Characteristics of the spatiotemporal distribution of daily extreme temperature events in China: Minimum temperature records in different climate states against the background of the most probable temperature*

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Based on the skewed function, the most probable temperature is defined and the spatiotemporal distributions of the frequencies and strengths of extreme temperature events in different climate states over China are investigated, where the climate states are referred to as State I, State II and State III, i.e., the daily minimum temperature records of 1961–1990, 1971–2000, and 1981–2009. The results show that in space the frequency of high temperature events in summer decreases clearly in the lower and middle reaches of the Yellow River in State I and that low temperature events decrease in northern China in State II. In the present state, the frequency of high temperature events increases significantly in most areas over China except the north east, while the frequency of low temperature events decreases mainly in north China and the regions between the Yangtze River and the Yellow River. The distributions of frequencies and strengths of extreme temperature events are consistent in space. The analysis of time evolution of extreme events shows that the occurrence of high temperature events become higher with the change in state, while that of low temperature events decreases. High temperature events are becoming stronger as well and deserve to be paid special attention.

Keywords: extreme temperature, most probable temperature, climate state

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1. Introduction

Extreme weather events frequently occur with global warming, which gives mankind a challenge for subsistence and development.[1,2] According to the IPCC AR3 and AR4, extreme weather events are small probability ones in a particular place and at a particular time, and their probability of occurring is about 10% or even less.[3] Some studies show that extreme low temperature events and frosty days each had a decreasing trend in recent years, and the inter-annual change in difference between extreme high and low temperature decreased obviously in the late 20th century.[4] Manton *et al.*[5] found that hot days and warm nights had increased notably in south east Asia and the south Pacific Ocean since 1961.

So far, the definitions of extreme events concerning temperature and precipitation are not the same, much less those about different seasons and regions, which leads to more uncertainty in studying extreme events.[6−10] Investigations about the relationship between extreme events and inter-decadal climate change are still limited, much less the change of extreme events frequencies and strengths before and after an abrupt climate change event happens. Thereby aiming at the skewed distribution of temperature we obtain a skewed probability density function. According to the function, extreme temperature events are defined and the characteristics of spatiotemporal distribution and time evolution based on three climatic states, i.e. 1961–1990, 1971–2000, and 1981–2009 (named State I, State II and State III respectively) are studied. Through these we intend to reveal the essence of extreme temperature event changes and development trends and try to answer whether extreme temperature events are more and more extreme and

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frequent.

2. Methods and data

The daily minimum temperature records at 597 stations from 1961 to 2009 were selected based on the requirement of data continuity from the climate dataset over China, released by the China Meteorological Administration. This contribution focused mainly on summer and winter.

In most previous studies, the statistics of climatic observation data was usually based on the hypothesis that the distribution of data is normal.[11−13] However, this hypothesis could bring many defects into practical data analysis. Therefore using the Box–Cox transformation to improve the normality of data, we obtained the probability density function of abnormal temperature distribution by theoretical derivation, i.e., a skewed distribution function $p(x)$,[14]

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma(\bar{T}_{i0} - T_{\min})^{\lambda}} \times \exp\left\{ -\frac{\left(\left(\frac{x - T_{\min}}{T_{i0} - T_{\min}}\right)^{\lambda} - 1 - \lambda u\right)^2}{2\lambda^2\sigma^2} \right\} \times (x - T_{\min})^{\lambda - 1}, \quad (1)$$

where $T_{\min}$ is the minimum of the time series $\{T_{i0}\}$, λ is the Box–Cox transformation exponent, σ and u are the deviation error and mean of the transformed data respectively.

According to Eq. (1), the most probable temperature (MPT) $T_{\rm p}$ is derived by making $\mathrm{d}p/\mathrm{d}T = 0$,

$$T_{\rm p} = \left(\frac{\bar{T}^{\lambda} + \sqrt{\bar{T}^{2\lambda} + \dfrac{2(\lambda - 1)}{b\lambda}}}{2} \right)^{1/\lambda}, \quad (2)$$

with $\bar{T} = \frac{1}{N}\sum_{i=1}^{N} T_{i0}$ and $b = 1/2\lambda^2\sigma^2\bar{T}^{2\lambda}$. Extreme low temperature events (LTEs) and extreme high temperature events (HTEs) are defined as those events that occur with a probability of not more than 10% and with a probability that is not less than 90% respectively. Here we especially focus on the HTEs in summer and LTEs in winter.

