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Abrupt change of temperature and precipitation extremes in the arid region of Northwest China

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ABSTRACT

Trends and abrupt detection of temperature and precipitation extremes are important in climate change research. Based on the meteorological data from 68 stations in the arid region of Northwest China (ARNC), we analyzed the trend and abrupt change in temperature and precipitation extremes from 1961 to 2010. Results showed that abrupt change in both temperature and precipitation extremes in Northwest China occurred in around 1986. Interestingly, an abrupt change in Index B of the Tibetan Plateau (TPI_B) was detected in 1985. The temperature and precipitation extremes had strong and significant associations with TPI_B over the period of 1961–2010 ($R = 0.685$, $p < 0.01$, and $R = 0.441$, $p < 0.01$, respectively). They behaved consistently, with a weakening and decreasing trend from 1961 to 1984 and a strengthening and increasing trend from 1985 to 2010. Thus, TPI_B was probably an important factor in the abrupt change in both temperature and precipitation extremes in the ARNC.

1. Introduction

Within the context of global warming, extreme climate events have recently received much attention because they are more sensitive to climate change than mean values (Klein Tank and Konnen, 2003; Alexander et al., 2007; Williams et al., 2010). Particularly, many researchers placed special emphasis on abrupt climate change and the impact on human society (Banderas et al., 2012; Schmidt et al., 2012). In October 2003, the United States Department of Defense released a report entitled *Process of Abrupt Climate Change and the Impact on the National Security of the United States* (Schwartz and Randall, 2003). The report points out that climate change might induce some major regions (including China) in the Northern Hemisphere to experience a shift to dry-cold climate, and then trigger water and food catastrophes and resulting famine and refugees, which will bring new challenges to the US national security. Wang et al. (2013a) indicated that temperature extremes show a warming trend, and precipitation indices show increasing trends in northern Xinjiang and exhibit decreasing trends in southern Xinjiang. Jiang et al. (2013) suggested that most precipitation indices show a potential regime shift starting from the middle of the 1980s in Xinjiang. Wang et al. (2013b) summarized that temperature and precipitation indices show significant change before and after 1986 in the arid region of Northwest China (ARNC). Chinese scholars have also conducted much research on abrupt climate change. Chen et al. (2006) found that the arid region of Northwest China (ARNC), a sensitive area to global change, actually had a significant abrupt climate change in the mid-1980s. The direct factors that caused the abrupt change, however, have not been identified.

Abrupt change denotes a rupture in the established range of experience, that is, a surprisingly fast transition from one state to another (Berger et al., 1985). Technically, an abrupt climate change occurs when the climate system is forced to cross a threshold, triggering a transition to a new state at a rate determined by the climate system itself, and faster than the cause (Matyasovszky, 2011; Powell and Xu, 2011; Bers et al., 2013; Soulet et al., 2013). Clark et al. (2002) points out that the Atlantic thermohaline circulation is weakening along with the increasing greenhouse gases, and the feedbacks of atmosphere and ocean may have caused abrupt climate change. Gong et al. (2009) analyzed the spatial-temporal characteristics of temperature change in China using the dynamic autocorrelation-factor indices, and found that extreme high and low temperatures had an abrupt change lagging behind the change of average temperature by 3–4 years. Recent work (Levermann et al., 2009) has revealed a defining moisture-

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advection feedback that dominates the seasonal heat balance, thereby possibly acting as an internal amplifier and leading to abrupt changes in response to relatively weak external perturbations. Williams and Kniveton (2012) suggest that the atmosphere-land surface feedback has been an important factor for the past abrupt climate change. Using the records of millennial changes in the glacial Asian monsoon, Marzin et al. (2012) showed that the Indian monsoon has been fluctuating simultaneously with the abrupt climate changes recorded in the North Atlantic. The interaction between freshwater in the North Atlantic and the Atlantic Meridional Overturning Circulation (AMOC) is the biggest driving force for the abrupt climate change globally (Schultz, 2012). Abrupt climate change is a particular performance of nonlinear properties of the climate system, and it can occur for many reasons (Alley et al., 2003). Currently, people have not known exactly about the dynamic processes and causes of abrupt climate change, so statistical approaches are often used to investigate the cause. However, few studies have been reported on the reasons for the abrupt change in the temperature and precipitation extremes of ARNC.

In this study, we detected abrupt change in the temperature and precipitation extremes of ARNC over the last 50 years (1961–2010). The statistical relationships between the changes and eight atmospheric circulations, including Tibetan Plateau Index_B (TPI_B), Siberian High (SH), the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific-North American pattern (PNA), Antarctic Oscillation (AAO), Southern Oscillation (SO) and Westerly Circulation Index (WCI), were investigated. The primary goal of this study is to suggest the possible direct factors for the abrupt climate change (temperature and precipitation extremes) in the ARNC.

