Changes in Temperature Extremes Based on a 6-Hourly Dataset in China from 1961–2005

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ABSTRACT

Changes in Chinese temperature extremes are presented based on a six-hourly surface air temperature dataset for the period 1961–2005. These temperature series are manually observed at 0200, 0800, 1400, and 2000 Beijing Time (LST), and percentile based extreme indices of these time series are chosen for analysis. Although there is a difference in time among the different time zones across China, as more than 80% of the stations are located in two adjacent time zones, these indices for all the stations are called warm (cold) nights (0200 LST), warm (cold) mornings (0800 LST), warm (cold) days (1400 LST), and warm (cold) evenings (2000 LST), respectively for convenience. The frequency of the annual warm extremes has generally increased, while the frequency of the annual cold extremes has decreased, and significant changes are mainly observed in northern China, the Tibetan Plateau, and the southernmost part of China. Based on the national average, annual warm (cold) nights increase (decrease) at a rate of 5.66 (−5.92) d (10 yr)$^{-1}$, annual warm (cold) days increase (decrease) at a rate of 3.97 (−2.98) d (10 yr)$^{-1}$, and the trends for the annual warm (cold) mornings and evenings are 4.35 (−4.96) and 5.95 (−4.35) d (10 yr)$^{-1}$, respectively. For China as a whole, the increasing rates for the occurrence of seasonal warm extremes are larger in the nighttime (0200, 2000 LST) than these in the daytime (0800, 1400 LST), the maximal increase occurs at 2000 LST except in the summer and the minimal increase occurs at 1400 LST except in autumn; the maximal decrease in the occurrence of seasonal cold extremes occurs at 0200 LST and the minimal decrease occurs at 1400 LST.

Key words: temperature, extreme, frequency, 6-hourly dataset

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1. Introduction

With global warming, the intensity and frequency of some climate extreme events have significantly changed, and it may have been caused by human activities, suggested by the IPCC AR4 (IPCC, 2007). It has been indicated that a small change in the mean of a probability distribution can result in a large change in the frequency of extremes (Mearns et al., 1984; Meehl et al., 2000). The temperature extremes have experienced large changes over some continents in the past few decades. In Europe, the indices of temperature extremes indicate symmetric warming of the cold and warm tails of the distributions of the daily minimum and maximum temperatures during 1946–1999 (Können, 2003). In the Middle East, during 1950–2003, significant increasing trends have been found in the annual maximum of daily maximum and minimum

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temperatures and in the annual minimum of daily maximum and minimum temperatures. The number of warm nights and warm days significantly increased while the number of cool days, cool nights, and daily temperature ranges significantly decreased (Zhang et al., 2005a). In South America, there were no consistent changes of the extreme indices based on daily maximum temperatures, while significant trends were found for the extreme indices based on daily minimum temperatures over the last 40 years of the 20th century (Vincent et al., 2005). Over southern and western Africa, the regional average occurrence of cold days and nights has decreased by −3.7 and −6.0 d $(10\ \mathrm{yr})^{-1}$, respectively while hot days and nights has increased by 8.2 and 8.6 d $(10\ \mathrm{yr})^{-1}$, respectively for the period 1961–2000 (New et al., 2006). From 1950 to 2003, there are fewer cold nights, cold days, and frost days, and conversely more warm nights, warm days, and summer days across Canada (Vincent and Mekis, 2006). Apart from researches focused on the variations of regional temperature extremes, Frich et al. (2002), Kiktev et al. (2003), and Alexander et al. (2006) have described the variations of temperature extremes over global land.

In China, there are also many works concerned with temperature extremes. As a whole of China, the minimum temperature was significantly increased in winter and autumn during 1951–1990 and the maximum temperature decreased significantly only in autumn (Ren and Zhai, 1998). The number of hot days (daily maximum temperature above 35°C) reduced significantly in eastern China, and the extreme maximum temperature of China shows no obvious trends, while the extreme minimum temperature displays a significant increase from 1951–1995 (Zhai et al., 1999). In northern China, the number of days with daily maximum temperatures above the 95th percentile significantly increased, while the number of days with daily minimum temperatures below the 5th percentile significantly decreased during 1951–1999 (Zhai and Pan, 2003a), and the occurrences of warm (cool) days and warm (cool) nights increased (decreased) for China as a whole (Zhai and Pan, 2003b). Qian and Lin (2004) carried out a detailed analysis on the variations of temperature extremes over China. His work was focused on spatial characteristics and revealed that there were significant changes in temperature extremes during 1961–2000, especially in northern China, the Yangtze River valley, and Xinjiang.