Trend coefficients[15] are often used to find out the long-term trend of meteorological elements, which are dimensionless and in the interval [−1, 1]. Trend coefficients are standard regression coefficients in essence, which eliminates the effects of elements' mean square error and unit on regression coefficients, that is why they can be compared between different regions and meteorological elements, especially as they can reflect long time spatial characteristics over a large area. All the trend coefficients derived in this work have been tested for significance.

In addition, the reference climatic state is viewed as a base point to describe basic climate conditions in a relatively stable period. The mean values of some kinds meteorological elements in 30 years are regarded as the values of reference climatic state[16] according to the definition of the World Meteorological Organization (WMO). In this paper, the daily temperature records are divided into three climate states as 1961–1990, 1971–2000, and 1981–2009 (just called State I, State II, and State III respectively), the frequencies and strengths of extreme temperature events in different states are compared, and spatiotemporal features of extreme temperature events are obtained.

3. Characterization of changes in MPT

In light of statistic physics, features of a macro system present the collective behaviour of a large number of microcosmic motions whose distributions are multifarious. Among those distributions, the maximum probability distribution is called the most probable one which typifies the equilibrium state of a macro-

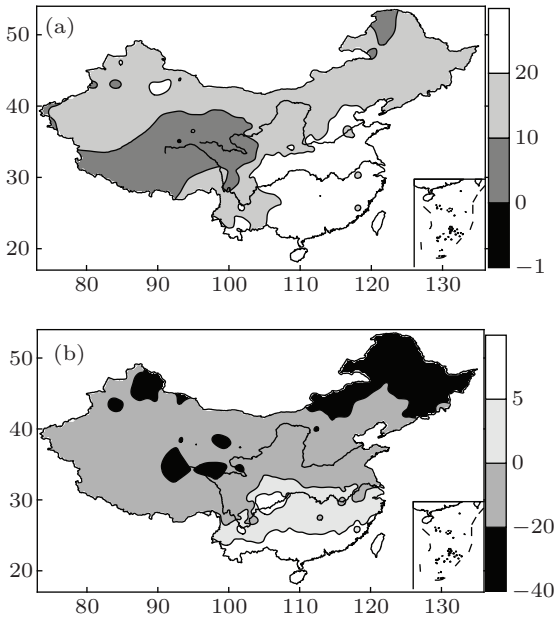


Fig. 1. (a) Most probable temperature in summer and (b) most probable temperature in winter over China in State I.

system.[17] So the most probable temperature (MPT) can describe the features of the equilibrium state of the temperature field in some regions and is the most likely temperature for this region. Then MPT can be regarded as the background of a region and reflect the region's climate changes. Figure 1 shows that the regional differences in MPT over China are obvious. In summer, MPT is low in the east of the Tibetan Plateau but high in most areas south of north China. In winter, the MPT changed across warp and became smaller with the growth of warp.

The changes of MPT in different climate states are shown in Fig. 2. In summer, compared with State I, MPT becomes widely warming and obviously in State II mainly in north of China, while in State III the warming trend slows down (cf. Figs. 2(a)–2(c)). In winter, the trend of MPT is similar to that in summer and is more obvious in each climate state. Notice that in State III, the MPT even drops off in some regions of south China. Whether it means climate transformation needs further research.

