Vol.19 No.4 **JOURNAL OF TROPICAL METEOROLOGY** December 2013

Article ID: 1006-8775(2013) 04-0349-08

INVESTIGATION OF THE SPATIAL AND TEMPORAL DISTRIBUTION OF EXTREME HIGH TEMPERATURE IN CHINA WITH DETRENDED FLUCTUATION AND PERMUTATION ENTROPY

YIN Ji-fu (尹继福)[1], ZHENG You-fei (郑有飞)[2], WU Rong-jun (吴荣军)[2, 3], FU Ying (傅　颖)[1],
WANG Wei (王　维)[3]

(1. College of Atmospheric physics, Nanjing University of Information Science& Technology, Nanjing 210044 China; 2. Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Nanjing University of Information Science & Technology, Nanjing 210044 China; 3. College of Environmental Science and Engineering, Nanjing University of Information Science & Technology, Nanjing 210044 China)

Abstract: With temperatures increasing as a result of global warming, extreme high temperatures are becoming more intense and more frequent on larger scale during summer in China. In recent years, a variety of researches have examined the high temperature distribution in China. However, it hardly considers the variation of temperature data and systems when defining the threshold of extreme high temperature. In order to discern the spatio-temporal distribution of extreme heat in China, we examined the daily maximum temperature data of 83 observation stations in China from 1950 to 2008. The objective of this study was to understand the distribution characteristics of extreme high temperature events defined by Detrended Fluctuation Analysis (DFA). The statistical methods of Permutation Entropy (PE) were also used in this study to analyze the temporal distribution. The results showed that the frequency of extreme high temperature events in China presented 3 periods of 7, 10—13 and 16—20 years, respectively. The abrupt changes generally happened in the 1960s, the end of 1970s and early 1980s. It was also found that the maximum frequency occurred in the early 1950s, and the frequency decreased sharply until the late 1980s when an evidently increasing trend emerged. Furthermore, the annual averaged frequency of extreme high temperature events reveals a decreasing-increasing-decreasing trend from southwest to northeast China, but an increasing-decreasing trend from southeast to northwest China. And the frequency was higher in southern region than that in northern region. Besides, the maximum and minimum of frequencies were relatively concentrated spatially. Our results also shed light on the reasons for the periods and abrupt changes of the frequency of extreme high temperature events in China.

Key words: extreme high temperature events; detrended fluctuation analysis; permutation entropy; spatial and temporal distribution

CLC number: P468.0.21 **Document code:** A

1 INTRODUCTION

The linear warming trend over the last 50 years (0.13°C [0.10°C to 0.16°C] per decade) is nearly twice that for the last 100 years, and eleven of the last twelve years (1995—2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850)[1]. Therefore, high temperature events have captured attention from governments and meteorologists[2]. In recent years, a variety of researches have examined the cause of high temperature and its distribution in China. Many scholars have investigated the trend for the number of high temperature days, features of high temperature weather in summer, and variation periods of high temperature frequency in China. In particular, some scholars focused on the reason for a hot weather and its spatial and temporal distribution in Jiangsu, Xinjiang, Shandong, Chongqing, and other regions in Eastern and Northern China[3-15]. However, some scholars defined the threshold of extreme high temperature based on the percentile method of

---

Received 2012-07-11; **Revised** 2013-07-17; **Accepted** 2013-10-15

Foundation item: Key Projects in the National Science & Technology Pillar Program during the Eleventh Five-Year Plan Period (2007BAC29B05); Jiangsu Key Laboratory of Meteorological Disaster (KLME05005)

Biography: ZHENG You-fei, professor, doctoral tutor, primarily undertaking research on environmental meteorology.