These studies on the temperature extremes were generally based on the daily maximum and minimum temperature time series, which were thought to be more efficient than daily or monthly mean temperature series in describing the variation of temperature extremes. Lots of climate indices calculated from daily temperature series are used in the study of temperature extremes, but some of them are often limited by time or space. For example, 35°C is often used to define a hot day in China, but the threshold seems to be too rigorous for temperature series over the Tibetan Plateau while easily exceeded by temperature records in desert areas. Since the influence of the monsoon is remarkable and the topography is complex in China, the regional and seasonal characteristics of climate are particularly prominent. As the percentile-based indices are neither bounded by time nor space, they are more frequently used for the study of temperature extremes. The percentile threshold varies with the time series being analyzed. Just as the definition of an extreme weather event given by IPCC AR4 (IPCC, 2007), an extreme weather event is an event that is rare within its probability density function at a particular place and time of year, the percentile based indices are mainly concerned about the frequency of extreme events, no matter which temperature series are selected. This study is focused on the variations in the frequency of temperature extremes. As the six-hourly temperature series includes four observations throughout the day, and we can get a fuller spectrum in the changes of temperature extremes, this would be a useful complement to previous studies, and the results can also be used as a new reference for modeling temperature extremes. In this paper, the data and methods are discussed in section 2 and 3, respectively. The analysis on the variations of the annual and seasonal temperature extremes is presented in section 4. Discussion and conclusion follow in section 5.

2. Data

2.1 *Data source*

The dataset used here is supplied by China Meteorology Administration. The 6-hourly temperature series are manually observed by 740 Chinese meteorological stations from 1951 to 2005. Since these stations are not set up at the same time, the temperature records are often different in length. There were less than two hundred stations with observation in 1951; other stations were set up subsequently. Five hundred stations had been set up till 1956 and then the number of stations evened out from 1960, so the temperature series covering the period 1961–2005 are chosen for our analysis. The stations without observations before 1965 or after 2000 are also removed. There are 614 stations for further analysis in this study.

2.2 *Data quality control and homogeneity test*

The 6-hourly temperature series have been tested

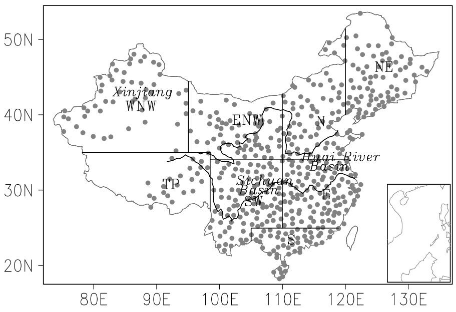

Fig. 1. Geographical distribution of the 524 stations used in the study and classification of regions: NE—Northeast China, N—North China, ENW—eastern Northwest China, WNW—western Northwest China, E—East China, S—South China, SW—Southwest China, TP—Tibetan Plateau.

with rigorous quality control before being used here, and the quality of this dataset is checked again in this study. All daily values outside of four standard deviations from the mean for that time of year are identified and then compared with the time series of nearby stations, all erroneous values are set to missing.

Comparing with the quality control process, the test for data homogeneity is much more difficult. In this study, data homogeneity is tested with a method based on the penalized maximal t-test (Wang et al., 2007) and the penalized maximal F-test (Wang, 2008a). This method is good at determining discontinuities in the time series and providing statistical significance to the detected change points, but it does not provide guidance as to whether the change is due to changes in climate itself or changes in observing practices (Peterson et al., 2008). This method can be applied to any time series with identically independently distributed Gaussian errors and a common nonzero trend throughout the series (Wang, 2008a), and has been used in many studies on temperature extremes. The same as the other temperature series, we find that the 6-hourly temperature series are also with a Gaussian distribution, so this method can be applied to the temperature series here. With the method introduced by Wang (2008b), autocorrelation of temperature series is also taken into account in detecting change points. Monthly mean temperature series for a certain observation time are tested, respectively. There are 302 stations without any change points in the time series at 0200 LST, 293 stations at 0800 LST, 307 stations at 1400 LST, and 322 stations at 2000 LST, but there are only 127 stations with homogenous time series for the four observation times simultaneously. Since most of the discontinuities occur in the year 1966, 1988, or 1998, and many of them are not significant at the 0.05 confidence level, the time series with change points are compared with the time series of their nearby stations by viewing the plots of the monthly mean series and their anomaly series with the seasonal cycles removed. For these change points, which are consistent with each other in space and time, they are not regarded as artificial change points, and other inhomogeneous time series are excluded as homogeneity adjustment is quite complex and there is limited success in doing it (Vincent et al., 2002). Inhomogeneity other than step changes, such as gradual changes in temperature, might occur through urbanization (Alexander et al., 2006). In order to avoid this influence as much as possible, these stations with city populations above one million (Zhou and Yu, 2004) are also excluded. Finally, there are 524 stations being used for analysis in this study (Fig. 1).

3. Methodology

3.1 *The indices*

Since the regional and seasonal characteristics of the climate are particularly prominent in China, and in order to compare the variations of temperature extremes among different regions, seasons and observation times conveniently, percentile based temperature indices, which are not bounded by space and time, are chosen for analysis (Table 1). These indices are calcu-

Table 1. Definition of the temperature extreme indices in this work: T02, T08, T14, and T20 denote daily temperatures at the different observation times, respectively.