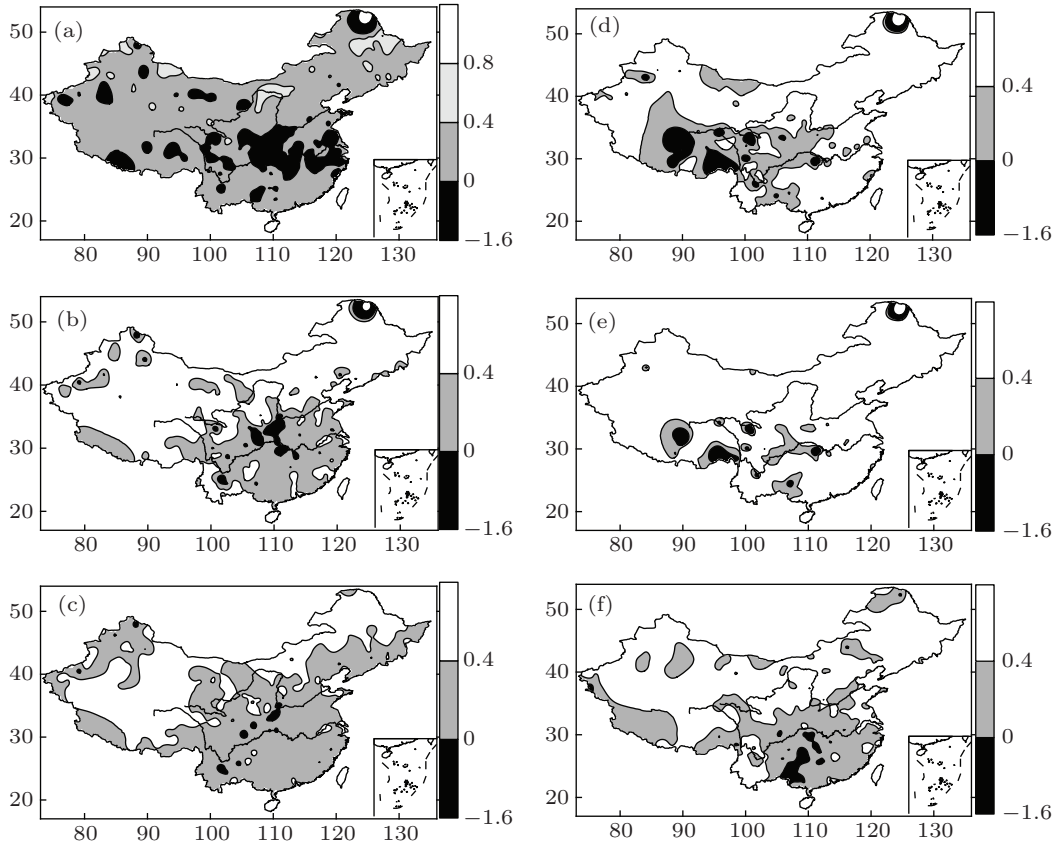


Fig. 2. Difference in MPT among three climate states: States II–I, States III–I, and States III–II respectively in summer (panels (a)–(c)); States II–I, State III–I, and State III–II respectively in winter (panels (d)–(f)).

4. Spatial features of extreme temperature events in different climate states

4.1. Features of frequencies

The frequency of extreme temperature events, i.e., the number of times the lowest temperature recorded a day is above (below) the threshold of HTE (LTE), depends on the threshold of state. The trend coefficient distributions about yearly frequencies of daily minimum temperature records in summer and winter in different climate states are shown respectively in Fig. 3. In State I, the frequencies of HTEs decrease obviously in the lower and middle reaches of the Yellow River, where the minimum trend coefficient is −0.66, and the rate of negative growth is −6.0 umbers/10a, while there are obvious increases in the Guangxi Province, Guangdong Province, and parts of Fujian Province (cf. Fig. 3(a)). In State II, frequencies of HTEs increase widely especially in the north east and the developed regions along the Yangtze River and on the southeast coast. The max-

imum trend coefficient even exceeds 0.7 and the rate of growth is more than 6.5/10a (cf. Fig. 3(b)). In State III, the frequencies of HTEs in most areas over China except the north east increase significantly. So HTEs in the north east are not obvious in the current climate state (cf. Fig. 3(c)).

