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Dynamic Variability in Daily Temperature Extremes and Their Relationships with Large-scale Atmospheric Circulation During 1960–2015 in Xinjiang, China

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Abstract: Climate changes are likely to increase the risk of numerous extreme weather events throughout the world. The objectives of this study were to investigate and analyze the temporal-spatial variability patterns of temperature extremes based on daily maximum (TX) and minimum temperature (TN) data collected from 49 meteorological stations in Xinjiang of China during 1960–2015. These temperature data were also used to assess the impacts of altitude on the temperature extremes. Additionally, possible teleconnections with the large-scale circulation pattern (the El Nino-Southern Oscillation, ENSO and Arctic Oscillation, AO) were investigated. Results showed that all percentile indices had trends consistent with warming in most parts of Xinjiang during 1960–2015, but the warming was more pronounced for indices derived from TN compared to those from TX. The minimum TN and maximum TX increased at rates of 0.16℃/10 yr and 0.59℃/10 yr, respectively during 1960–2015. Accordingly, the diurnal temperature range showed a significant decreasing trend of –0.23℃/10 yr for the whole study area. The frequency of the annual average of the warm events showed significant increasing trends while that of the cold events presented decreasing trends. Over the same period, the number of frost days showed a statistically significant decreasing trend of –3.37 d/10 yr. The number of the summer days and the growing season showed significant increasing trends at rates of 1.96 and 2.74 d/10 yr, respectively. The abrupt change year of each index was from the 1980s to the 1990s, showing that this periodic interval was a transitional phase between cold and warm climate change. Significant correlations of temperature extremes and elevation included the trends of tropical nights, growing season frequency, and cold spell duration indicator. This result also indicated the clear and complex local influence on climatic extremes. In addition, the relationship between each index of the temperature extremes with large-scale atmospheric circulation (ENSO and AO) demonstrated that the influence of ENSO on each index of the temperature extremes was greater than that of the AO in Xinjiang.

Keywords: climate variability; temperature extremes; altitude; atmospheric circulation; Xinjiang, China

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1 Introduction

During recent decades, a change in extreme climatic events has been observed. A study found that all twenty of the warmest years on record globally are seen to have occurred since 1990 and 15 out of 16 warmest years on record (during the period 1880–2015) have occurred since 2001 (Kundzewicz, 2016). Each of the past 15

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years since 2001 has been warmer by at least 0.54℃ than the long-term average during the period 1910–2000 (Kundzewicz, 2016). According to the Intergovernmental Panel on Climate Change (IPCC, 2013), it is likely that the intensity, frequency, duration, and extent of climate-related extremes (e.g., heat waves, droughts, cyclones, floods, and wildfires) has increased throughout much of the world. It is very likely that the number of hot days and nights has increased, and that the number of cold days and nights has decreased in the background of global warming (Fontaine et al., 2013; IPCC, 2013). Any change in the frequency or severity of extreme climatic events, attributed to an increased concentration in human-induced greenhouse gas emissions in the atmosphere (Braganza et al., 2004; Abatan et al., 2016), could have far-reaching influences on nature and society, such as large-scale melting of snow and ice, a global rise in sea level (Chen et al., 2013), alteration of ecosystems, disruption of grain yields (Chen et al., 2016), destruction of infrastructure and disruption to human activities, and injury and loss of life (Piao et al., 2010; Kundzewicz, 2016). For example, a large-scale European heat wave event killed approximately 40 000 people in 2003 (García-Herrera et al., 2010). Yields of corn were found to increase with temperature up to 29℃–30℃, but higher temperatures above these levels can cause serious losses in crop yields (Chen et al., 2016). In addition, cryogenic freezing rain and snow disasters during the winter of 2008 affected large parts of southern China and caused massive losses of life and property (Jiang et al., 2013). Extreme weather and climate events, therefore, have raised widespread concerns from the government, public, and domestic and foreign scholars, in particular because they may cause overwhelming impacts on nature and human society (Katz and Brown, 1992; Alexander et al., 2006; Goswami et al., 2006; Caesar et al., 2011; You et al., 2011; Donat et al., 2013; Grotjahn et al., 2016; Sun et al., 2016). These scholars conducted studies regarding extreme temperature events in many regions of the world, including Canada (Bonsal et al., 2001), the United States (Degaetano and Allen, 2002), South America (Skansi et al., 2013), Nigeria (Abatan et al., 2016), western Germany (Hundecha and Bárdossy, 2005), India (Goswami et al., 2006; Revadekar et al., 2012), the Indo-Pacific region (Caesar et al., 2011), Iran (Tabariand Talaee, 2011), South Africa (Kruger and Sekele, 2013), the Arctic (Overland et al., 2014), and some regions of China (Zhai and Pan, 2003; Xu et al., 2011; Zhang et al., 2012; Wang et al., 2013a; Guan et al., 2017). The aforementioned studies have demonstrated that temperature extremes showed significant widespread changes in most global regions throughout the 20th century, and were particularly pronounced during the most recent periods and for these indices related to daily minimum temperature. However, the variability in climatic extremes in different climatic regions is not uniform because of the great differences in certain geographical locations, topographies, climatic backgrounds, and climatic driving forces (Li et al., 2012a). Overland et al. (2014) documented that the Arctic is warming greater than twice as fast as the global average. Guan et al. (2015), examining daily minimum and maximum temperature, found that the Yangtze River Basin was dominated by a general cooling trend during the period 1960–1985, but a warming trend in 1986–2012 and that cold-related indices significantly decreased and warm-related indices significantly increased. The increased extreme warm temperature and decreased extreme cold temperature events at a regional scale strongly influence the natural environment (Overland et al., 2014; Yu et al., 2017). Therefore, a quantitative analysis and prediction of the trends and changes of extreme temperature in local scale is highly required.

Xinjiang, accounting for one-sixth of the area of China, is the largest province-level administrative region in China. Situated in the hinterland of the Eurasian continent and far from the ocean with encompassing mountains all around, Xinjiang has a marked continental climate characterized by drastic changes in temperature, an abundance of sunshine, and low precipitation which are typical for arid and semi-arid inland areas. As far as we know, the inter-annual variability of extreme climatic events in Xinjiang has not been well studied (Shi et al., 2007; Zhang et al., 2012; Jiang et al., 2013; Wang et al., 2013a), although researchers have found that Xinjiang showed a shift from a warm-dry climate to a warm-wet climate over the last few decades. These studies only assessed a part of temperature or precipitation extremes; the explanations are incomplete. The researchers did not delve into temperature or precipitation extremes, and connect the annual changes in extreme weather events to topographic influence and large-scale atmospheric circulation. Several studies in mountainous areas have revealed altitudinal differences in the rate of change of temperature during recent decades (Li et al., 2012b). Studies of temperature changes on the Tibetan Plateau have indicated that the linear rates of temperature increase in the Mt. Everest region between 1971 and 2004 exceeded the global average as well as the mean rate for China (Yang et al., 2006).