ID	Indicator name	Definitions
T02p10	cold nights	No. of days with T02<10th percentile
T02p90	warm nights	No. of days with T02>90th percentile
T08p10	cold mornings	No. of days with T08<10th percentile
T08p90	warm mornings	No. of days with T08>90th percentile
T14p10	cool days	No. of days with T14<10th percentile
T14p90	warm days	No. of days with T14>90th percentile
T20p10	cold evenings	No. of days with T20<10th percentile
T20p90	warm evenings	No. of days with T20>90th percentile

lated with a reference period of 1961–1990 using FClimDex, a Fortran-based software package, which is available at the link http://cccma.seos.uvic.ca/ ETC-CDI/software.shtml. The bootstrap resampling procedure of Zhang et al. (2005b) has been implemented in FClimDex to ensure that the percentile based temperature indices do not have artificial jumps at the boundaries of the in and out-of reference periods. In this work, both annual and seasonal indices are computed. The threshold is firstly computed for each day in a certain year with the method introduced by Zhang et al. (2005b), and then compared with the temperature value for that day. The annual warm (cold) indices equal the number of days with a temperature value above (below) the threshold.

3.2 *Regional average series*

Regions discussed in this study are shown in Fig. 1, and climatology characteristics are similar in specific regions. Since there is some difference in climatology among temperature series of different stations, the climatology for the period 1961–1990 is firstly subtracted from the original time series of the extreme indices at each station, and then the regional average series are calculated as an arithmetic mean of all the anomaly time series in this region. Average time series are also computed for the whole country. Anomalies of extreme indices on the station level are firstly averaged into $2° \times 2°$ grid boxes, and then the grid values are averaged on an area-weighted basis to create the time series of China.

3.3 *Trend calculation*

A linear trend is computed from the anomaly time series of extreme indices by a Kendall's tau based slope estimator (Sen, 1968). Comparing with the best-fit linear trend estimator, it is insensitive to outliers and does not assume a distribution for residuals. Since the result of Kendall's tau test could be affected by autocorrelation of the time series, the lag-1 autocorrelation effect is taken into account in trend estimation and significance testing (Zhang et al., 2000). The trends are computed if less than 20% of the values are missing during the period 1961–2005. In this work, the statistical significance of the trends is assessed at the 95% confidence level.

4. Analysis

4.1 *Annual indices*

4.1.1 *Cold indices*

As shown in Fig. 2, the annual cold events generally decreased, although there are a few stations with

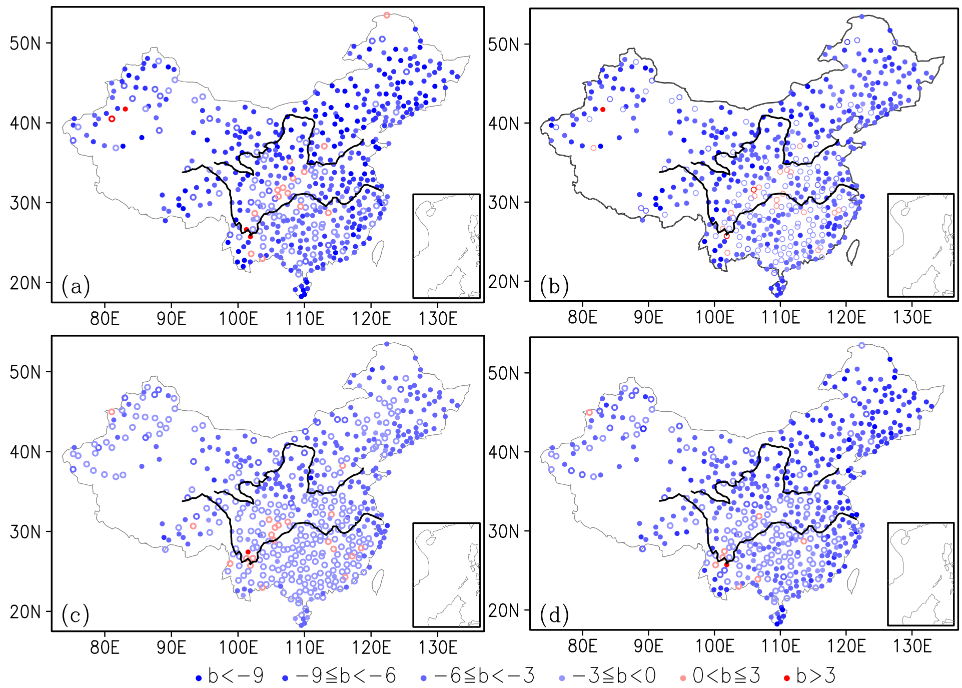

Fig. 2. Trends for the period 1961–2005 in the frequency of annual cold extremes, (a) cold nights; (b) cold mornings; (c) cold days; (d) cold evenings. The letter b denotes trend. The red circles denote positive trends and the blue circles denote negative trends; the filled signs indicate statistical significance at the 0.05 significance level. [units: d (10 yr)$^{-1}$]

increasing trends. The maximal decrease occurs at 0200 LST with more than four hundred stations showing significant decreasing trends, and the minimal decrease occurs at 1400 LST with only 225 stations showing significant decreasing trends. For cold nights, cold mornings, and cold evenings, nonsignificant decreasing trends are mainly located in southern China; for cold days, the stations with significant decreasing trends are concentrated in the upper and middle valley of the Yellow River, the lower valley of the Yangtze River, and Northeast China. Some of the stations in Southwest China exhibit nonsignificant decreasing or increasing trends in the frequency of all cold extremes; this is consistent with the changes in the mean temperature there (Ren et al., 2005; Xiang and Chen, 2006). For China as a whole, cold nights, cold mornings, and cold evenings decrease at the rate of -5.92, -4.96, and -4.35 d (10 yr)$^{-1}$, respectively; the minimal decreasing trend of -2.98 d (10 yr)$^{-1}$ occurred at 1400 LST, but it is also significant at the 0.05 confidence level. As shown in Fig. 4a, the national average anomaly series of cold extremes exhibit similar annual variations although there are some differences among the values in a given year.