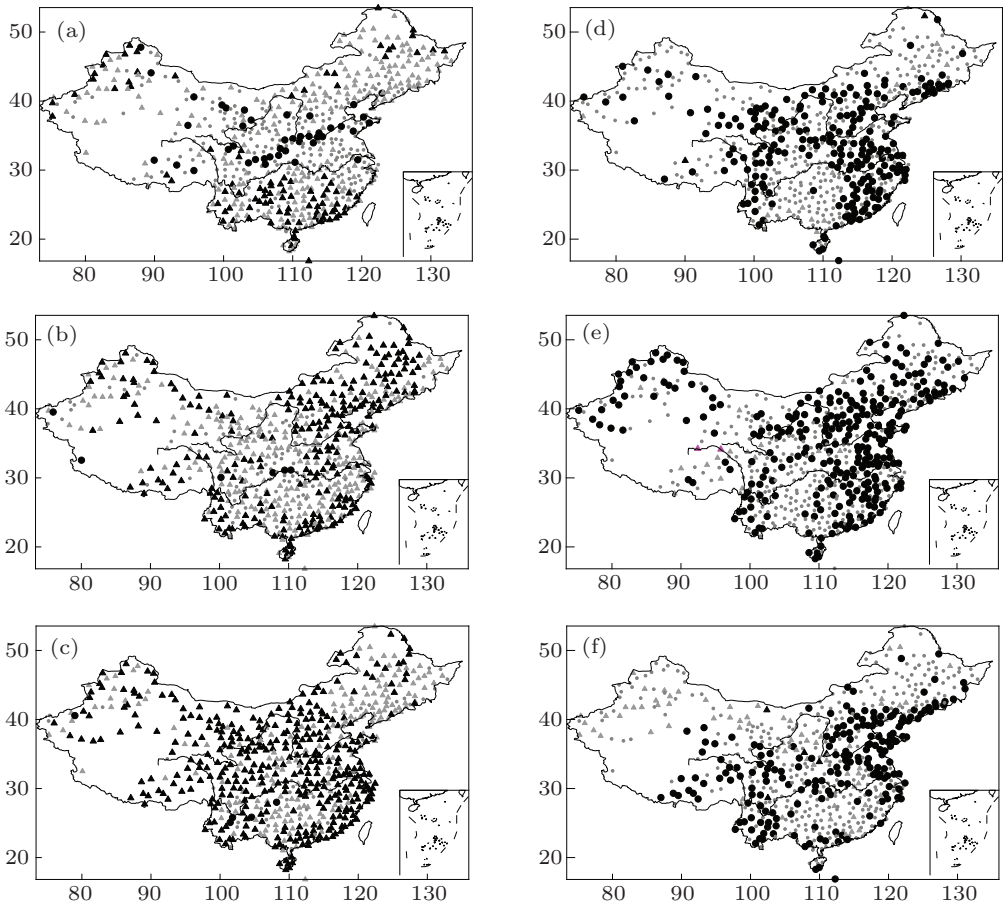


Fig. 3. (a)–(c) Spatial distributions of frequency trend coefficients of extreme HTEs; (d)–(f) spatial distributions of frequency trend coefficients of extreme LTEs. In 0.05 level steps, the stations with trend coefficients bigger than the critical value of 0.35 are marked with black triangles, while those with trend coefficients smaller than −0.35 are marked with black dots.

The frequencies of LTE decline rapidly in State I mainly south of the Yangtze River and in the north of northern China and on the southeast coast (cf. Fig. 3(d)), while the decreasing regions extend to north east in State II (cf. Fig. 3(e)). In State III, the notable regions showing a reduction are mainly in northern China and the regions between the Yangtze River and the Yellow River (cf. Fig. 3(f)).

Compared with the studies on daily maximum records,[18] the growing trend of HTEs and the reducing trend of LTEs concerning daily minimum records are more notable. This shows that the warming trend is more obvious in minimum records than in maximum records. The frequencies of HTEs, in State I, in southern parts of the Yangtze River, start to increase significantly; in State II, in north-east China, along the Yangtze River and south-eastern areas, they rise quickly; in State III, in most of China they grow notably in quantity. The frequencies of LTEs, however, decrease distinctly in most of China in each climate state, especially in State II.

According to previous studies,[7,8,19] the warm days in summer decrease clearly in the Yangtze–Huaihe river valley and the Yellow River and Huaihe river valley; The warm days in winter have increased clearly in northern China. Compared with our results of different states, the frequencies of HTEs decrease in the areas above mainly in State I and those of the LTEs decrease in northern China in State II. In the present state, the increase of HTEs and the decrease of LTEs concentrate on the developed Yangtze River delta and the south-east areas of China.