2. Study area and data

2.1. Study area

The arid region of Northwest China refers to the vast area generally defined by 30°N–50°N and 70°E–110°E (Fig. 1), covering the region bounded by the Kunlun–Qilianshan Mountains to the south and the Helan Mountains to the east. It is characterized by a basin-and-range geomorphologic pattern. The Altai Mountains, Tianshan Mountains, Kunlun Mountains, and Helan Mountains are located in the north, middle, south and east part of the region, respectively. The Junggar Basin, Tarim Basin, and Hexi Corridor are distributed between these mountains. The total area of the region is about 2.5 million km^2, accounting for over 1/4 of China. It has a typical temperate and continental climate. The mean annual temperature is about 8 °C, and the mean annual rainfall is less than 200 mm.

2.2. Data

Extreme climate events can be defined from various aspects, such as extreme temperature, extreme precipitation, or even storm events such as hurricanes. As climate extremes can be defined as large areas experiencing unusual climate values over a long period of time, one way to investigate the trends in climate extremes over time is to develop indices. In order to reduce the data dimensions, factor analysis was used to extract key extreme temperature and precipitation indices. Considering the climate characteristics of the ARNC, we chose four extreme temperature indices (Tav_ANN, Tnav_ANN, Txav_ANN and Txf90_ANN) and four extreme precipitation indices (Pav_ANN, Pn10mm_ANN, Pxcdd_ANN and Pxcwd_ANN) from 57 extreme indices (24 for extreme temperature and 33 for extreme precipitation) recommended by STARDX (http://www.cru.uea.ac.uk/projects/stardex/) for this study. The chosen indices were calculated based on the meteorological data from 68 stations in the ARNC for the period of 1961–2010 (Fig. 1). The eight circulation indices data (SOI, AAOI, NAOI, AOI, PNAI, WCI_DJF, SHI and TPI_B) were obtained from China's National Climate Center (http://cmdp.ncc.cma.gov.cn/cn/download.htm).

The Tibetan Plateau Index_B (TPI_B) is defined as an accumulative value of all geopotential height values at 500 hPa after removing the hundreds in the area ranging from 30°N to 40°N and 75°E to 105°E (unit: geopotential meter). It roughly reflects the activities of low vortex and high pressure at 500 hPa over the Tibetan Plateau (Wang and Wu, 1997). The other seven atmospheric circulations (SHI, AOI, NAOI, PNAI, AAOI, SOI, WCI_DJF) status can be

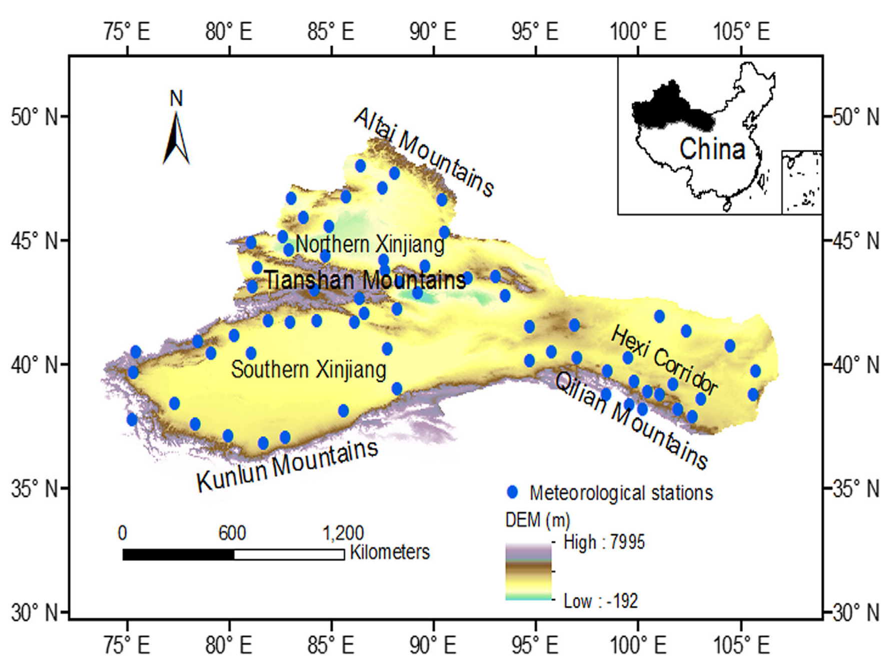

Fig. 1. Sketch map of study area.

seen in relevant references (Barnston and Livezey, 1987; Thompson and Wallace, 2000; Gong and Ho, 2002; Ho et al., 2005; Hurrell and Deser, 2009; Trouet and Taylor, 2010; Li et al., 2012a).