For the regional average anomaly series of those divided regions in Fig. 1, the decreasing trends are larger for cold nights and cold evenings than for cold mornings and cold days in eastern China; the decreasing trends are also minimal for cold days; the decreasing trends are maximal for cold nights, with the exception of Southwest China and western Northwest China, where cold mornings decrease more significantly (Table 2).

4.1.2 *Warm indices*

From the spatial distribution (Fig. 3), significant increasing trends are most homogeneous for warm nights, and the increasing trends in East China and South China have greatly decreased till 0800 LST, and the area with significant change is further reduced in northern China at 1400 LST; the number of stations with significant increasing trends is greatly increased from 1400 LST to 2000 LST and the trends for warm nights and warm evenings are quite similar to each other in the spatial distribution. The occurrences of warm extremes have decreased at some stations in southern China, especially for warm mornings; there is a small area in the Huaihe River basin with a decreasing trend for warm days. On the nationwide average, the increasing rate has reached 5.95 d (10 yr)$^{-1}$ for warm evenings, and the rates are 4.35 d (10 yr)$^{-1}$ for warm mornings and 5.66 d (10 yr)$^{-1}$ for warm nights. Warm days have also increased significantly and the increasing rate is 3.97 d (10 yr)$^{-1}$. As shown in Fig. 4b, the annual variations of the national average anomaly series of warm extremes are quite similar to each other.

For these divided regions (Table 2), the increasing trends are larger for warm nights and warm evenings

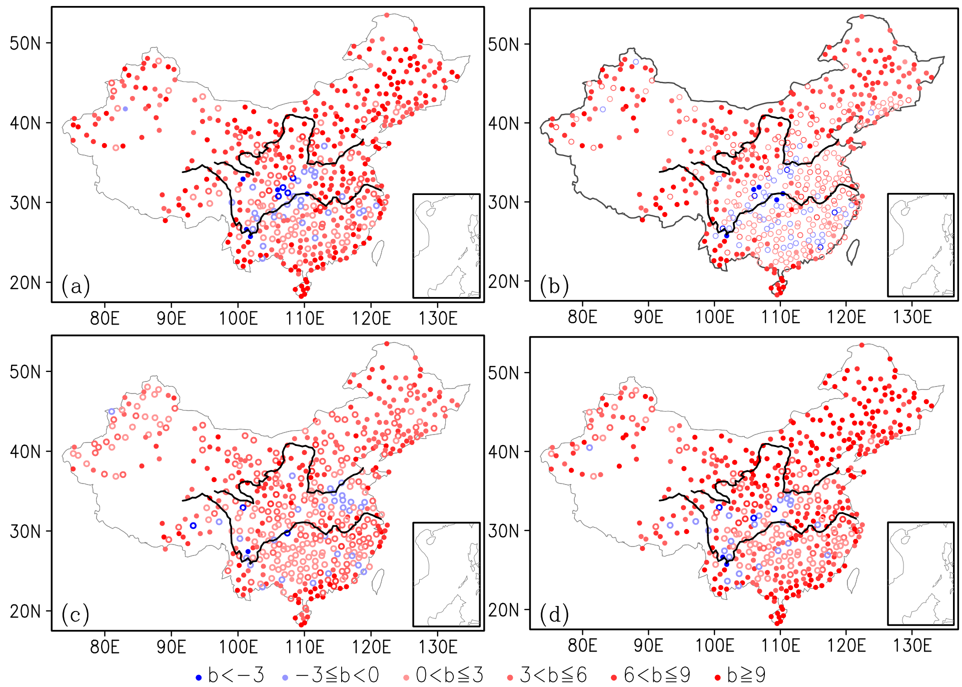

Fig. 3. Same as Fig. 2, but for warm extremes, (a) warm nights; (b) warm mornings; (c) warm days; (d) warm evenings.