4.2. Features of strength

The strength of an extreme temperature event is defined as the mean annual value of absolute difference between the extreme temperature value and the threshold, which can denote the extremity of the extreme event. Figure 4 shows that the strengths of HTEs are growing with the climate state. In State I, the positive trends are weak and show that HTE occurrence concentrates near the threshold; while the negative trends are significant in parts of the middle reaches of Yellow River, where the trend coefficient exceeds −0.6, and the rate of decrease is −0.32 °C/10a. In State II, the areas of positive trends especially extend along the lower and middle reaches of the Yellow River and the Yangtze River and on the south-east coast, where the trend coefficient exceeds 0.7 and the rate of growth attains to 0.6 °C/10a. In State III, the areas of significantly positive trends continue to expand, mainly along the Yangtze River and the Yellow River and developed Yangtze River delta.

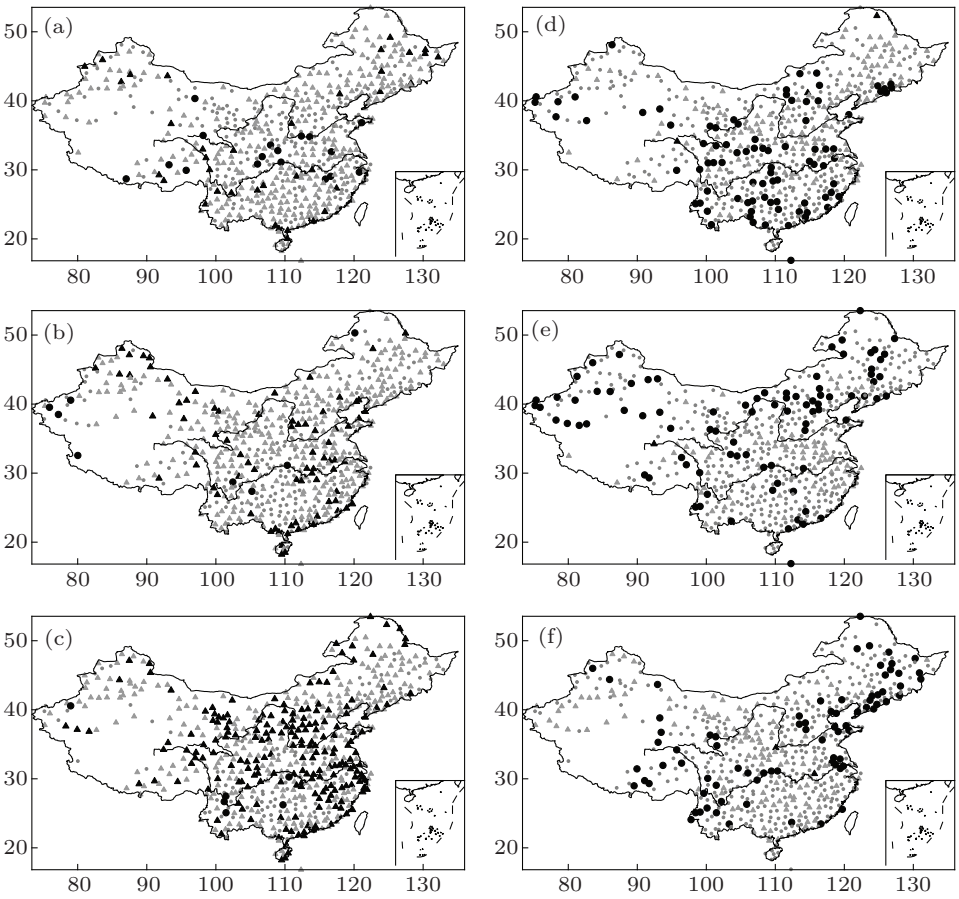


Fig. 4. (a)–(c) Spatial distributions of strength trend coefficients of extreme HTEs; (d)–(f) spatial distributions of strength trend coefficients of extreme LTEs.