However, previous climate change research in China has concentrated on mean temperature and precipitation with few studies of climatic extremes and their altitude dependency. In addition, large-scale circulation patterns (El Nino-Southern Oscillation (ENSO) and Arctic Oscillation (AO)) have been the most active atmospheric circulation patterns during recent years and have had far-reaching consequences on global climate change (Renom et al., 2011). Research indicates that temperature extremes are substantially affected by ENSO, and these effects are seen most clearly around the Pacific Rim and in North America (Kenyon and Hegerl, 2008). Zhong et al. (2017) found that the AO showed significant positive correlations with warm indices and negative correlations with cold indices in the Songhua River basin. The aforementioned researchers not only analyzed extreme temperature events but also confirmed their relation to large-scale circulations.

Consequently, in response, this study mainly attempted to solve the following two problems. Can these large-scale circulations that influence the climate of Xinjiang also have significant effects on extreme temperature events in Xinjiang? If so, how and to what extent can they impact extreme temperature events? Objectives were to: 1) analyze the temporal and spatial variations of daily temperature extremes in Xinjiang during 1960–2015, 2) understand the impacts of altitude on temperature extremes in Xinjiang, and 3) investigate the large-scale circulation patterns (ENSO and AO) associated with these extreme indices. This study could provide a scientific basis for the studies of natural hazards in Xinjiang and regional responses to global climate change.

2 Data and Methods

2.1 Study area

Xinjiang (73°40′E–96°18′E, 34°25′N–48°10′N), along in the northwestern border of China (Fig. 1), has a distinctive temperate continental climate that is dry in the southern part of the region and rainy in the northern region. The whole region is marked by great seasonal differences in temperature and precipitation; the annual average temperature is 10.4℃ and the average annual precipitation is 147 mm. During the summer, the average temperature in the Turpan Basin exceeds 33℃; the absolute maximum temperature has reached 49.6℃. Thus, it is reputed as a 'flaming place' in China. The temperature in southern Xinjiang is lower than that in northern Xinjiang during the winter. The average temperature in Fuyun County, however, along the northern margin of the Junggar Basin, is the coldest in China, with an absolute minimum temperature of –50.15℃. At an altitude of approximately 3500–3700 m above sea

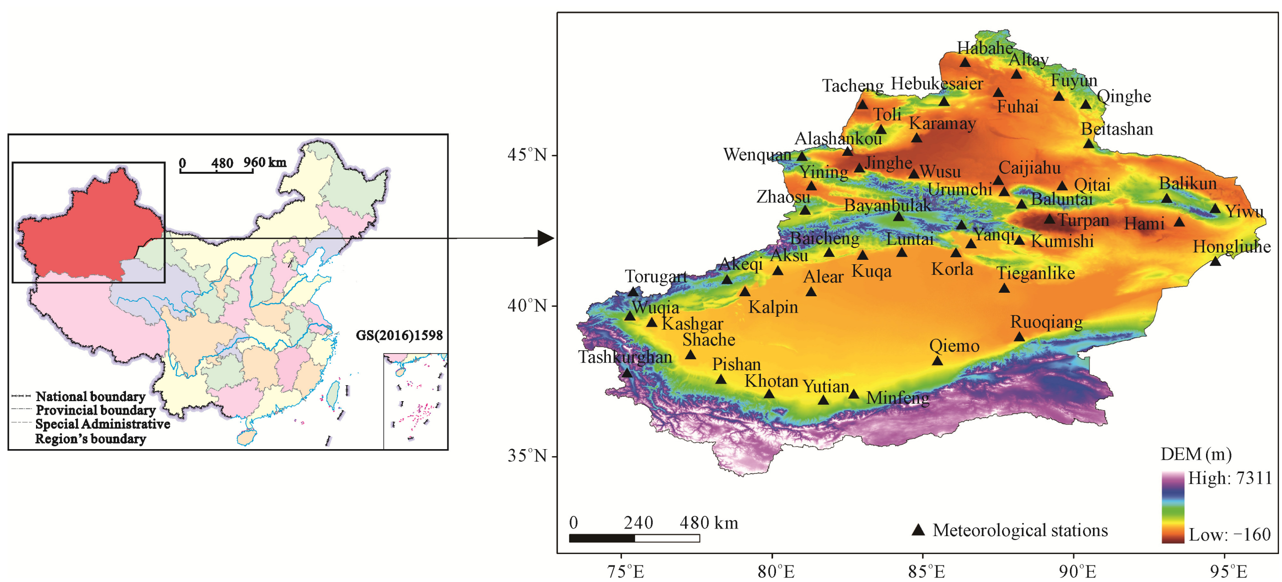

Fig. 1 The digital elevation model (DEM) and location of meteorological stations in Xinjiang, China

level, continuous permafrost is typically found in the Tianshan Mountains (Zhang et al., 2012). Discontinuous alpine permafrost typically appears in the mountains at 2700–3300 m above sea level, but in small areas, because of the peculiarity of the microclimate, it can be found at elevations as low as 2000 m. The regional differences in temperate in this area are considerable. Additionally, the annual average precipitation in the southern area is 106 mm and 255 mm in the northern area (Ling et al., 2012).

2.2 Data

In this study, daily maximum and minimum temperature observational data from 1960 to 2015 were collected from 49 meteorological stations in Xinjiang (Fig. 1) which was provided by the National Climate Center of the China Meteorological Administration (http://www. nmic. gov.cn/). The altitude of the selected stations ranges from 34.5 m (Turpan) to 3504.4 m (Torugart) (Data were obtained from http: //www.nmic. gov.cn/). Data quality control is a precondition in climate change research. First, the stations with a time series of less than that of the period from 1960 to 2015 were excluded. After data quality control and homogeneity, 16 temperature indices (Table 1) were selected. These indices are widely used to evaluate changes in temperature extremes (New et al., 2006; Choi et al., 2009; Vincent et al., 2011). These extreme indices are divided into four major categories (Table 1): extremal indices (TXx, TXn, TNn, and TNx), relative indices (TN10p, TX10p, TN90p, and TX90p), absolute indices (FD, ID, SU, and TR), and other indices (WSDI, CSDI, GSL, and DTR) (Zhou and Ren, 2010). Generally, the AO and ENSO were used to represent large-scale climatic anomalies and to analyze their relationships with the temperature extremes in Xinjiang. Data were obtained from http:// www.cpc.noaa.gov and http://www.cdc.noaa.gov/people/klaus.wolter/ MEI/.