Corresponding author: ZHENG You-fei, e-mail: zhengyf@nuist.edu.cn statistics analysis without considering the variation of temperature data and systems[16]. In fact, the climate system is featured by self-memory and climatic sequence with sustainability[16-18]. For better capturing the long-range power-law correlations in the climate event sequence, it is necessary to identify the trend components caused by internal long-range fluctuation. If the trend components are not removed, the strong trend components will distort the results of long-range analysis. Detrended Fluctuation Analysis (DFA) is used to remove the sequence trend before studying its memory characteristics[19]. In addition, the climate system is a giant system with characteristics of nonlinearity, free scales, multiple levels, and complex forced dissipation[20]. Therefore, it is more reasonable to use statistics to examine the climatic characteristics in China for reflecting the uncertainty of climate system changes[21]. Here we used an index called Entropy, which is a thermo-dynamic concept. It can be adopted to describe the chaos degree of thermo-dynamic degree. Among the numerous calculation modes[22], Permutation Entropy (PE) is a complex parameter according to the comparison of adjacent data of longer time series. Its advantage is that it is simple, practical and easy to calculate[25]. PE is primarily applied in medical science[26, 27] in recent years. In addition, lots of scholars have declared that PE is extremely reliable in detecting abrupt changes and identifying temperature periods[22, 28].

The study on the temporal-spatial structure of temperature variability not only can help to further understand the characteristics of climate changes, but also has practical application in understanding and predicting climatic disaster risks[23]. Thus, in this paper, the threshold of extreme high temperature at every station is defined by the DFA method. The period and abrupt change of regional frequency of extreme high temperature are analyzed by the PE method. The study objective is to contribute to the development of operational warning systems against extreme high temperature weather in cities, which is significant to improving public service and people's life quality.

2 MATERIALS AND METHODS

2.1 *Materials*

Observed temperature is quite sensitive to anthropogenic activity. For example, station relocation could lead to dataset inhomogeneity. Therefore, the China Meteorological Administration (CMA) National Meteorological Information Center (NMIC) started in 2006 to release the homogenized historical temperature datasets of China (1951—2004). This study adopts this data with relatively good homogeneity provided by CMA.

According to the missing data principle that the continuous lack of observation is less than 182 days and accumulated absence of observation is not more than 1 year, 77 stations are eligible to be used in defining the high temperature events. The observation data at Golmud in Qinghai (from April of 1953 to 2008), Madoi in Qinghai (from 1953 to 2008), Xining in Qinghai (from 1954 to 2008), Tianjin (from 1954 to 2008) and Lhasa in Tibet (from 1955 to 2008) are supplemented to complete the space information. Besides, the data at Shanghai station is only from 1991 to 2008, while Longhua station misses data from 1997 to 2006. Considering Shanghai is very important for both Yangtze River Valley and even the whole country and the distance between Longhua and Shanghai is relatively small, the data at Shanghai site (1997-2006) is merged with the time sequence of Longhua meteorological station. Eventually, there are a total of 83 stations (Table 1).

2.2 *Detrended Fluctuation Analysis (DFA)*

DFA is a method based on both the new development of the theory of random process and chaotic dynamics. It is usually applied to detect the physical characteristics of time series. From a dynamics perspective, the sequence derived from the method keeps certain characteristics of the original sequence. Specifically, the persistence or anti-persistence quality of the derived sequence is the same as that of the original sequence[16]. The traditional methods may be responsible for less reliable analysis results because of some trend components or noise of the observed meteorological data which is usually non-stationary. In contrast, DFA has a great advantage on the analysis of such series with trend components[19]. As a tool for scale analysis, DFA can effectively filter the trend components in each scale to process unstable data and eliminate spuriously correlated phenomena remarkably. Therefore, DFA can examine the correlation of non-stationary time sequences. Based on Yang's research, the threshold of extreme high temperature can be defined by DFA as follows[16].

①Determine the maximum value (x_{max}) of a series (x_i);

②Identify a medium value (R) of the series x_i, where R can be the average value of the series (x_{ave}) or a certain R value (x_{med}) between the x_{max} and minimum value of the series (x_{min});

③Remove data in the interval $\{x_i, x_i \geq x_{max}-d\times k\}$ successively until $x_{max} = R$ to obtain a new series Y_J ($J = x_{max}-d\times k$) each time, where $k = 1, 2, ..., (x_{max}-R)/d$, and d is the interval size;

④Determine the variation of D_J related to the change of interval J by calculating the long-range correlation coefficient D_J of every new series Y_J;

⑤The threshold is defined as the value of D_J

changes tending to stabilize and converge; and

⑥The interval size d represents the resolution of this method. The smaller the value d takes, the higher the threshold resolution and the more complex the computation become. When k is small, the threshold resolution is relatively small. Conversely, when k and the threshold resolution are small, the computational complexity is relatively low. Considering the accuracy and range of temperature in summer, k and R are set as 1000 and 15.0℃ in this study, respectively.

