0.37	**0.30**	0.2		**0.18**
TN10p (days/decade)	**−0.93**	**−2.06**	**−1.26**	**−2.38**	**−1.3**	**−5.70**	**−1.63**
TX10p (days/decade)	**−2.36**	0.62	**−0.62**	**−0.85**	−0.4	**−2.60**	**−1.00**
DTR (°C/decade)	**−0.24**	**−0.18**	**−0.08**	**−0.20**	**−0.12**	**−0.12**	−0.01
TNx (°C/decade)	**0.32**	**0.21**	**0.30**	**0.25**	**0.23**		**0.19**
TXx (°C/decade)	0.17	0.07	**0.21**	**0.28**	0.07	**0.17**	**0.16**
TN90p (days/decade)	**2.10**	**1.75**	**1.58**	**2.54**	**1.2**	**6.86**	**2.35**
TX90p (days/decade)	**1.25**	0.62	**0.89**	**1.26**	**0.66**	**4.72**	**2.24**
WSDI (days/decade)	**1.08**	–	–	–	–		**2.74**
Precipitation							
RX1day (mm/decade)	0.41	1.37	**0.85**	0.27	0	1.02	0.05
SDII ((mm/day)/decade)	0.04	0.06	0.05	0.03	−0.006	–	**0.088**
CDD (days/decade)	−2.52	−1.22	−0.55	**−4.64**	**−5.0**	–	**3.57**
PRCPTOT (mm/decade)	2.85	3.21	**10.59**	6.66	−0.3	6.87	−0.052
R10 (days/decade)	0.07	–	–	0.23	−0.03	0.11	−0.38
R95p (mm/decade)	1.64	**4.06**	**4.07**	1.28	−0.3	**6.46**	0.024
Sources		(Kang et al. 2011)	(Alexander et al. 2006)	(You et al. 2008)	(Zhang et al. 2005)	(Tank et al. 2006)	(New et al. 2006)

Trends significant are marked in bold

negative relationships (except for PRCPTOT), but only the PRCPTOT and R10 show significant. Our study suggests that in the arid region, there are significant negative correlations between warm extremes trends and mean temperature.

At individual stations, statistically significant increases in the percentage of warm nights (days) and decrease in the percentage of cool night (days) are observed, and the trend magnitudes in cool (warm) nights are larger than those in cool (warm) days. The trends in minimum temperature extremes are greater than the trends in maximum temperature extreme, which is in accordance with the observed decrease in the DTR. The warming climate also causes the number of the FD0 and ID0 to decrease significantly. For temperature extremes, the trend of TNn (TXn) is greater than TNx (TXx), indicating the greater change of the magnitude in the lowest of minimum (maximum) temperature. For the indices of precipitation, there are few consistent and statistically significant trends in precipitation indices. Extreme precipitation indices (RX1day, SDII, PRCPTOT, R10, and R95) have a regional increasing trend but few trends at individual stations are statistically significant.

The medians (both at individual and regional values) of FD0, ID0, TNn, TXn, TN10p, and TX10p after 1986 related to cold extremes show statistical significant changes comparing that before 1986. Warm extremes also have changed especially for the indices of TN90p, Tx90p, and WSDI. Those results also indicate that the arid region in a warming world are decreasing in cold extreme events and increasing in warm extreme events. The medians of precipitation indices show a slower change than those of temperature indices, and among those precipitation indices only regional medians of CDD show statistically significant change.

Compared with other regions in the world (Table 5), patterns in arid region of China are broadly similar, but there are some differences. In the arid region of northwest China, the trends of most temperature extremes are greater than the corresponding trends in the mean annul surface temperature, which increased by 0.02–0.87 °C/decade. A lot of results, such as decreasing in cold extremes and the decreasing in extreme minimum temperature which are greater than the increases in extreme maximum temperature, agree with the earlier global study (Alexander et al. 2006) and the regional study (Kioutsioukis et al. 2010). The tendency of extreme indices also present differences, for example, the rate of decline for DTR is much higher than that for the global and other regions (Table 5). Comparing the Tibetan Plateau of China with climate extremes, the trends of cold extreme events seem to have greater decreases and warm extreme events seem to have less increase. For precipitation indices, only a small fraction of stations are statistically significant for any index. This is perhaps to be expected, as secular trends are difficult to detect against the larger interannual and decadal-scale variability of precipitation over regions (New et al. 2006). Most indices of temperature extremes after 1986 have changed, indicating the change of climatic extremes with warming in past several years.

Acknowledgments The research is supported by the National Basic Research Program of China (973 Program: 2010CB951003). The authors thank the National Climate Central, China Meteorological Administration, for providing the meteorological data for this study. Assistance on data processing from Li CX is greatly appreciated.

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