2.3. Methods

2.3.1. Mann–Kendall test for monotonic trend

The Mann–Kendall nonparametric trend test has been widely-used in long-term trend analysis on meteorological and hydrological time series. In this study, we employed it to detect the changes in temperature and precipitation extremes. In the Mann–Kendall test, the elements of a time series n ($X_1, X_2, \ldots\ldots, X_n$) are replaced by their ranks ($R_1, R_2, \ldots\ldots, R_n$). The test statistic S is calculated as

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

Where

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

A positive S indicates an increasing trend in the time series and a negative S indicates the opposite. S can be assumed to be approximately normally distributed with

$$\mu = 0$$

$$\sigma = n(n-1)(2n-5)/18 \quad (3)$$

The z score of S is calculated as

$$z = |S|/\sigma^{1/2} \quad (4)$$

2.3.2. Mann–Whitney test for step trend

Given the data vector $X = (x_1, x_2, \ldots, x_n)$, partition X so that $Y = (x_1, x_2, \ldots, x_{n1})$ and $Z = (x_{n1+1}, x_{n1+2}, \ldots, x_{n1+n2})$. The Mann–Whitney test statistic is given as

$$Z_c = \left[\sum_{t=1}^{n_1} r(x_t) - n_1(n_1+n_2+1)/2\right] \Big/ [n_1 n_2 (n_1+n_2+1)/12)]^{1/2} \quad (5)$$

in which $r(x_t)$ is the rank of the observations. The null hypothesis H_0 is accepted if $-Z_{1-\alpha/2} \le Z_c \le Z_{1-\alpha/2}$, where $\pm Z_{1-\alpha/2}$ are the $1-\alpha/2$ quantiles of the standard normal distribution corresponding to the given significance level α for the test.

2.3.3. Spearman's correlation analysis

We used Spearman's correlation test, a nonparametric test, to detect the correlation between two variables. The correlation coefficient ρ_x can be calculated as,

$$\rho_x = S_{xy}/(S_x * S_y)^{0.5} \quad (6)$$

Where

$$S_x = \sum_{i=1}^{n}(x_i - \bar{x})^2 \quad (7)$$

$$S_y = \sum_{i=1}^{n}(y_i - \bar{y})^2 \quad (8)$$

$$S_{xy} = \sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \quad (9)$$

2.3.4. Singular Value Decomposition, SVD

Singular Value Decomposition (SVD) (Oubeidillah et al., 2011; Tang et al., 2011) is a preferable method for analyzing the coupled correlation between two spatial-temporal fields. By separating several independent coupled modes from two spatial-temporal fields, it reveals the spatial association of temporal correlations between the two fields. The spatial distribution patterns of coupled modes can explain most cross-covariance of the two fields. In this paper, SVD is used to investigate the possible relationship between the frequencies of temperature and precipitation extremes in the ARNC during 1961–2010. The Kriging method (Goovaerts, 2000) is used to spatially interpolate the SVD analysis results from site to grid.

3. Results and analysis

3.1. Trend and abrupt change in temperature extremes

Over the last 50 years, temperature in the ARNC has increased by 0.029–0.039 C°/y, showing an obvious warming trend (Li et al., 2012a). The Mann–Kendall test revealed that the average annual temperature (Tav_ANN), annual minimum temperature (Tnav_ANN), and annual maximum temperature (Txav_ANN) all exhibited significant increasing trends at the 0.01 significance level (Table 1). Among the three, Tnav_ANN had the highest rate (0.043–0.056 C°/y), followed by Tav_ANN (0.029–0.039 C°/y) and Txav_ANN (0.023–0.031 C°/y).

Table 1
The test results of change trends and abrupt points of the climate extreme indices in the ARNC.

Region	Indices	Trend test			Abrupt points
		Trend rate	Z value	Significance level	
ARNC	Tav_ANN	0.033 °C/a	5.45	0.01	1986[a]
	Tnav_ANN	0.046 °C/a	6.77	0.01	1986[a]
	Txav_ANN	0.025 °C/a	3.96	0.01	1986[a]
	Pav_ANN	0.658 mm/a	3.379	0.01	1986[a]
	Pn10mm_ANN	0.017 days/a	3.17	0.01	1986[a]
	Pxcdd_ANN	−0.273 days/a	−2.71	0.01	1986[a]
	Pxcwd_ANN	0.006 days/a	2.44	0.05	1986[a]

[a] Significant at $P < 0.01$.

The Mann–Whitney test detected abrupt change in all the three time series around 1986 at the 0.01 significance level (Table 1, Fig. 2). Spatially, the largest variability of Tav_ANN occurred in northern Xinjiang and Hexi Corridor with values over 15%, and in southern Xinjiang with 7.8%. The variability of Txav_ANN was around 6.4% in Hexi Corridor, 5.4% in northern Xinjiang, and 3.6% in southern Xinjiang. The variability of Tnav_ANN in northern Xinjiang was about 1.5 C° and above 1.1 C° in southern Xinjiang and Hexi Corridor (Fig. 3). The variability values indicate that Tnav_ANN had the largest increase in magnitude since 1986.