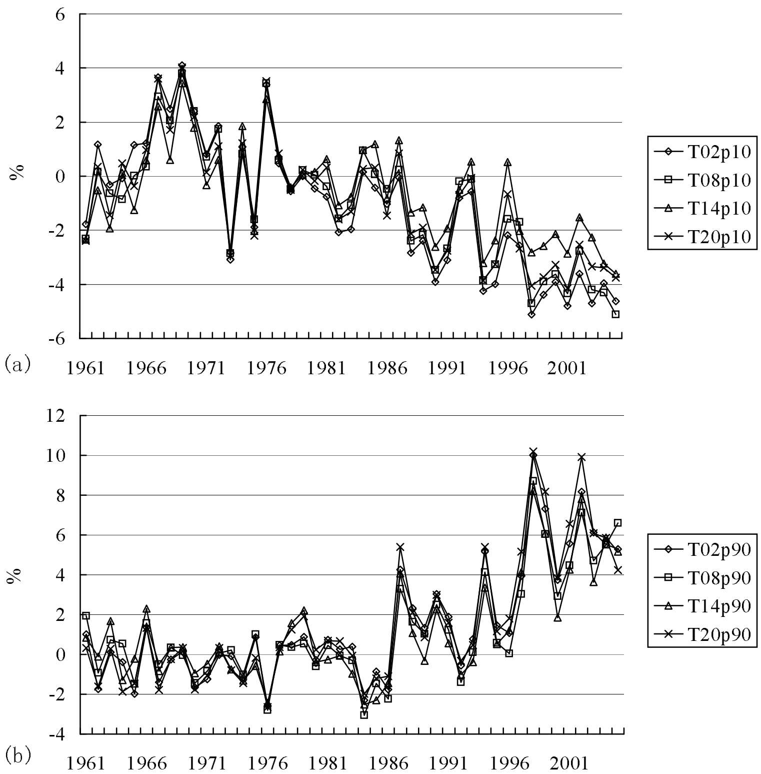

Fig. 4. Anomaly time series of the frequency of annual (a) cold indices and (b) warm indices over 1961–2005, based on the national average. The vertical axis represents percent of the number of days of the year.

than for warm mornings and warm days, and the maximal increases occur at 2000 LST, with the exception of western Northwest China and the Tibetan Plateau; the minimal increases all occur in the daytime, either at 0800 LST or at 1400 LST. In western Northwest China, the trend for warm mornings is comparable to the trend for warm nights, which displays the maximal increase there. In the Tibetan Plateau, the trend for warm mornings is maximal among the four warm indices.

As shown in Fig. 4b, decadal trends in the occurrence of warm extremes are very small from 1961 to 1985, but significant increases occur from then on, and the time is consistent with the annual mean temperature of China displaying a sharp warming. The turning point is about the year 1986 (Ding and Dai, 1994), which is lagged to the time when the mean temperature of the whole Northern Hemisphere began to sharply increase. As the annual variations of the warm extremes and the mean temperature of the whole country (Ren et al., 2005) being similar to each other, correlation coefficients between the regional average time series of them are computed in order to further analyze the relationship between them. The correlation coefficients are computed by using Kendall's tau rank correlation, and all of them are significant at the 0.001 significance level. Table 3 reveals that the annual variations in the occurrence of temperature extremes are similar with the annual variations of the mean temperature for any region, season, and observation time, i.e. the occurrences of warm (cold) events are apt to higher (lower), while the mean temperature is on the high side, vice versa; of course, as for decadal trends, there are also exceptions that warm events are not reduced as the mean temperature decreases (Table 2). On the whole, since the annual variations in the frequency of temperature extremes and the mean temperature are so similar to each other, and both of them began sharply increasing at the same time, the changes in the occurrence of temperature extremes should be closely related to global warming.

4.2 *Seasonal indices*

Seasonal variation characteristics of temperature extremes are analyzed in this section. Trends of the seasonal anomaly series based on national average extreme indices are shown in Fig. 5. For warm extremes at different observation times, the maximal increasing trend occurs in winter except warm nights, which have a larger increase in the summer. From the spatial dis-

Table 2. Trends for regional averaged seasonal and annual extreme indices at the different observation times. The values out of (in) bracket correspond to cold (warm) indices. The letter y denotes significant trends and n denotes non-significant trends. 02, 08, 14, and 20 denote the different observation times. DJF—winter, MAM—spring, JJA—summer, SON—autumn, ANN—annual.