For State I, the strengths of the LTEs in the southeastern part of China decrease notably, where the trend coefficient reaches −0.52, and the rate of negative growth is −0.30 °C/10a. For State II, most of China is in a weak LTE trend, but the northern part of China is in a strong trend. For State III, the strength of the LTEs decrease significantly mainly in north China and along the Yangtze River, the trend coefficient exceeds −0.6, the reduction rate is more than −0.52 °C/10a.

Compared with the results of daily maximum records,[18] the regional distribution of strength is strong. In particular, the strength of the HTEs increase rapidly in the Yangtze–Huaihe river valley, the Yellow River and Huaihe River valley, and south-east areas in State III.

In short, the strength of the HTEs decrease significantly in northern China and the Yellow River

and Huaihe River valley in State I, and increases notably in the developed Yangtze River delta in State III, which is consistent with the results of Qian and Huang's work.[8] The strength of the LTEs reduce wholly and the regional difference of the distribution is not obvious. Figures 3 and 4 show that the distributions of frequencies and strengths of extreme temperature events are very consistent spatially, and that the frequencies increase (decrease) in areas where the strength increases (decreases). It is indicated that the extreme temperature events exceeding the threshold are greatly reduced.

5. Evolutions of extreme temperature events in different climate states

In order to find out the evolution laws of extreme temperature events, the change of frequencies and responding regression coefficients every 5 years in each climate state are analysed as shown in Fig. 5 and Table 1. For the daily minimum records, the mean frequencies of HTEs increase rapidly in State II and significantly in State III. The frequency of the LTE decreases weakly in State I and decreases notably in States II and III, but the lowering trend in State III slows down (cf. Table 1).

Table 1. Regression coefficients of the mean frequencies in different climatic states: times/10a (the coefficients in italic type are significant to the 5% level).

	State I	*State II*	State III
HTE	0.18	1.88	2.98
LTE	*–0.72*	*–0.77*	*–0.73*

The changes in frequency show that the frequencies of the HTEs decrease obviously, especially in State III, while the frequencies of the LTEs increase during the period of 1976–1985, which may be related to the climate abruptly changing at the end of the 1970s and beginning of the 1980s.[20] In common intervals of the three climate states, the frequencies of HTEs in the latter state are smaller than the former, while those of LTEs are contrary to the above, which is caused by the background temperature growing with the states changing. At the present state, the frequencies of the HTEs increase quickly and those of the LTEs each show a steadily slowing down trend (cf. Fig. 5).

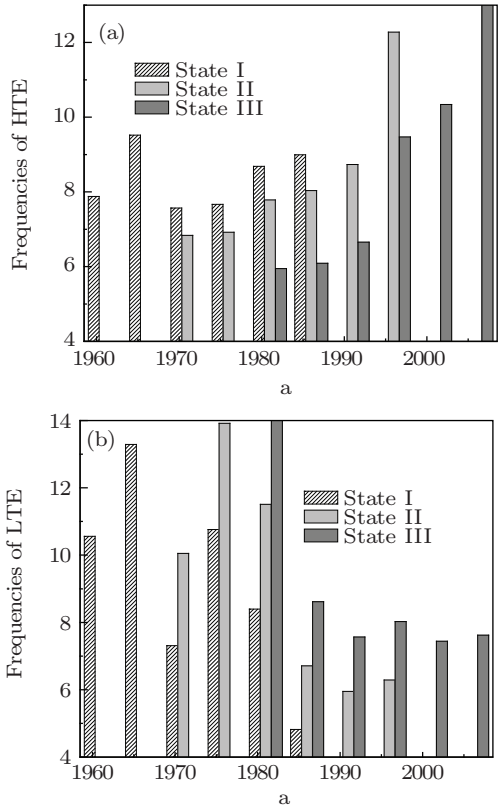


Fig. 5. Time evolutions of the frequencies of extreme temperature events.

The analysis of changes in the strength of extreme temperature events indicates that the strength of the HTE increases obviously in State III, which is consistent with the results of frequencies. The strengths of LTEs weaken significantly in State II and the decreasing trend remains stable and even slows down in State III, (cf. Table 2).

Table 2. Regression coefficients of the mean strength in different climatic states: °C/10a (the coefficients in italic type are significant to the 5% level).