Table 1. Threshold of extreme high temperature at stations determined by the DFA method.

Station	Threshold/℃	Station	Threshold/℃
Jiuyang, Chongqing	35	Zhijiang, Hunan	36.9
Shapingba,Chongqing	39.3	Lingling, Hunan	38.6
Quzhou,Zhejiang	38.4	Changde, Hunan	38.2
Hangzhou, Zhejiang	38.1	Yichang, Hubei	38.4
Tengchong,Yunnan	28.9	Wuhan, Hubei	37.5
Mengzi, Yunnan	33.4	Laohekou, Hubei	38
Lijiang, Yunnan	28.8	Qiqihar, Heilongjiang	34.6
Kunming, Yunnan	29.2	Nenjiang,Heilongjiang	33.7
Chuxiong, Yunan	30.8	Mudanjaing,Heilongjiang	33.9
Urumqi, Xinjiang	37.3	Keshang, Heilongjiang	33.2
Qitai, Xinjiang	37.5	Jixi, Heilongjiang	33.7
Kuche, Xinjiang	37.5	Haerbin, Heilongjiang	34.4
Kashgar,Xinjiang	36.5	Zhengzhou, Henan	38.2
Kami, Xinjiang	40.1	Xinyang, Henan	37.3
Lasha,Tibet	27.3	Anyang, Henan	38
Tianjin	36.9	Chengde, Hebei	36.4
Yinchuan, Ningxia	34.8	Haikou, Hainan	37.1
Dalian, Liaoning	31.6	Beijing	37.3
Dandong, Liaoning	32.3	Changchun, Jilin	34.2
Jinzhou, Liaoning	34.6	Siping, Jilin	33.4
Shenyang, Liaoning	34	Yingkou, Liaoning	32.7
Burke, Inner Mongolia	32.1	Pingliang, Gansu	32.9
Tongliao, Inner Mongolia	35.6	Lanzhou, Gansu	35.3
Wuzhou, Guangxi	36.9	Jiuquan, Gansu	34.6
Nanning, Guangxi	36.4	Dunhuang, Gansu	38.6
Guilin, Guangxi	36.7	Bijie, Guizhou	32.2
Baise, Guangxi	38.5	Xingyi, Guizhou	32
Shaoguan, Guangdong	37.8	Guiyang, Guizhou	33.2
Nanping, Fujian	38.2	Yibin, Sichuan	36.7
Longhua, Shanghai	36.9	Songpan, Sichuan	28.6
Yulin, Shanxi	35.6	Nanchong, Sichuan	38.3
Xian, Shanxi	35.8	Xichang, Sichuan	33.9
Hanzhong, Shanxi	35.4	Ganzi, Sichuan	27.7
Taiyuan, Shanxi	34.8	Hohhot, Inner Mongolia	34
Yanzhou, Shandong	37.5	Hailar, Inner Mongolia	33.8
Weifang, Shandong	36.8	Chifeng, Inner Mongolia	36.3
Jinan, Shandong	38.2	Zunyi, Guizhou	35.1
Huiming, Shandong	37.6	Ganzhou, Jiangxi	38.2
Xining, Qinghai	30.6	Nanjing, Jiangsu	37.2
Maduo, Qinghai	19.7	Guangzhou, Guangdong	36.3
Gelmud, Qinghai	31.4	Wudu, Gansu	36.1
Wuqiaoling, Gansu	23.9		

2.3 *Permutation Entropy (PE)*

According to Hou's study, the PE algorithm can be summarized as follows[28].

①Assume a discrete time series x_i, i=1, 2, ..., n, and reconstruct the phase space of every series element to obtain:

$$X(i)=\left[x(i),x(i+1)\ldots\ldots,x(i+(m-1)l)\right] \quad (1)$$

where m is the embedded dimension and l is the delay time.