2.3 Methods

Data were analyzed using the RclimDex package, which can calculate 16 temperature extremes based on daily minimum and maximum temperature. Linear regression and the non-parametric Mann-Kendall (M-K) test, which are widely employed in climate change research (Fu et al., 2004; Zhang et al., 2009; Huo et al., 2013). A positive Z_c value indicates a positive trend, while a negative Z_c value denotes a negative trend. Meanwhile, the nonparametric method of M-K is commonly used to assess the existence and significance of a trend, which also gives the abrupt changes and approximate starting point of a trend in climate (Goossens and Berger, 1986;

Table 1 Definitions of 16 temperature indices used in this study

Category	Index	Description name	Definitions	Unit
Extremal indices	TXx	Warmest day	The maximum value of TX records	℃
	TXn	Coldest day	The minimum value of TX records	℃
	TNn	Coldest night	The minimum value of TN records	℃
	TNx	Warmest night	The maximum value of TN records	℃
Relative indices	TN10p	Cold nights	Days when TN<10th percentile	d
	TX10p	Cold days	Days when TX<10th percentile	d
	TN90p	Warm nights	Days when TN>90th percentile	d
	TX90p	Warm days	Days when TX>90th percentile	d
Absolute indices	FD	Frost days	Annual count of days where TN< 0℃	d
	ID	Ice days	Annual count of days where TX<0℃	d
	SU	Summer days	Annual count of days where TX>25℃	d
	TR	Tropical nights	Annual count of days where TN>20℃	d
Other indices	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	d
	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	d
	GSL	Growing season length	Annual count between first span of at least 6 days with TG>5℃ after winter and first span after summer of 6 days with TG <5℃	d
	DTR	Diurnal temperature range	Annual mean difference between TX and TN	℃

Notes: All indices are calculated from January to December. TX is daily maximum temperature. TN is daily minimum temperature. TG is daily mean temperature

Liu et al., 2008). Details regarding M-K method are described elsewhere (Huo et al., 2013; Zhang et al., 2015). Variations in temperature extremes were analyzed at a temporal and spatial scale based on OriginPro, SPSS 22.0, ArcGIS and Matlab. The indices of the regional annual series were calculated as the arithmetic mean at 49 stations over Xinjiang. To explore the spatial distribution of trends on the temperature extremes over Xinjiang, the linear regression slope was interpolated based on each station's slope value for the entire study period (1960–2015). This provided more detailed information regarding how the magnitudes of rates vary in extreme temperature indices among the 49 weather stations.

Additionally, the correlations among the large-scale circulation patterns (ENSO and AO) associated with these extreme indices were investigated using the continuous wavelet transform (CWT), cross wavelet transform (XWT), and Pearson correlation analysis methods. The CWT and XWT were adopted to study the time-frequency characteristics and multi-time scale correlations between the AO and ENSO indices. Detailed information regarding applying CWT and XWT can be found in Torrence and Compo (1998) and Grinsted et al. (2004).

3 Results

3.1 Temporal and spatial variation in extreme temperature indices

3.1.1 Variation trend of extremal indices

The regional annual series of the extremal indices for the extreme temperature in Xinjiang during 1960–2015 are shown in Figs. 2a, 2b, 2c, and 2d. The linear trends of the warmest days (TXx), coldest days (TXn), warmest nights (TNx), and coldest nights (TNn) were 0.155℃/10 yr, 0.295℃/10 yr, 0.346℃/10 yr, and 0.593℃/10 yr, respectively. The trend of the TNx, which yielded a M-K test value Z_c = 3.26 (Fig. 3), showed the most obvious change of all the extremal indices. TXx and TXn showed increasing trends but did