3.2. Trend and abrupt change in precipitation extremes

The Mann–Kendall trend detection showed that over the last 50 years, Pav_ANN, Pn10mm, and Pxcwd_ANN in the ARNC had obvious increasing trends, while Pxcdd_ANN had an opposite trend. Except for the Pxcwd_ANN, the other three time series

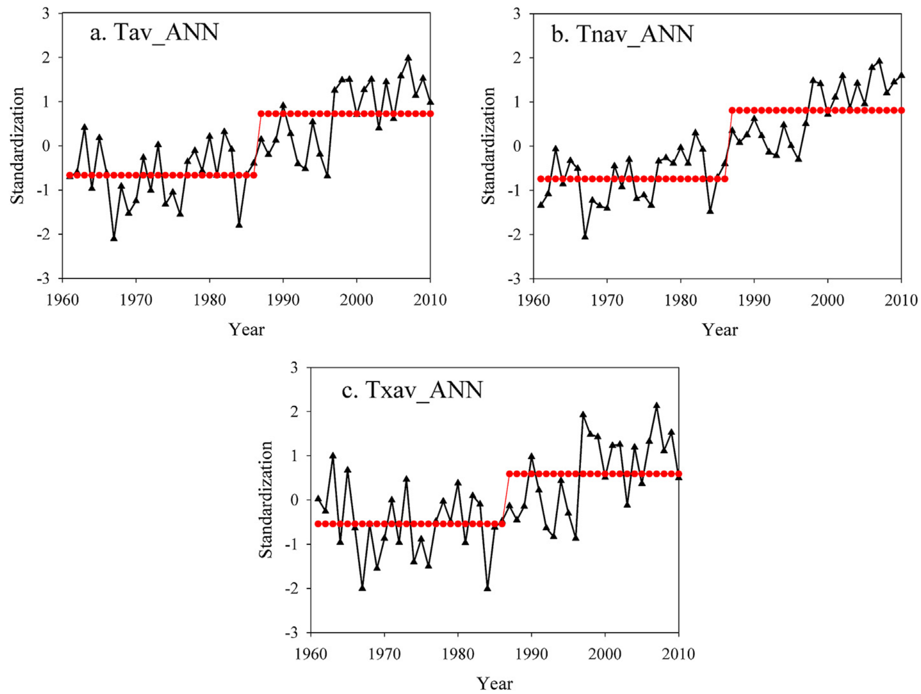

Fig. 2. Changes of the temperature extreme indices in ARNC. (a) annual mean temperature, (b) annual mean minimum temperature, (c) annual mean maximum temperature.

passed the 0.01 significance level test (Table 1). The Mann–Whitney step change test indicated that an abrupt change in precipitation extremes was detected in about 1986 (Fig. 4) at the 0.01 significance level (Table 1). Spatially, the increase in magnitude of Pav_ANN (Fig. 5) reached 23.52% and 29.67%, in northern Xinjiang and southern Xinjiang, respectively. In Hexi Corridor it increased by 6.47%, but did not pass the 0.01 significance level. Pn10mm_ANN and Pxcwd_ANN also increased, whereas Pxcdd_ANN decreased.

3.3. *Relationship between frequencies of temperature and precipitation extremes*

The SVD analysis of Pn10_ANN and Txf90_ANN identified the significant regions ($p < 0.01$) in the ARNC during 1961–2010. In-phase analysis of Pn10_ANN and Txf90_ANN can explain 65.5% of the Square Covariance Fraction (SCF) for the first mode of spatial correlation field. The correlation coefficient of the two spatial-temporal fields was 0.62.

This represents the heterogeneous correlation distribution of significant change regions for the Pn10_ANN (Fig. 6a) and Txf90_ANN (Fig. 6b) for the first mode of SVD in the ARNC during 1961–2010. The results indicated that there was an inverse correlation between Pn10_ANN and Txf90_ANN in some parts of southern Xinjiang, northern Xinjiang, and northern Hexi Corridor. The distribution patterns show that when the Tx90 reduced in northern Xinjiang and increased in northern Hexi Corridor, the Pn10_ANN increased in northern Xinjiang and decreased in northern Hexi corridor. The anomalies of standardized time

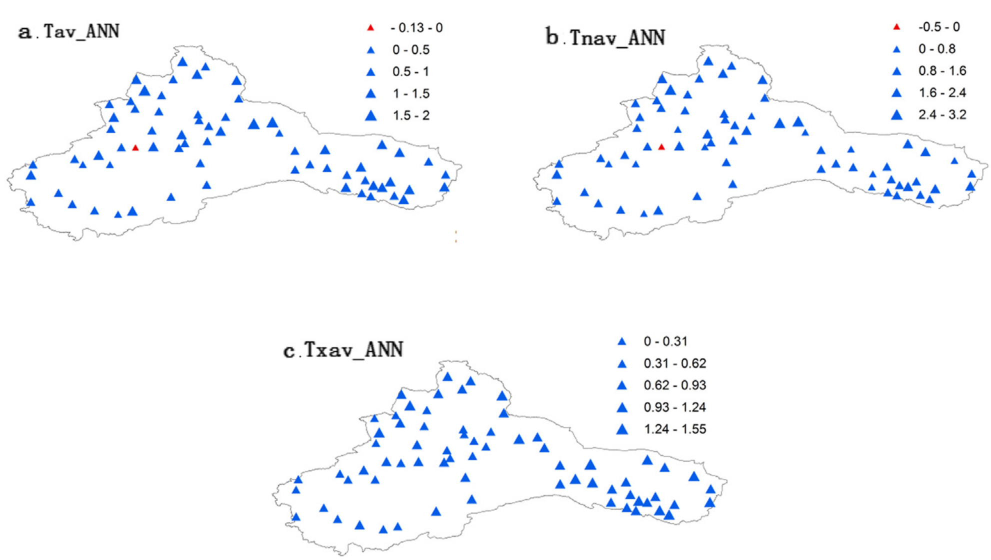

Fig. 3. Trends of the temperature extreme indices before and after step change point in ARNC. (a) annual mean temperature, (b) annual mean minimum temperature, (c)annual mean maximum temperature.