	Day	NE	N	ENW	WNW	E	S	SW	TP
DJF	02	−2.19y (1.86y)	−2.46y (2.21y)	−1.90y (2.40y)	−1.34y (2.26y)	−2.33y (1.51y)	−2.06y (1.58y)	−1.74y (1.05y)	−1.57y (1.80y)
	08	−2.12y (1.65y)	−2.31y (2.03y)	−1.80y (2.06y)	−1.38y (2.15y)	−2.30y (1.45y)	−2.01y (1.51y)	−1.78y (0.98y)	−1.94y (1.34y)
	14	−1.42n (1.55y)	−1.53n (1.35y)	−1.80y (1.74y)	−0.82n (1.56y)	−1.38y (0.27n)	−0.78n (1.37y)	−0.80n (0.70n)	−0.38n (1.90y)
	20	−2.21y (2.15y)	−2.23y (2.39y)	−1.84y (2.76y)	−1.29y (2.06y)	−1.82y (1.11y)	−1.50n (1.74y)	−1.12n (1.07y)	−0.68n (2.31y)
MAM	02	−2.23y (1.71y)	−2.09y (1.77y)	−1.12y (1.59y)	−0.30n (0.83n)	−1.49y (1.17n)	−1.16y (1.92y)	−0.47n (0.69n)	−1.30y (1.44y)
	08	−2.13y (1.02y)	−1.48y (1.24n)	−0.97y (1.44n)	−0.72n (0.70n)	−1.24y (0.51n)	−0.79n (1.25y)	−0.62n (0.68n)	−1.46y (1.37y)
	14	−1.49y (0.80n)	−1.10y (1.13n)	−0.51n (0.89n)	0.57n (−0.09n)	−0.61n (1.09n)	−0.12n (1.66y)	0.10n (0.75n)	−0.35n (0.56n)
	20	−2.32y (1.97y)	−1.55y (2.06y)	−0.67y (1.91y)	0.25n (0.28n)	−0.93n (1.39y)	−0.40n (2.24y)	0.04n (1.06y)	−0.41n(1.08n)
JJA	02	−1.55y (1.81y)	−1.15y (1.22y)	−1.55y (1.90y)	−1.08y (1.59y)	−0.17n (1.73y)	−1.27y (2.98y)	−0.55n (0.91y)	−1.10y (1.99y)
	08	−0.69n (0.38n)	−0.06n (-0.48n)	−1.12y (1.72y)	−1.28y (1.59y)	0.46n (0.22n)	−0.71n (1.28y)	−0.42n (0.56n)	−0.98n (2.81y)
	14	−0.41n (0.57n)	−0.11n (0.36n)	−0.24n (1.57n)	−0.15n (0.64n)	0.55n (0.64n)	−0.24n (2.29y)	−0.06n (0.88y)	−0.73y (1.78y)
	20	−1.05y (1.87y)	−0.51n (0.84n)	−0.46n (1.69n)	−0.19n (0.86n)	0.30n (1.41y)	−0.59n (3.15y)	−0.33n (0.78y)	−0.98y (1.97y)
SON	02	−1.59y (1.39y)	−1.44y (1.42y)	−1.14y (1.38y)	−1.28y (1.36y)	−1.06n (0.66n)	−1.06y (2.01y)	−0.98n (0.86n)	−2.08y (1.34y)
	08	−0.97n (0.77n)	−0.63n (0.88n)	−1.07y (1.04y)	−1.46y (1.24y)	−0.52n (−0.03n)	−0.24n (0.68n)	−0.80n (0.63n)	−1.71y (1.73y)
	14	−0.58n (0.69n)	−0.45n (1.05y)	−1.02y (1.98y)	−0.88n (1.35y)	−0.43n (0.80n)	−0.59n (1.74y)	−0.47n (0.52n)	−1.47y (0.54n)
	20	−1.42y (1.50y)	−1.27y (1.66y)	−1.20y (2.05y)	−0.99n (1.69y)	−0.98n (0.88n)	−1.06y (2.73y)	−0.93y (1.14y)	−2.07y (1.00n)
ANN	02	−7.19y (7.53y)	−7.22y (6.62y)	−6.43y (7.03y)	−5.40y (6.13y)	−5.08y (4.77y)	−5.66y (8.64y)	−3.81y (2.95y)	−6.75y (6.75y)
	08	−5.30y (5.17y)	−4.70y (4.26n)	−5.78y (5.88y)	−6.00y (5.94y)	−3.35y (1.82n)	−3.63y (4.54y)	−3.92y (2.49y)	−6.69y (7.61y)
	14	−3.60y (5.39y)	−3.44y (4.13n)	−4.36y (5.97y)	−2.96y (4.08y)	−2.01y (4.29n)	−1.87n (6.44y)	−1.36n (2.84y)	−3.41y (4.93y)
	20	−6.38y (9.21y)	−5.81y (7.18y)	−4.88y (8.39y)	−3.91y (5.38y)	−3.63y (5.04y)	−4.27y (9.50y)	−2.63y (3.29y)	−4.55y (6.55y)

Table 3. Correlation coefficients between regional average extreme temperature time series and mean temperature time series. The values out of (in) bracket correspond to correlation coefficients between the time series of cold (warm) extremes and the mean temperature.