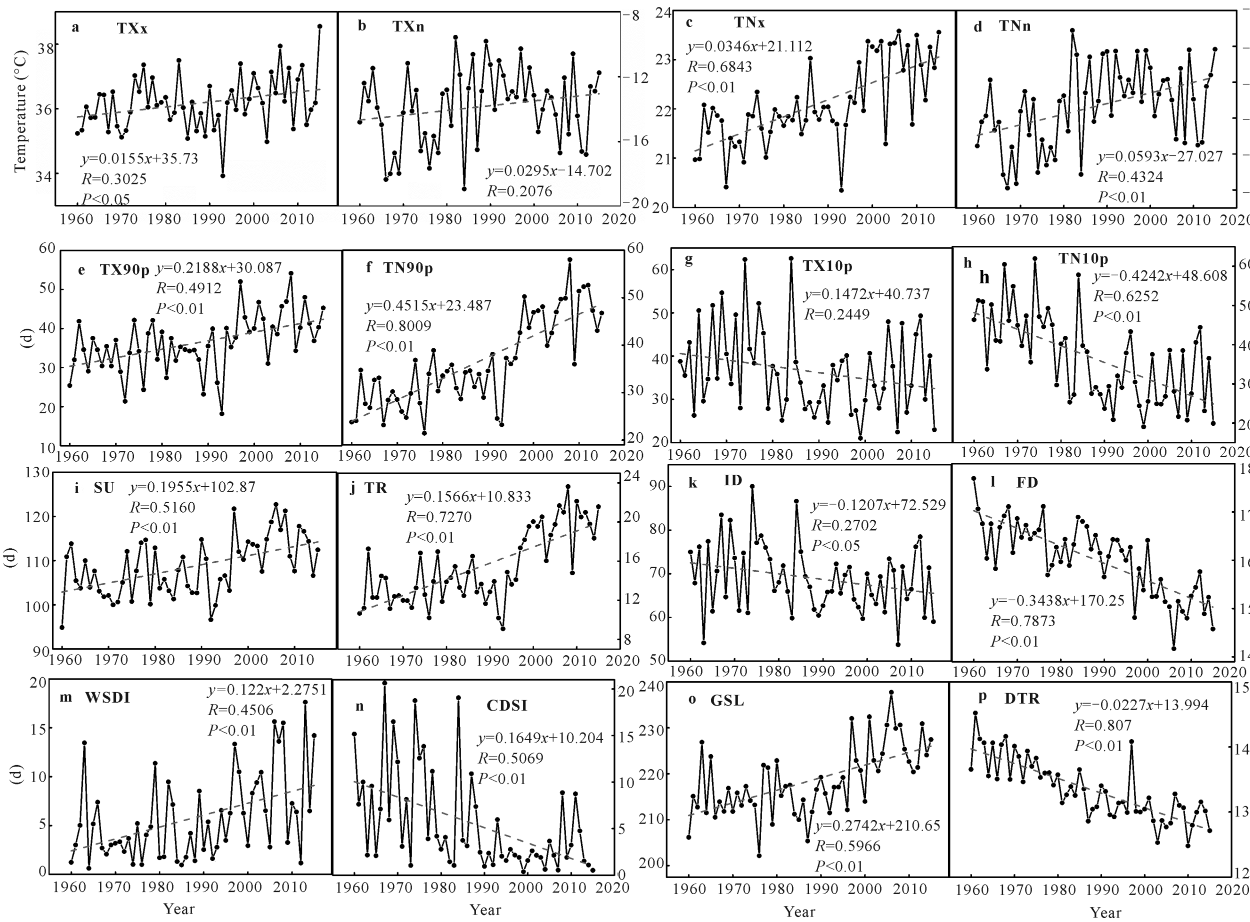

Fig. 2 Inter-annual variation of temperature extremes indices in Xinjiang during1960–2015. (Abbreviations can be found in Table1)

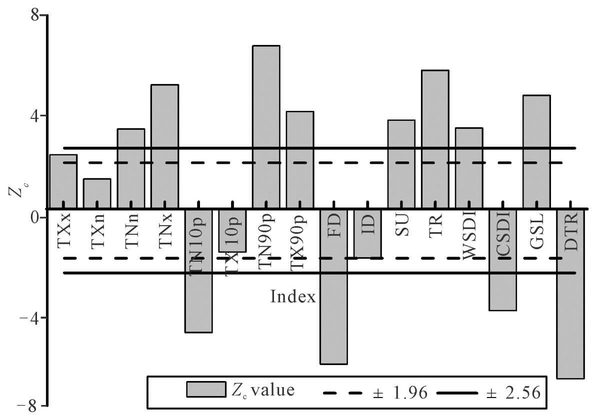

Fig. 3 Annual series (1960–2015) of Z_c-value for temperature extremes in Xinjiang. The dotted line indicates those indices were significant at the 0.05 level; the continuous line indicates those indices were significant at the 0.01 level. (Abbreviations can be found in Table1)

not achieve statistical significance. In addition, the changes of the extremal indices related to TN were greater in magnitude than those related to TX, indicating that changes in temperature during the night are more significant. The M-K method was applied to annual extreme temperature indices series in Xinjiang and the time of the abrupt change is shown in Table 2. The results showed that the year of the abrupt change for extremal indices ranged from 1973 to 2010. For TXx, there were two abrupt change years in the whole change process of the time sequence: 1973 and 1994 (Table 2).

Most of the stations were characterized by a positive tendency in the extremal indices. The increase in TXx mainly occurred in most parts of Xinjiang and a reduction was sporadically distributed (Fig. 4a). Regarding TXx, approximately 79.6% of the stations showed increasing trends (Table 3). The stations with TXn and TNx increasing trends were distributed in most parts of Xinjiang (Figs. 4b, 4d). As to TXn, only two areas (Jinghe and Kuqa) did not present an increasing trend and the only station, Yining, in this district was significant at the 0.01 level. As to TXn and TNx, 95.9% and 91.8% of the stations showed a positive trend, respectively. TNn showed increasing trends over the whole Xinjiang, but the stations of significant increases (30.6%) were mainly concentrated in the north-central study area (Fig. 4c and Table 3).

3.1.2 Variation trend of relative indices

The regional annual series of the relative indices in the whole region from 1960 to 2015 are shown in Figs. 2e, 2f, 2g, and 2h. There was a significant increase in warm nights (TN90p) and warm days (TX90p). TX90p and TN90p presented significant increasing trends with corresponding rates of change of 2.2 and 4.5 d/10 yr, respectively (Figs. 2e, 2f). However, the number of TX10p and TN10p significantly decreased by a rate of –1.5 and 4.2 d/ 10 yr during the period 1960–2012. The decreasing and increasing trends of TX90p, TX10p, and TN90p were significant at the 0.01 level (Fig. 3). The M–K test showed that the decreasing trend for TX10p was not significant but had an abrupt point (1996) from 1960 to 2015. However, according to the abrupt change years for TX90p and TN90p (Table 3), the trend showed obvious increasing trends after 1994.

From a spatial perspective, the stations showing decreasing trends for TN10p appeared throughout the whole study area and most stations were statistically significant at the 0.01 level (Fig. 4e and Table 2). Approximately 98% of the stations showed decreasing trends with fluctuations and 81.6% of the stations were statistically significant for TN10p. Changes in TX10P were not insignificant (Figs. 4f and Table3) and only a few stations showed significant trends. The value of the cold indices (TN10p and TX10p) decreased from north to south in Xinjiang. The increases in TN90p and TX90p, with 87.8% of the stations showing significant increasing trends (Figs. 4g, 4h and Table 3), were mainly distributed throughout much of the study area and a reduction was sporadically observed in Xinjiang.

Table 2 M-K verification of the extreme temperature indices over Xinjiang during 1960–2015

Index	Year	Index	Year
TXx	1973, 1994	FD	1994
TXn	1979, 2010	ID	1978, 1986
TNn	1980	SU	1996
TNx	1994	TR	1997
TN10p	1981	WSDI	1996
TX10p	1980	CSDI	1986
TN90p	1994	GSL	1996
TX90p	1996	DTR	1981

Note: Abbreviations can be found in Table1.