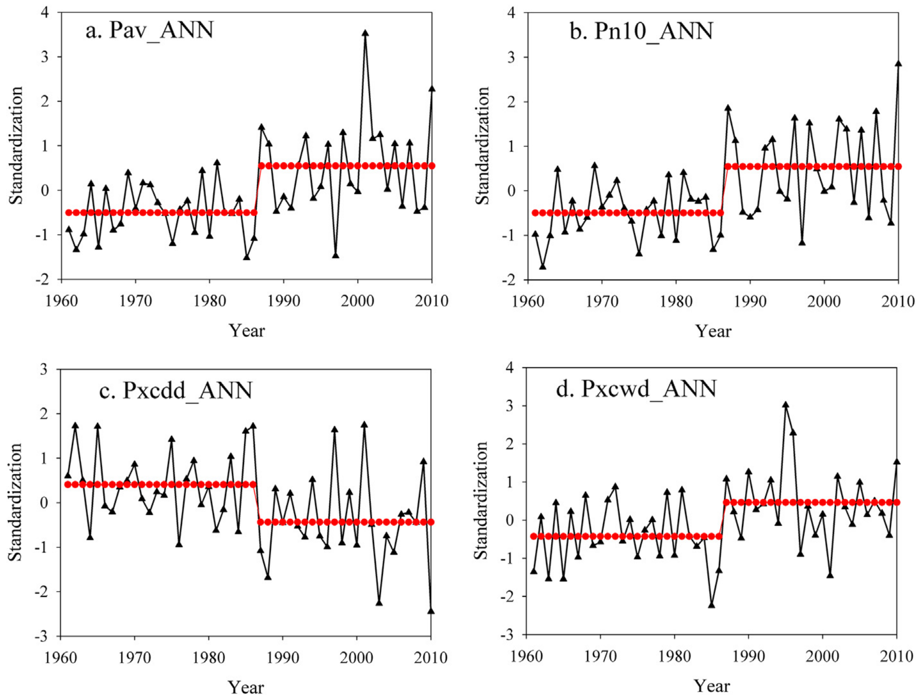

Fig. 4. Changes of the precipitation extreme indices in ARNC. (a) annual mean precipitation, (b) annual precipitation ≥ 10 mm days, (c) annual maximum consecutive wet days, (d) annual maximum consecutive dry days.

coefficient of Pn10_ANN and Txf90_ANN for the first mode revealed that an abrupt change occurred in 1986 from a negative phase to a positive one (Fig. 6c), indicating a significant interdecadal variation of Pn10_ANN and Txf90_ANN.

3.4. Potential causes of abrupt change in temperature and precipitation extremes

Both temperature and precipitation extremes showed decreasing trends during the period of 1961–1985 and then an abrupt change in 1986, resulting in increasing temperature and somewhat increasing precipitation. Thus, the abrupt change in the temperature and precipitation extremes might have associations with regional atmospheric circulation. The statistical relationships between the changes and eight atmospheric circulations, including SHI, AOI, NAOI, PNAI, AAOI, SOI, WCI_DJF and TPI_B, were investigated.

The Spearman's correlation coefficient values showed that TPI_B had good consistency with the temperature and precipitation extremes (Table 2). The correlation was strong for the temperature extremes indices ($R = 0.685$, 0.664, and 0.691 for TPI_B, $R = 0.451$, 0.514 and 0.352 for WCI_DJF, and $R = 0.315$, 0.377 and 0. 245 for