	Day	NE	N	ENW	WNW	E	S	SW	TP
DJF	02	−0.65 (0.63)	−0.65 (0.60)	−0.62 (0.64)	−0.45 (0.58)	−0.63 (0.52)	−0.60 (0.51)	−0.66 (0.56)	−0.51 (0.66)
	08	−0.65 (0.63)	−0.63 (0.65)	−0.60 (0.63)	−0.47 (0.58)	−0.66 (0.51)	−0.64 (0.51)	−0.66 (0.58)	−0.51 (0.63)
	14	−0.66 (0.63)	−0.53 (0.53)	−0.53 (0.54)	−0.42 (0.59)	−0.46 (0.46)	−0.46 (0.47)	−0.60 (0.54)	−0.50 (0.60)
	20	−0.68 (0.67)	−0.62 (0.59)	−0.56 (0.61)	−0.45 (0.59)	−0.53 (0.46)	−0.52 (0.50)	−0.59 (0.54)	−0.48 (0.63)
MAM	02	−0.79 (0.78)	−0.76 (0.74)	−0.75 (0.81)	−0.67 (0.73)	−0.58 (0.65)	−0.61 (0.62)	−0.57 (0.66)	−0.72 (0.81)
	08	−0.79 (0.77)	−0.77 (0.73)	−0.74 (0.81)	−0.71 (0.74)	−0.56 (0.64)	−0.58 (0.64)	−0.61 (0.63)	−0.74 (0.74)
	14	−0.73 (0.72)	−0.69 (0.66)	−0.63 (0.69)	−0.76 (0.67)	−0.48 (0.63)	−0.62 (0.58)	−0.47 (0.69)	−0.76 (0.79)
	20	−0.77 (0.77)	−0.73 (0.75)	−0.67 (0.71)	−0.74 (0.65)	−0.59 (0.65)	−0.61 (0.60)	−0.48 (0.68)	−0.77 (0.81)
JJA	02	−0.71 (0.67)	−0.77 (0.73)	−0.77 (0.84)	−0.71 (0.77)	−0.70 (0.64)	−0.75 (0.74)	−0.63 (0.62)	−0.71 (0.78)
	08	−0.70 (0.67)	−0.71 (0.77)	−0.74 (0.82)	−0.73 (0.79)	−0.68 (0.65)	−0.68 (0.70)	−0.67 (0.52)	−0.78 (0.72)
	14	−0.66 (0.72)	−0.70 (0.77)	−0.63 (0.74)	−0.57 (0.65)	−0.65 (0.62)	−0.61 (0.69)	−0.68 (0.66)	−0.68 (0.77)
	20	−0.65 (0.68)	−0.64 (0.78)	−0.66 (0.79)	−0.61 (0.70)	−0.64 (0.65)	−0.65 (0.77)	−0.64 (0.67)	−0.65 (0.81)
SON	02	−0.69 (0.66)	−0.72 (0.67)	−0.71 (0.66)	−0.80 (0.69)	−0.63 (0.62)	−0.65 (0.63)	−0.70 (0.69)	−0.70 (0.70)
	08	−0.67 (0.62)	−0.71 (0.64)	−0.76 (0.68)	−0.81 (0.72)	−0.63 (0.62)	−0.61 (0.63)	−0.73 (0.69)	−0.72 (0.65)
	14	−0.63 (0.63)	−0.69 (0.54)	−0.58 (0.61)	−0.69 (0.58)	−0.60 (0.43)	−0.68 (0.60)	−0.53 (0.57)	−0.76 (0.66)
	20	−0.69 (0.63)	−0.69 (0.61)	−0.63 (0.60)	−0.69 (0.57)	−0.59 (0.48)	−0.66 (0.67)	−0.64 (0.58)	−0.76 (0.72)
ANN	02	−0.75 (0.69)	−0.72 (0.74)	−0.79 (0.78)	−0.76 (0.76)	−0.65 (0.60)	−0.64 (0.66)	−0.79 (0.74)	−0.80 (0.83)
	08	−0.71 (0.65)	−0.72 (0.63)	−0.78 (0.76)	−0.80 (0.77)	−0.64 (0.54)	−0.64 (0.64)	−0.75 (0.71)	−0.80 (0.81)
	14	−0.64 (0.65)	−0.69 (0.63)	−0.68 (0.71)	−0.74 (0.65)	−0.55 (0.60)	−0.61 (0.60)	−0.69 (0.75)	−0.78 (0.78)
	20	−0.73 (0.72)	−0.70 (0.70)	−0.71 (0.76)	−0.74 (0.68)	−0.60 (0.60)	−0.62 (0.66)	−0.72 (0.74)	−0.76 (0.79)

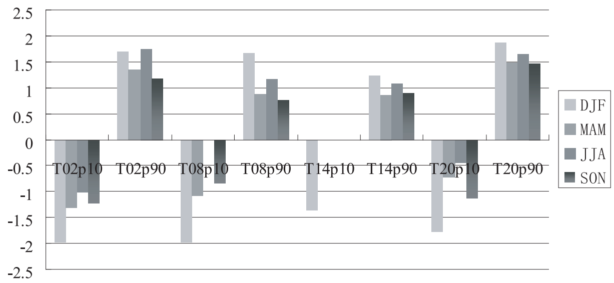

Fig. 5. Trends for the national averaged seasonal time series of cold and warm extremes. The abscissa axis represents extreme indices and the vertical axis shows the trends of them [units: d (10 yr)$^{-1}$]. Trends not significant at the 0.05 significance level are shown by a dotted bar. DJF—winter, MAM—spring, JJA—summer, SON—autumn.

tribution (not shown), warm nights have more significantly increased over southern China in the summer than in winter. Comparing warm extremes given a certain season, the maximal increase occurs at 2000 LST except in the summer in which the maximal increase occurs at 0200 LST. The regional average warm evenings also display the maximal increase among warm indices in winter, spring, and autumn nearly for all the divided regions (Table 2). The minimal increase for the national average warm extremes occurs at 1400 LST except in autumn, in which the trend for warm mornings is minimal. In autumn (not shown), lots of stations in southern China exhibit decreases in warm mornings while exhibit increases in warm days, and the increasing trends for warm days are greatly larger than the increasing trends for warm mornings in the upper valley of the Yellow River. As shown in Fig. 5, the increasing trends in the frequency of seasonal warm indices are all significant at the 0.05 significance level.