②Rearrange the reconstructed components of $X(i)$ in ascending order to get a symbol sequence:

$$A(g)=\left[j_1,j_2,\ldots\ldots,j_m\right] \quad (2)$$

in which g = 1, 2, ..., k and $k \le m!$

There are $m!$ permutations for m with different signs. The probability of every symbol series is denoted as P_1, P_2, ..., P_n. In accordance with the form of Shannon information entropy, we define

$$H_p(m)=\sum_{v=1}^{k} p_v \ln p_v \quad (3)$$

③When $P_v=1/m!$, $H_p(m)$ reaches the maximum value $\ln(m!)$, we can obtain the following relation by standardized treatment

$$0 \le H_p = H_p(m)/\ln(m!) \le 1 \qquad (4)$$

Bandt and Pompe have showed that PE algorithm would lose its validity for $m \le 4$ and it is not appropriate to take large value of m (such as $m = 12$). Thus m is 7 in this study[23].

3 RESULTS AND DISCUSSION

In this study, an extreme high temperature event is defined as one for which the daily maximum temperature is above the threshold according to DFA, and the result is showed in Table 1. Consequently, we obtained the spatio-temporal distribution of annual extreme high temperature frequency (AEHTF) in China from 1951 to 2008 (Figs. 1 and 2). Fig. 1 clearly showed that the AEHTF was higher in the early 1950s and then sharply dropped until the end of the 1970s and early 1980s when it began to present an increasing trend. Chen et al.[29] conducted a comprehensive analysis on the characteristics of climate change in China in the past few decades and claimed that China experienced the first warm period in the 1940s, subsequently witnessed sharp temperature decrease in the 1950s, which was followed by fluctuations until the 1980s when it began to record sharp increases again[30]. This may be caused by the fact that sunshine hours over the Chinese mainland and global solar radiation decreased from the 1950s to the 1980s and then both of them increased after the 1980s[31-34]. Fig. 2 showed that the annual mean frequency of extreme heat presents a decrease-increase-decrease trend from Southwest to Northeast China but an increase-decrease trend from Southeast to Northwest China. Besides, it was also found that the higher values of AEHTF primarily appeared in Yunnan, Guangxi, Guangdong, Henan and Southern Hebei. However, smaller values mainly scattered in Guizhou and Gansu provinces and Inner Mongolia Autonomous Region. In general, the frequency of extreme high temperature events in the southern China is higher than that in the northern China and high and low frequencies are concentrated spatially.

In order to further analyze the regional characteristics, the Chinese mainland was divided into 10 regions according to the tempo-spatial distribution of AEHTF (Fig. 3). They were (A) Junggar Region, (B) Northeast Region, (C) East of Junggar Region, (D) East of Southwest Region, (E) West of Southwest Region, (F) Beijing-Tianjin-Hebei Region, (G) Southeast Region, (H) Central South Region, (I) Taihang-Qinling mountains Region, and (J) South China Region, respectively. This was mostly consistent with Gong's regionalization[35] based on the index of dynamical autocorrelation factor and Xiang's regionalization[36] based on Rotated Empirical Orthogonal Function (REOF) and Cluster Analysis Method from Center for Advanced Spatial Technologies (CAST), University of Arkansas, USA.

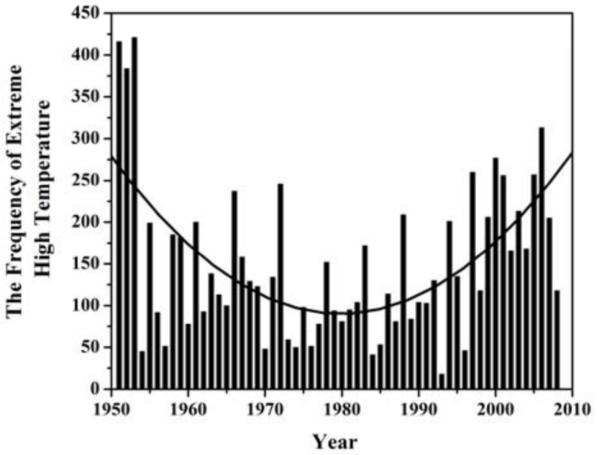

Figure 1. Temporal distribution of annual mean frequency of extreme heat events in China from 1951 to 2008.