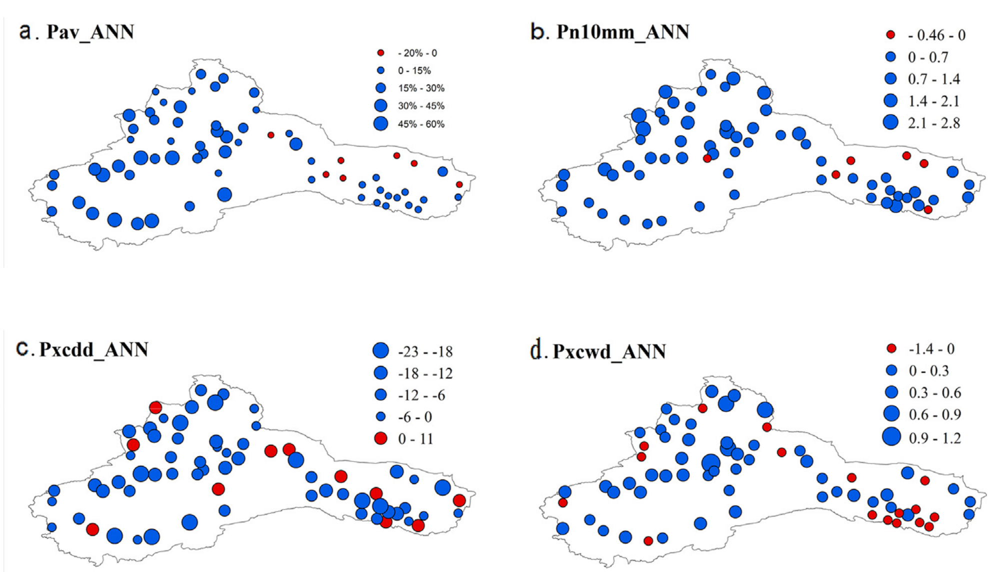

Fig. 5. Trends of the annual precipitation extreme indices before and after step change point in ARNC. (a) annual mean precipitation, (b) annual precipitation ≥ 10 mm days, (c) annual maximum consecutive wet days, (d) annual maximum consecutive dry days.

PNAI, respectively, with $p < 0.01$) and relatively strong for the precipitation extremes index Pav_ANN ($R = 0.441$, $p < 0.01$). The correlations between the climate (temperature and precipitation) extremes and the other circulations were weak or insignificant. WCI_DJF was highly correlated with Tav_ANN ($R = 0.451$, $p < 0.01$), but not with Pav_ANN ($R = 0.098$, $p > 0.05$). Thus, we consider that TPI_B is very important in temperature and precipitation change in the ARNC.

Junggar basin and Northeast China both increased during 1948–2005, while frequencies of extreme low temperature in South China decreased. Gong et al. (2009) found that the abrupt change of extreme high/low temperature in the 1970s was 3–4 years later than that of average temperature. This implies that the process of abrupt temperature change might be an intergrade of temperature change from one state to another. Li et al. (2012b) showed that there was a typical pattern with fewer hot days and more precipitation extremes in the northern part of eastern China, and more hot days and fewer precipitation extremes in the southern part during 1980–1996. This geographic pattern tended to reverse after 1997. The average annual temperature in China has been increasing, especially since the 1980s. Warming has been prominent in northern China (Li and Yan, 2009). Many climate indices exhibited abrupt changes during the 1960s, around 1980, and the 1990s (Tu et al., 2010; You et al., 2011), which is consistent with the findings in this paper. In particular, summer precipitation in eastern part of China changed abruptly in the late 1970s, resulting in the Yangtze-River flooding and North China drought pattern (Ding et al., 2008).

Table 2
The Correlation Coefficients between the Abrupt Change of Extreme Temperature and Precipitation in the ARNC and atmospheric Circulation Factors.

Indices	Circulation index							
	SOI	AAOI	NAOI	AOI	PNAI	WCI_DJF	SHI	TPI_B
Pav_ANN	−0.014	0.027	−0.02	−0.047	0.414[b]	0.098	0.229	0.441[b]
Tav_ANN	−0.151	0.18	−0.092	0.172	0.315[a]	0.451[b]	−0.175	0.685[b]
Tnav_ANN	−0.121	0.228	−0.58	0.188	0.377[b]	0.514[b]	−0.049	0.664[b]
Txav_ANN	−0.089	0.185	−0.151	0.136	0.245	0.352[a]	−0.314[a]	0.691[b]

[a] Significant at $p < 0.05$.
[b] Significant at $p < 0.01$.

Fig. 7 shows comparisons between the change of TPI_B and the change of temperature and precipitation extremes over the period of 1961–2010. It appears that an abrupt change of TPI_B occurred in 1985. For the period before 1985, TPI_B decreased gradually and reached the minimum in 1984. Since 1985, it began to increase. Correspondingly, the temperature and precipitation extremes (Pav_ANN, Tav_ANN, Tnav_ANN, Txav_ANN) in the ARNC also decreased in most of the time over 1961–1984, then they have increased significantly since 1985. The time point when TPI_B shifted from weak to strong well matches the turning points of the temperature and precipitation extremes. Since 2000, the temperature extremes have kept increasing (by a rate of 0.027 C°/y), while the precipitation extremes have been experiencing larger fluctuations without an obvious increasing trend.

4. Discussion

Extreme climate events have received much attention in recent years, due to the great loss of human lives and exponentially increased costs associated with the events (Karl and Easterling, 1999). To understand how weather and climate extremes influence society and ecosystems, it is vital to conceptually address how such extremes change in a statistical sense. However, a lack of access to high-quality and long-term climate data with time resolution appropriate for analyzing extreme events is an obstacle to quantifying the change of extreme events. In this study, we detected the trends and abrupt changes in the temperature and precipitation extremes in the ARNC over the last 50 years (1961–2010). The temperature extremes (Tav_ANN, Tnav_ANN, Txav_ANN) increased remarkably at the 0.01 significance level, and the precipitation extremes (Pav_ANN, Pn10mm, Pxcdd_ANN, Pxcwd_ANN) also experienced similar changes. Detailed analysis on temperature and precipitation extremes found an abrupt change around 1986. Both temperature and precipitation extremes showed decreasing trends during the period of 1961–1985 and increasing trends from 1986 to 2010.