	State I	*State II*	State III
HTE	0.03	0.05	0.10
LTE	*–0.12*	*–0.17*	*–0.15*

The changes in strength are similar to those in frequency (cf. Fig. 6). The strength of the HTEs decrease obviously in the period 1981–1985 and those of the LTEs increase in the period 1976–1985. In three common climatic states, the strengths of the HTEs in the latter state are lower than in the former state while those of LTEs are contrary to the case.

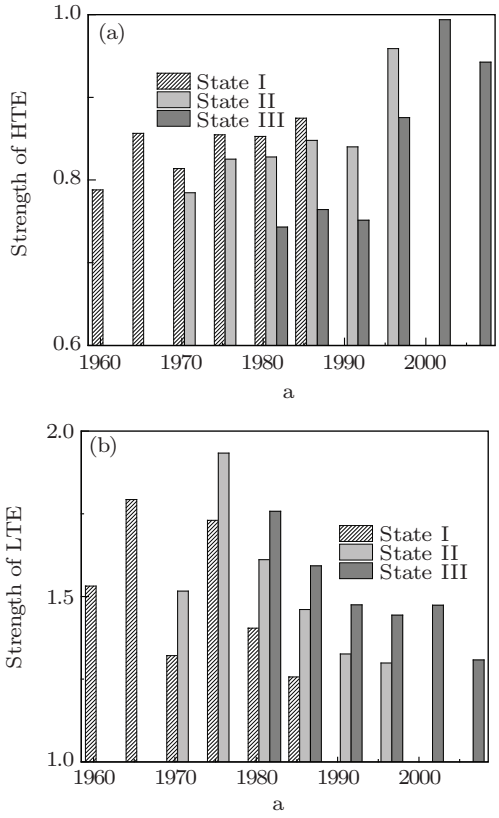


Fig. 6. Time evolution of the strength of extreme temperature events.

In the light of the above definition of extreme events, the extremes of the HTEs become more and more strong with the states changing while those of LTEs are lower and lower, i.e., exceeding threshold events in summer occur more, such as heat waves; while near-threshold events in winter occur so often that the whole LTEs decrease obviously, which is consistent with global warming. The strength of HTEs totally change at about 0.7 °C–1°C and those of LTEs change at about 1.2 °C–1.9°C. It is indicated that the extremes of HTEs are lighter than those of LTEs. Currently the strengths of HTEs each have an increasing trend and the strengths of LTEs change steadily, which reminds us that HTEs should be paid more attention.

6. Conclusions

In this study, 1961–2009 daily minimum temperatures of China are divided into three climate states. The most probable temperature (MPT) as the background temperature for some regions rises and the MPT difference between different climate states indicates that global warming is widely happening and is particularly obvious in State II, mainly in north China; while the warming trend slows down in State III. It is worth noting that in State III, MPT even drops off in part of regions of south China. Whether this means climate transformation needs further research.

Extreme HTEs in summer and extreme LTEs in winter are defined according to the skewed function and their spatiotemporal distribution characteristics of frequencies and strength are analysed.

The frequency of HTEs decreases clearly in the lower and middle reaches of the Yellow River in State I and those of LTEs decrease in northern China in State II. In the present state, the frequencies of HTEs increase significantly in most areas over China except the north east, while the frequency of LTEs decrease in north China and the regions between the Yangtze River and the Yellow River.

The strength of the HTEs decreases significantly in parts of the middle reaches of the Yellow River in State I; they increase notably mainly along the Yangtze River and Yellow River and developed Yangtze River delta in State III. The strength of the LTEs decrease significantly mainly in north China and along the Yangtze River. The distributions of frequencies and strengths of extreme temperature events are consistent spatially. The extreme temperature events greatly exceeding the threshold become less.

Analysis of the time evolution of extreme events shows that the extremes of the HTEs become stronger and stronger with the states changing, while those of LTEs become lower and lower. The extremes of HTEs are lighter than those of LTEs. Currently the strengths of HTEs each have an increasing trend and those of LTEs each have a decreasing trend that slows down and remains stable, which indicates that HTEs are becoming stronger and deserve to be paid special attention.

All the results of daily minimum records are more notable than those of daily maximum records, which indicates that the growing warming trend from daily minimum records is more obvious.

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