Fig. 4 Spatial distribution of temperature extremes in Xinjiang during 1960–2015. (Abbreviations can be found in Table1. The squares in the figures identify the region in which the contents of this district were significant at the 0.01 level) (The squares in the figures identify the region in which the contents of this district were significant at the 0.01 level)

Table 3 Percentage of stations with positive negative trends and non-trend for the temperature indices during 1960–2015 (%)

Index	Trend	Positive	Negative	Non-trend
TXx	+	79.6 (20.4)	20.4 (2.0)	0
TXn	+	95.9 (10.2)	4.1	0
TNn	+	100.0 (30.6)	0.0	0
TNx	+	91.8 (59.2)	8.2 (4.1)	0
TN10p	–	2.0	98.0 (81.6)	0
TX10p	–	16.3	83.7 (16.3)	0
TN90p	+	87.8 (75.5)	12.2 (4.1)	0
TX90p	+	87.8 (42.9)	12.2 (4.1)	0
FD	–	2.0 (2.0)	98.0 (89.8)	0
ID	–	8.2	91.8 (10.2)	0
SU	+	93.9 (51.0)	4.1 (2.0)	2.0
TR	+	79.6 (59.2)	12.2 (4.1)	8.2
WSDI	+	85.7 (32.7)	14.3	0
CSDI	–	6.1	93.9 (51.0)	0
GSL	+	98.0 (46.9)	2.0	0
DTR	–	12.2	87.8 (75.5)	0

Notes: –, indicates that the regional trends is decreased; +, indicates that the regional trends is increased. The Numbers in brackets indicate ratio of stations which have significant trend (P < 0.01) to total stations during 1960–2015. Abbreviations can be found in Table1.

3.1.3 Variation trend of absolute indices

The regional annual series of the absolute indices in the study area from 1960 to 2015 are shown in Figs. 2i, 2j, 2k, and 2l. The trends of summer days (SU) and tropical nights (TR) showed the most significant increasing trend, with a variation trend 1.96 and 1.57 d/10 yr (Figs. 2i, 2j), respectively. The long-term changes in SU were very similar to these of TX90p and TN90p in that there was a limited trend prior to 1996 but thereafter sharply increased during the last few decades. These findings correspond very well to the results that most of the increasing trend for TX90p and TN90p is attributable to the increase in temperatures during the warmer seasons of the previous two decades. There was also decreasing trend (–3.4 d/10 yr) in the frequency of frost days (FD), which was related to dramatic positive anomalies after 1994. In comparison to FD, ice days (ID) showed a decreasing trend with a variation trend of –1.21 d/10 yr. The M-K test showed that the trends for SU, TR, and FD were significant (P < 0.05) during the period 1960–2015 while ID did not achieve statistical significance (Fig. 3). Furthermore, the mutation test results showed that SU and TR showed an obviously increasing trend prior to 1996 and maintained an increasing trend after 1996 (Table 2), while the ID presented a slowly decreasing trend. There was a slow decreasing trend in FD before 1995 followed by a drastic decrease.

Considering the spatial distribution of ID trends (Fig. 4j), a decreasing trend was evident, but a significant decrease was only found in northern study area. Four stations that have increasing trends for ID were in the central region and the most stations with significant decreasing trends were in the northern region of Xinjiang. For the period 1960–2015, FD showed a strong pattern of decreasing trends; 89.8% out of the 98% of decreasing stations showed significance at the 0.05 level (Fig. 4i and Table 3). For SU and TR, approximately 51.0% and 59.2% of the stations significantly increased during the past 55 yr (Figs. 4k, 4l, and Table 3). The increased trends for TR were significant in the southern region and declining trends were mainly observed in the central region of Xinjiang.

3.1.4 Variation trend of other indices

Four additional indices were calculated and analyzed for extreme temperature. They included the length of cold and warm spells (WSDI and CSDI, respectively), length of growing season (GSL) and diurnal temperature range (DTR) (Figs. 2m, 2n, 2o, and 2p). The CSDI showed a significantly decreasing trend at a rate of 1.7 d/10 yr, whereas the WSDI showed an increasing trend of 1.2 d/10 yr (Figs. 2m, 2n). The GSL demonstrated a significant decreasing trend of 2.7 d/10 yr. Because of a rapid increase in minimum temperature compared to maximum temperature during recent years, the DTR series shows a significantly decreasing trend (Zhang et al., 2005). The present study also showed a warming trend in the DTR at a rate of –0.23℃/10 yr with significance at the 0.05 level (Fig. 2p). A significant abrupt decrease step change for DTR was found in 1981, while GSL experienced statistically significant abrupt changes in 1996 (Table 2). The abrupt change in the average duration for the WSDI and CSDI occurred in 1996 and 1986, respectively.

At most weather stations, the CSDI showed a decreased trend during the period 1960–2015 and the significant trend stations mainly occurred in northern Xinjiang (Fig. 4n). In contrast, the WSDI showed an increasing trend and the significant trend stations mainly occurred in southern Xinjiang (Fig. 4m). For the CSDI and WSDI, approximately 32.7% and 51.0% of the stations showed statistically significant trends (Table 3). The spatial change trends for GSL were similar to those of SU, namely, increasing GSL and SU regions were widely distributed in the study area. Approximately 98% of the stations showed an increasing trend for GSL, which was statistically significant at about 46.9% of the stations (Fig. 4o and Table 3). As for DTR, the stations showing distinctly decreasing trends were centered in northern and western Xinjiang, but increasing trend regions were scattered fragmentarily in the central region (Fig. 4p).

3.2 Relationship between temperature extremes and altitude

To investigate whether topography influenced the results obtained, Pearson correlation coefficients were calculated for extreme temperature indices and altitude in Xinjiang from 1960 to 2016. Table 4 shows the relationships between the trend magnitudes at individual stations and the altitude. There were positive correlations between elevation and the trends of TXx, TNx, TN10p, TN90p, WSDI, CSDI, and GSL showing increasing trends with the increasing altitude in Xinjiang from 1960 to 2015 (Table 4). As elevation increased, the stations of CSDI and GSL exhibited increasing trend which were statistically significant at the 0.05 and 0.01 levels, respectively. These characteristics indicated obvious warming with elevation. However, the correlations between altitude and the trends of TXn, TNn, TX10p, TX90p, FD, ID, SU, and DTR showed decreasing trends with increasing altitude. The trend of TR displayed a statistically negative correlation with elevation, showing that the tropical nights occurred mainly at lower altitudes. Briefly, these analyses showed an enhanced sensitivity of temperature extremes to altitude in Xinjiang under the background of recent warming.