Climatic records show that large, widespread and abrupt climate change had repeatedly occurred throughout the geological period. Yan et al. (1990) pointed out that the early signals of abrupt climate change occurred in the 1960s, showing as increasing global temperature, declining precipitation stretching from Japan to the northeast area in North Africa, as well as increasing precipitation in South Europe and South America. Gong et al. (2009) found that temperature and frequencies of high temperature extremes in the

Facts of abrupt climate change have been reported in various regions worldwide, however, the reasons for it are far from clear. Solar variability, volcanicity, tropospheric aerosols, and carbon dioxide, among other factors, have been invoked to produce change, but no clear lines of evidence have been developed (Berger and Labeyrie, 1985). A number of modeling studies have suggested that atmosphere–land surface interactions, and in particular a strong positive feedback mechanism between the two, led to sudden and abrupt climatic change (Trenberth, 1999; Liu et al., 2007b; Patricola and Cook, 2008) proposed a conceptual model showing the effect of increased greenhouse gases on the hydrologic cycle and other factors affecting many climate extremes. The main expressions are as follows: increased radiative forcing increased surface heating and latent heating, which resulted in both increased air temperature and evaporation. This would lead to increased atmospheric water vapor content, and enhanced precipitation rates. Chinese scholars have pointed out the relationship between the atmospheric circulation and the abrupt climate change in earlier time. Yan (1992) pointed out that the early signals of abrupt climate change in the 1960s can be traced back to the sharp decline of the sea surface's temperature in the high latitudes of Atlantic. Zhu et al. (1993) found that there had simultaneity of abrupt climate change and the rapid changes in the geomagnetic field and the short-term drift of magnetic field direction. Gong et al. (2009) found that the abrupt change in the extreme high and low temperatures in China was associated with the Northern Oscillation, Southern Oscillation, and the North Pacific Oscillation. Li et al. (2012b) considered that the climate extremes and changes in eastern China are closely related to variations of the East Asian summer monsoon and corresponding atmospheric circulations. Scores of papers described the current state of our knowledge concerning the attributions of weather and climate extremes from several points of view; all of them are interrelated.