Trends in the occurrences for all of the seasonal cold extremes are negative (Fig. 5). Comparing variations at different observation times, cold nights display the maximal decrease among the four cold indices, and cold days display the minimal decrease. The decreasing trend for cold mornings is comparable to that for cold nights in the winter. Comparing variations in different seasons, the maximal decreases for cold indices all occur in the winter and the minimal decreases in the summer. The nonsignificant decreasing trends all occur in the daytime.

From the spatial distribution (not shown), changes in the frequency of seasonal extreme indices exhibit a notable regional characteristic that there are some concentrated areas with decreasing trends for warm events or increasing trends for cold events. This characteristic is especially remarkable in the spring and summer.

In winter, the decreasing trends of seasonal cold indices are more homogenous in space than that of the annual cold indices, although the latter with a significant change is more homogenous in space. For warm indices, significant increasing trends are concentrated in northern China and the Tibetan Plateau. There are a few stations in the Sichuan basin with decreasing trends in the frequency of warm indices, especially for warm days, which also decrease in the southern part of the Huaihe River basin.

In the spring, lots of stations in Southwest China exhibit increasing cold events, and it is consistent with the decreased mean temperature there (Ren et al., 2005; Xiang and Chen, 2006); there are also some stations in western Northwest China with increasing occurrences of cold events, especially for cold days. As the occurrence of warm events generally increased in Southwest China and western Northwest China, it illustrates that warm events do not always decrease while cold events increase as the mean temperature decreases.

In the summer, the stations with increasing cold events are mainly situated in the valley of the Yangtze River and the lower valley of the Yellow River, and the area with positive trends is most extensive for cold days. Warm events generally decrease in the area between the Sichuan Basin and the Huaihe River Basin, especially for warm mornings, and it is consistent with the cooling there (Ren et al., 2005). The number of stations with decreasing warm events, with the exception of warm mornings, is less than half of the one with increasing cold events; this also reflects that the occurrences of warm extremes and cold extremes do not always exhibit opposite trends on the station level.

In autumn, all of the cold extremes exhibit a significant decrease in frequency in the Tibetan Plateau and the upper valley of the Yellow River. The stations with a decreasing occurrence of warm extremes are scattered except for warm mornings, for which there is a relatively concentrated area in Southeast China with decreasing trends.

5. Discussion and conclusion

A 6-hourly surface air temperature dataset is used for analysis on changes in temperature extremes in China. This study is focused on the variations in the frequency of temperature extremes. With four observations throughout the day, the dataset can exhibit a fuller spectrum of the changes in temperature extremes; it would be a useful complement to previous studies and can also be used as a new reference for the modeling of temperature extremes. Seasonal and annual percentile based indices are chosen for our analysis, and they are computed for each station, for each divided region, and for China as a whole.

For China as a whole, the annual cold nights, cold mornings, cold days, and cold evenings decrease at the rate of -5.92, -4.96, -2.98, and -4.35 d (10 yr)$^{-1}$, respectively; the annual warm nights, warm mornings, warm days, and warm evenings increase at the rate of 5.66, 4.35, 3.97 and 5.95 d (10 yr)$^{-1}$, respectively; the seasonal warm events all significantly increased and the seasonal cold events all decreased.

For the frequency of the regional average annual cold extremes, the minimal decreases occur at 1400 LST; the maximal decreases occur at 0200 LST, with the exception of Southwest China and western Northwest China, where cold mornings decrease more significantly. For the frequency of the regional average annual warm extremes, the minimal increases occur in the daytime, either at 0800 LST or at 1400 LST; the maximal increases occur at 2000 LST except western Northwest China and the Tibetan Plateau.

The annual variations in the frequency of the national average annual warm events are quite similar to the annual variations in the annual mean temperature of China, and they shared the same time while sharply increasing, so the changes in temperature extremes should be closely related to global warming. As revealed by correlation coefficients between the regional average anomaly series of mean temperature and extreme indices, the occurrences of warm (cold) events are apt to higher (lower) while the mean temperature is on the high side, and vice versa; nevertheless, as for decadal trends, the regional average warm events are not always reduced as the mean temperature decreases. For the anomaly time series of extreme indices on the station level, there is often a great difference between the number of stations with decreased warm events and that with increased cold events, i.e. a decreased mean temperature does not always correspond to decreased warm events and increased cold events. On the whole, it seems to be more reasonable for the regional average case that the variation of the mean temperature is consistent with variations in the frequency of warm events and cold events.

Based on the relationship between temperature extremes and the mean temperature, the mechanism of the changes in the mean temperature could be used for explaining the changes in temperature extremes to some extent. For example, Li et al. (2005) indicated that early spring cooling in the Sichuan basin was caused by the positive cloud-temperature feedback, which was triggered by the increase of midlevel stratiform clouds and Gao et al. (2007) found that land use change could contribute to cooling along the valley of the Yangtze River in the summer. These factors might also be responsible for the increased occurrences of cold extremes in the corresponding season and area. In regard to the difference in changes in temperature extremes of different observation times, the mechanism is worth further research.

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