3.3 Relationship between extreme temperature indices and the ENSO/AO

The ENSO has been the most active atmospheric circulation patterns during recent years and has had a profound impact on global climate change. Meanwhile, the AO is also a key aspect of climatic variability in the Northern Hemisphere. This study further explored how changes in the ENSO and AO affect the temperature extremes using the XWT. As shown in Fig. 5, the CWT between ENSO and TXx, TXn, TNn, TX10, TN10, SU, WSDI, and CSDI showed a significant common power in the 2–6 yr bands during the period from 1980 to 1990 in Xinjiang (Figs. 5a, 5b, 5d, 5g, 5i, 5m, 5n, and 5p), demonstrating that ENSO had a certain extent influence on these indices. However, there are non–significant periods of syntony of 2–4 and 4–6 yr between ENSO and the remaining indices from 1990 to 2000, considering that ENSO is not the driving factor for these indices in the study area (Figs. 5c, 5e, 5f, 5h, 5j, 5k, 5l, and 5o). Furthermore, the CWT relationship between the AO and TXn and TNn (Figs. 6a and 6b) showed a significant shared power with 2–4 yr from 1980 to 1990. There was a significant period of syntony of 7–9 yr between the AO and TX10 and ID from 1972 to 1994 (Figs. 6c, 6d), although there was a small area during the period 1960–1970 period with 1–3 yr periodicity in Xinjiang. The CWT between the AO and the remaining indices showed that the AO is not associated with these remaining indices (figures not shown).

Table 4 Pearson correlation coefficients between the extreme temperature indices and elevation

Index	Correlation coefficient	Index	Correlation coefficient	Index	Correlation coefficient	Index	Correlation coefficient
TXx	0.0403	FD	–0.219	TN10p	0.075	WSDI	0.143
TXn	–0.1191	ID	–0.236	TX10p	–0.057	CSDI	0.327*
TNn	–0.2050	SU	–0.080	TN90p	0.155	GSL	0.497**
TNx	0.1313	TR	–0.300*	TX90p	–0.032	DTR	–0.100

Notes: ** correlation is significant at the 0.01level; * correlation is significant at the 0.05level. (Abbreviations can be found in Table1)

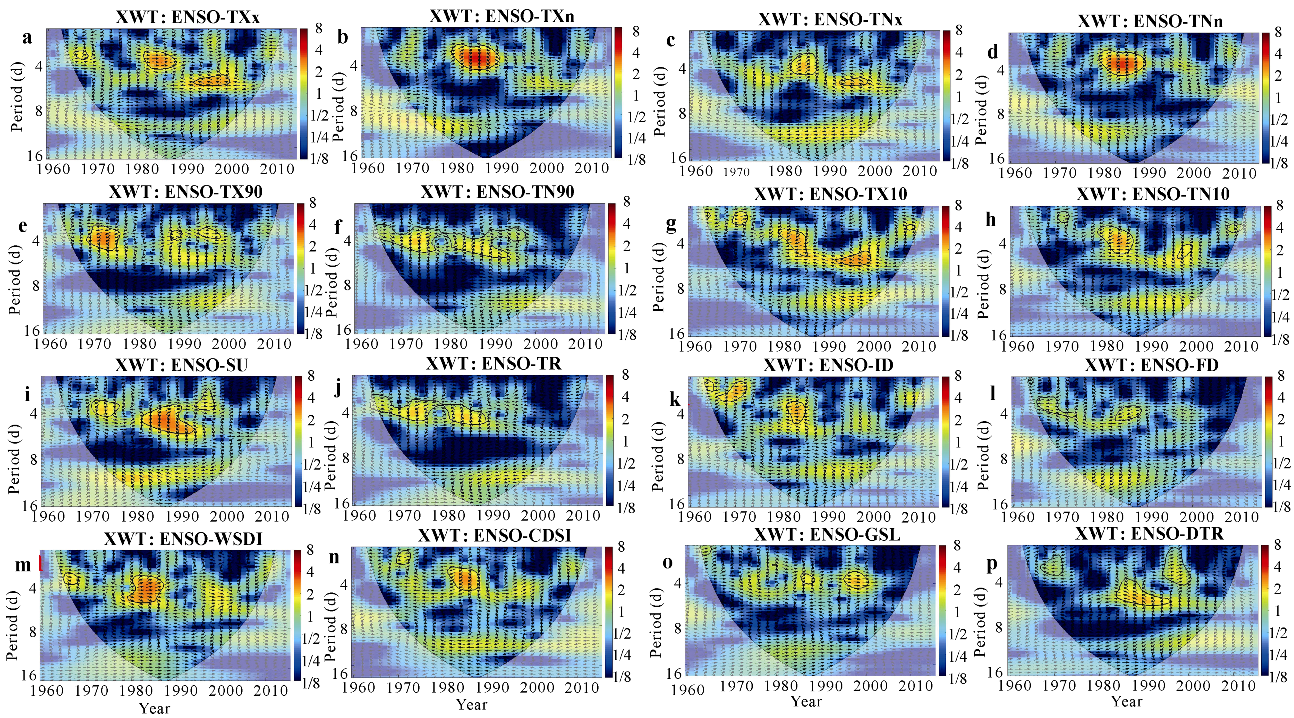

Fig. 5 The Cross wavelet transform of temperature extremes and ENSO in Xinjiang during 1960–2015. (The thick black contours depict the 5% confident level of local power relative to red noise, and the black line is the cone of influence. Right-pointing arrows indicate that the two signals are in phase while left-pointing arrows are for anti-phase signals. Abbreviations can be found in Table 1)

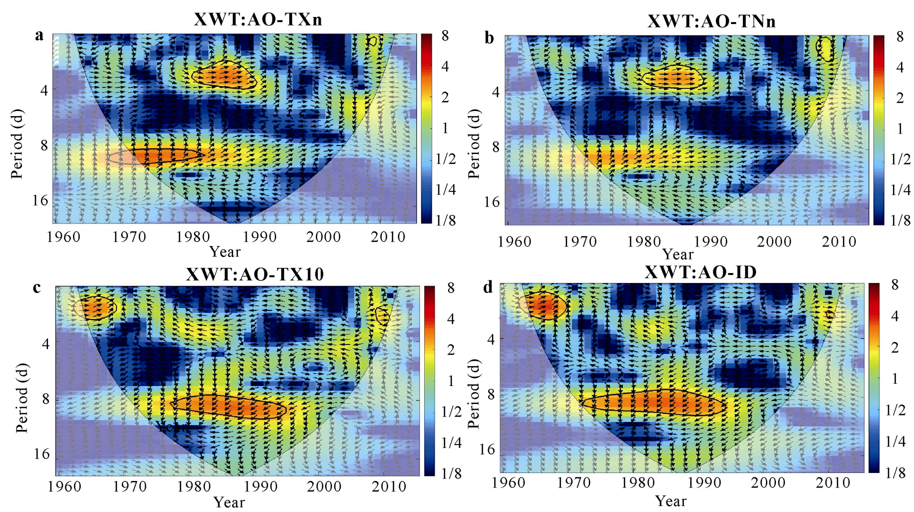

Fig. 6 The Cross wavelet transform of temperature extremes and AO in Xinjiang during 1960–2015. (The thick black contours depict the 5% confident level of local power relative to red noise, and the black line is the cone of influence. Right-pointing arrows indicate that the two signals are in phase while left-pointing arrows are for anti-phase signals. Abbreviations can be found in Table 1)