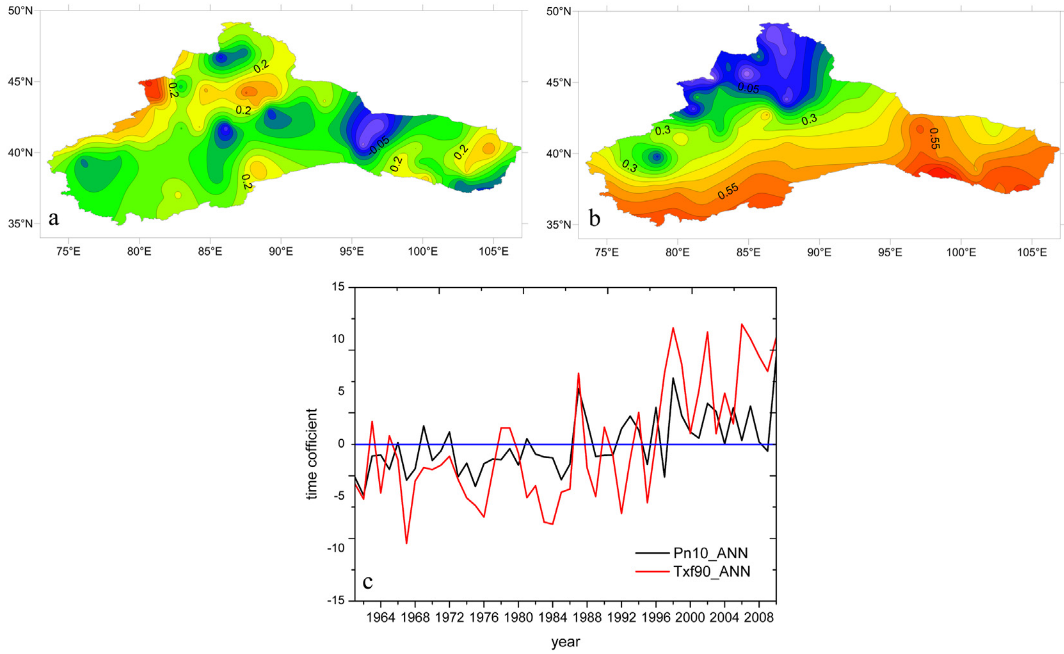

Fig. 6. Heterogeneous correlation maps for the first mode of (a): Pn10_ANN; (b): Txf90_ANN; (Contours represent correlation values. Significant (>99%) positive/negative Pn10_ANN and Txf90_ANN were approximated by red/blue shading); (c): anomalies of standardized time coefficients of Pn10_ANN (black line) and Txf90_ANN (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The Tibetan Plateau affects the atmospheric circulation, and is a key factor for the climates in Asia. The Tibetan Plateau is a heat source in summer and a weak heat sink in winter. The air column over the Tibetan Plateau descends and ascends in different seasons, working as an air pump and regulating the atmospheric circulation (Wu et al., 2007). The thermal adaptation results in a cyclonic circulation in the lower layer and an anticyclone circulation in the upper layer (Liu et al., 2007a). Therefore, west and central Asia will become dry and hot (Duan and Wu, 2005). There is an anticyclone circulation in the north of the Tibetan Plateau and a cyclone circulation in the south of the Tibetan Plateau (Wu et al., 2007). This will cause a moisture increase from the Caspian Sea into the ARNC

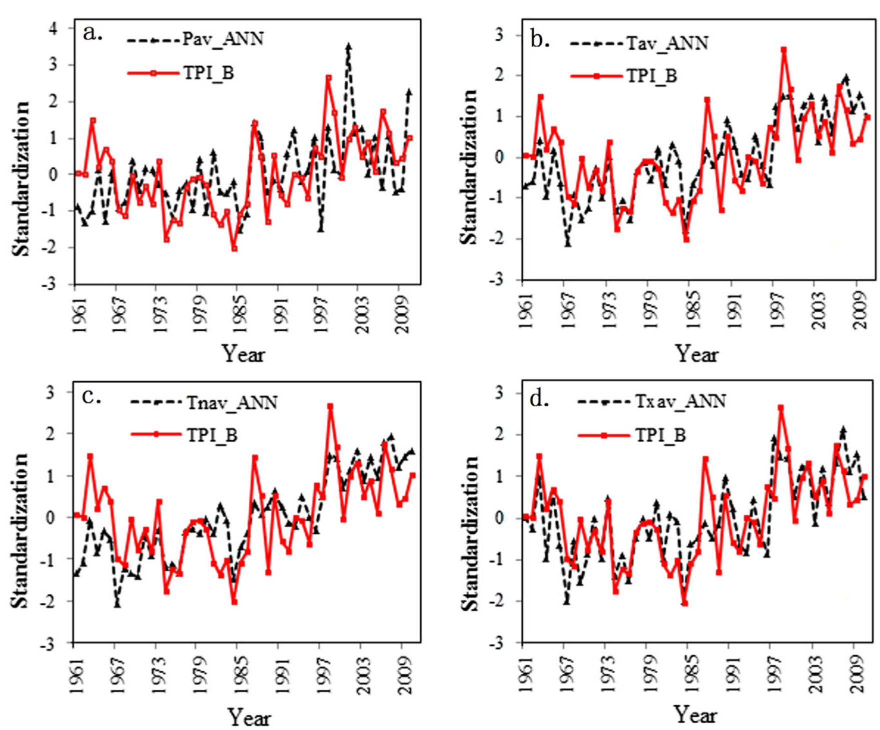

Fig. 7. Comparison of Index B of the Tibetan Plateau with precipitation and temperature extremes indices in ARNC. (a) annual mean precipitation, (b) annual mean temperature, (c) annual mean maximum temperature, (d) annual mean minimum temperature.

(Bothe et al., 2012), and daily precipitation extremes may increase in the southern ARNC. In general, thermal and dynamic forcing by the Tibetan Plateau has profound impacts on the climate system. The impact of Tibetan Plateau thermal and dynamic processes on the ARNC temperature and precipitation is highly complex, and to gain an in-depth understanding of this complexity is an important item in our future research agenda.

5. Conclusions

In this study, we speculated that the abrupt change in the temperature and precipitation extremes of ARNC over the last 50 years might be associated with regional atmospheric circulation, and thus investigated the statistical relationships between the abrupt change and the eight atmospheric circulations. The correlation analysis between TPI_B and the temperature and precipitation extremes reveals that a stronger TPI_B is probably a factor in the abrupt change of temperature and precipitation extremes in the ARNC over the last 50 years.

The Tibetan Plateau Index_B (TPI_B) roughly reflects the activities of low vortex and high pressure at 500 hPa over the Tibetan Plateau. The temperature and precipitation extremes in the ARNC had strong and significant associations with TPI_B over the period of 1961–2010 ($R = 0.685$, $p < 0.01$, and $R = 0.441$, $p < 0.01$, respectively). They behaved consistently, with a weakening and decreasing trend from 1961 to 1985 and a strengthening and increasing trend from 1986 to 2010. Based on this finding, we suggest that TPI_B is probably an important factor influencing the abrupt change in the temperature and precipitation extremes in the ARNC over the last 50 years.

With climate models better developed, climate simulation will be a better alternative means of expecting the changes in climate extremes. One prescription for predictive scenarios, based on the findings in this paper, is that TPI_B should be carefully considered in the future climate modeling and simulation.

Acknowledgements

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