Thoroughly explore whether atmospheric circulation influenced the results obtained, Pearson correlation coefficients were also calculated for the extreme temperature indices and atmospheric circulation in Xinjiang during the period 1960–2012 (Table 5). There were significant negative correlations between the cold indices (TX10p, TN10p, FD, ID, and CSDI) and ENSO, positive significant correlations between TNn and ENSO, and insignificant positive correlations between the TXx, TNx, TN90p, GSL, WSDI, SU, and ENSO in Xinjiang (Table 5). These results revealed that TX10p, TN10p, FD, ID, and CSDI decreased with an increase

Table 5 Pearson's correlation coefficients between the extreme temperature indices and the large scale atmospheric circulation

Index	Correlation coefficient (ENSO)	Correlation coefficient (AO)	Index	Correlation coefficient (ENSO)	Correlation coefficient (AO)
TXn	–0.020	0.153	TX10	–0.329*	–0.211
TXx	0.216	0.341*	TN10	–0.434**	–0.305*
TNn	0.345**	0.224	TX90	–0.012	0.030
TNx	0.054	0.105	TN90	0.031	0.063
DTR	–0.298*	–0.210	SU	0.028	0.169
GSL	0.167	0.127	FD	–0.296*	–0.190
WDSI	0.200	0.222	ID	–0.292*	–0.186
CDSI	–0.368**	–0.181	TR	–0.044	0.048

Notes: ** correlation is significant at the 0.01 level; * correlation is significant at the 0.05 level. Abbreviations can be found in Table 1

ENSO, while opposite trend was observed for TNn. However, TXx showed a significant positive correlation with AO ($P < 0.01$) and TN10p showed significant negative correlations with AO, indicating that TXx rapidly increased while TN10p decreased with an increasing AO. Thus, the AO showed no clear linear relationship with most of the temperature extremes in Xinjiang, except for TXx and TN10p. By analyzing the aforementioned aspects, we can conclude that the influence of ENSO on the extreme temperature indices was greater than that of the AO for the studied indices in Xinjiang.

4 Discussion

Trends and variability analyses of daily temperature extremes in Xinjiang from 1960 to 2015 showed remarkable changes associated with warming over most of the regions analyzed and the warming trends were greater in the minimum temperature indices than in the maximum temperature indices (Fig. 2). While the determined changes in the extreme temperature indices in Xinjiang are similar to those of other works (Table 6), there are also some differences. In this study, warming trends were observed in the indices of TXx and TNn, but the trend magnitude for TNn (0.59℃/10 yr) was much greater than that of TXx (0.16℃/10 yr), consistent with a decrease in DTR. This asymmetry between the magnitudes of the changes in TNn and TXx agrees with earlier global study (Alexander et al., 2006) and regional studies (Gao et al., 2015; Wang et al., 2018). The trend magnitude of TNn in Xinjiang was lower than the average value of China and less than that on a global scale (Table 6) but greater than that of the Yangtze River Basin (0.42℃/10 yr; Guan et al., 2015). The trends of the temperature extremes in this study are in accord with the reported by Wang et al. (2013a). The small differences were mainly because of the trend computation method or the subtle difference in the time periods for the meteorological stations. In most cases, the trend magnitudes of the WSDI, CSDI, and GSL were in line with those of many previous studies at a regional or national scale but were lower than those on the Tibetan Plateau (Wang et al., 2013c). Our results showed that changes in extreme temperature events in Xinjiang were strongly consistent with those of other similar studies in many regions in term of their response to recent global warming. Although changes in warm/cold nights and days in the study area were largely similar to those of other regions, the changes in ice days were much lower and less significant. This is true both for frequencies and annual extremes. The decrease in the DTR was greater in Xinjiang than that reported in all other regions (Table 6). Zhai and Pan (2003) considered that the significant increase in mean minimum temperature in northern China from 1951 to 1995 resulted in a great contribution to the DTR. Other scholars have also indicated that minimum temperatures are increasing more rapidly than maximum temperatures (Liu et al., 2004). The increases in minimum and maximum temperatures, however, are more comparable, which has muted recent DTR trends since the 1980s (Vose et al., 2005). Furthermore, changes in atmospheric circulation, precipitation, soil moisture and the urban heat island effect likely account for the DTR variation (Vose et al., 2005). However, we cannot completely explain the changes in DTR in Xinjiang. Presently, there is no agreed-upon conclusion regarding the physical reasons for the DTR changes, particularly the DTR increase. Further studies are needed to clarify this issue.

Table 6 Trends of temperature extreme from this study and other works

Index	This paper	Global	China	Loess Plateau (China)	Yangtze River Baisn	Northwest (Xinjiang)	Tibetan Plateau	Southwest China	Northeast China (Songhua River)
TXx	0.16*	0.21*	0.07	–	0.14*	–	–	0.11*	0.2
TXn	0.3	0.37	0.35*	–	0.28*	–	–	0.13*	–
TNn	0.59*	0.71*	0.63*	–	0.42*	–	–	0.29*	0.7*
TNx	0.35*	0.3*	0.21*	–	0.18*	–	–	0.17*	–
DTR	–0.23*	–0.08*	–0.18*	–0.06	–0.09*	–0.26*	–0.2*	–0.18*	–
TN10p	–4.24*	–1.26*	–2.06*	–4.31*	–3.45*	–6.57*	–4.92*	–3.7*	–4.1*
TX10p	–1.47	–0.62*	–0.47*	–2.71*	–1.03*	–2.6*	–2.84*	–1.3*	–1.4*
TN90p	4.52*	1.58*	1.75*	2.6*	2.95*	6.23*	4*	3.6*	3.8*
TX90p	2.19*	–	0.62	3.41*	1.71*	3.59*	3.43*	2.2*	2.1*
FD	–3.44*	0.89*	–3.73*	–3.2*	–3.04*	–3.69*	–5.68*	–2.9*	–3.7*
ID	–1.21	–	–	–2.2*	–0.42*	–1.61*	–7.74*	–0.9	–
SU	1.96*	–	1.18	2.76*	2.16*	2.14*	0.42	–	2.6*
TR	1.57*	–	–	1.24*	1.05*	1.71*	–	–	–
WSDI	1.22*	–	–	0.68*	0.73*	–0.88*	3.31*	–	–
CSDI	–1.65*	–	–	–0.69	–1.6*	–1.27*	–2.55*	–	–
GSL	2.74*	–	3.04*	3.16*	/	2.74*	4.35*	1.2*	–
Data resource		Alexander et al. (2006)	You et al. (2011)	Sun et al. (2016)	Guan et al. (2015)	Wang et al. (2013a)	Wang et al. (2013c)	Li et al. (2012b)	Zhong et al. (2017)

Note: * presents these values are significant at the 5% level. –, indicates the data not available

In addition to the rate of warming, warming dissymmetry has also been found in this study if the time period is divided into two sub-periods of 1960–1990 and 1991–2015 (Fig. 7). TN10, TX10, FD, ID, CSDI, and DTR showed significant decreasing trends during the period 1960–2015 but showed significant increasing trends during the period 1960–1990 and decreasing trends during the period 1991–2015. This conclusion is inconsistent with the results that the widespread decrease in DTR is only evident from the 1950s to 1980s (Vose et al., 2005). A discontinuous warming phenomenon can also be found in the cold-related extremes, when dividing the period into two sub-periods. TNn, TX90, TN90, SU, and TR showed an obviously increasing trend during the period 1960– 2015 and maintained an increasing trend after 1991 (Fig. 7), but showed a slowly decreasing trend from 1960 to 1990. Thus, for the sub-period 1960–1990, an episode of slight cooling, the warm-related extremes decreased. For the 1991–2015 sub-period, an episode of pronounced warming, an abrupt increment was detected in the warm-related extremes (Table 4). Chen et al. (2014) also found that the temperature extremes showed a weakening and decreasing trend from 1961 to 1984 and a strengthening and increasing trend from 1985 to 2010 in the arid region of Northwest China. Guan et al. (2015) found that the Yangtze River Basin was dominated by a general cooling trend before the mid-1980s but a warming trend thereafter. Although the time periods in each study slightly differed, they mainly covered the second half of the 20th century, during which time the abrupt change points occurred. Anthropogenic drivers (e.g., greenhouse gas emissions and urbanization) and climatic natural variability have been considered to the primary factors influencing extreme temperatures since the mid-20th century (Kiktev et al., 2003; Hegerl et al., 2004). Urbanization has affected the series of extreme temperature indices in northern China (Zhou and Ren, 2010) and intensified the increasing trend in warm indices related to minimum temperature (summer days and warm nights) and the decreasing trend in the cold indices series (cool nights/days and frost days) (IPCC, 2013).

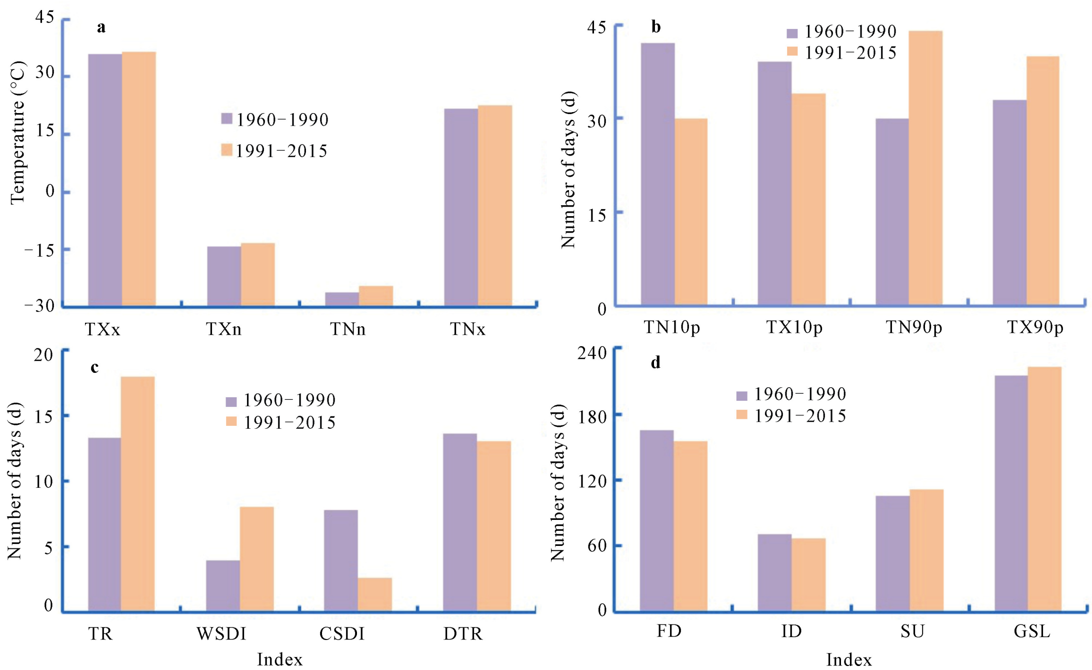

Fig. 7 The values of the temperature extreme indices in Xinjiang during 1960–1990 and 1991–2015

5 Conclusions

In this study, we investigated the temporal-spatial variability patterns of temperature extremes and analyzed possible teleconnections with the large-scale circulation pattern (the El Nino-Southern Oscillation, ENSO and Arctic Oscillation, AO) in Xinjiang during 1960–2015. We found that all percentile indices had trends consistent with warming in most parts of Xinjiang during 1960–2015, but the warming was more pronounced for indices derived from the daily minimum temperature compared to those from the daily maximum temperature. All of the temperature indices showed widespread significant changes associated with global warming in most regions of Xinjiang during the period 1960–2015. Furthermore, the spatial distribution of all extreme climate indices in Xinjiang illustrated here reflects the climatic complexity in mountainous regions. These findings were consistent with many regional previous studies, and some trends of extreme indices in Xinjiang were stronger than those in southwestern China, the Yangtze River Basin and Northeast China. The mutation analysis indicated that the abrupt change year of each index occurred from the 1980s to the 1990s, showing that this period interval was a transitional phase between cold and warm climate change. Additionally, the relationship between large-scale atmospheric circulation (ENSO and the AO) and the temperature extreme indices demonstrates that the influence of ENSO on temperature extremes was greater than that of the AO for these indices in Xinjiang. These results suggest that Xinjiang might be at risk of increased extreme high temperature events and that considerable attention should be paid to this higher risk of extreme climatic events.

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