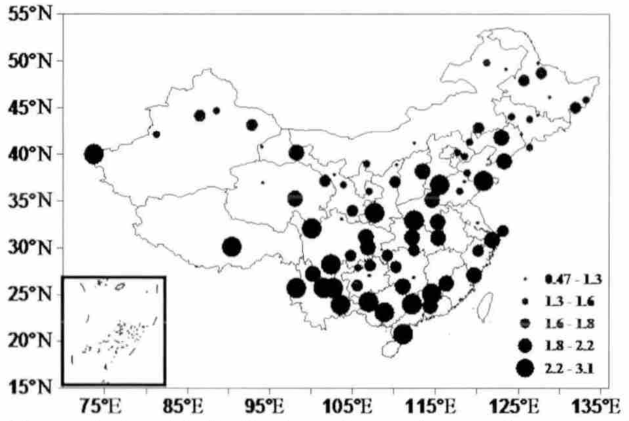

Figure 2. Spatial distribution of annual mean frequency of extreme heat in China from 1951 to 2008.

Because the maximum missing duration of the six added stations was 4 years, PE was calculated from 2008 to 1956 and standardized according to Eq. (4). Fig. 4a showed that the AEHTF for Junggar Region had a quasi 10—11-year period with mutations occurring in 1963 and 1994. A 14—15-year period variation was present in Northeast Region (primarily a 14-year period) and the mutation occurred from 1960 to 1964 (Figure 4b). We also found that AEHTF presented a 10-year period first and a 13—15-year period after with mutations occurred in 1969 and 1978—1980 in the east of Junggar Region (Fig. 4c). In addition, AEHTF's first period was 13—14 years and its second period was 18—20 years in the east of Southwest Region with mutations in 1984—1985 (Fig. 4d). Fig. 4e clearly demonstrated that there were 3 stable periods in the west of Southwest Region which was 7, 9 and 13—14 years respectively, and its mutation years were 1965 and 1976—1979. The first and second period of AEHTF were 7 years and 10 years in Beijing-Tianjin-Hebei Region, respectively, which were small relative to other regions; low HP lasted for 2 years from 1980 (Fig. 4f). In addition, 2 stable periods of Southeast Region were 11—13 years and 15 years (primarily 13-year), and the mutations occurred in 1977—1978 (Fig. 4g). There were 3 periods in Central South Region (Fig. 4h) which were quasi-8-year, quasi-10-year and quasi-11-year with the mutation in 2007. Fig. 4i showed that the first and second period of AEHTF were 13 years and 16 years and only one mutation appeared in 1979 in Taihang-Qinling Mountains Region. Besides, double periods for South China Region were 10 years and 15 years and the mutations in this region occurred in 1966—1970, 1976 and 1979.

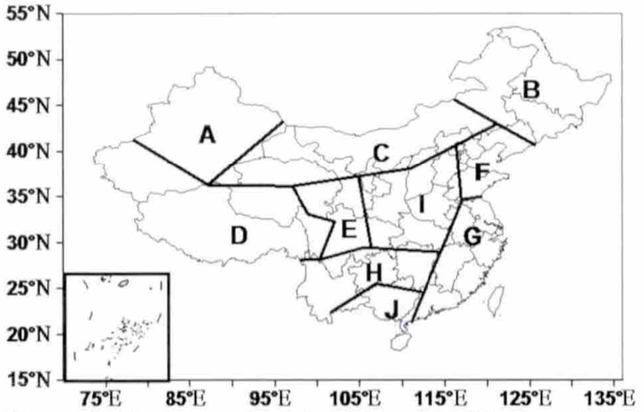

Figure 3. The ten regions divided in the Chinese mainland according to the spatio-temporal distribution of extreme heat frequency.

Dong et al.[37] studied the characteristics of spatial and temporal distribution of temperature variation based on a 50-year dataset (including the 91 stations) using MHF wavelet analysis, nonparametric statistical Mann-Kendall and Yamamoto method. Dong claimed that the 14-year period oscillation of temperature variation was stronger in Northeast Region with mutation in 1964. The climatic characteristics for high temperature frequency in Guangzhou from 1951 to 2004 were analyzed according to the EOF and correlational analysis method by Liu et al.[38]. The results showed that high temperature frequency in Guangzhou steadily increased from 1980 and a positive mutation occurred in 1980. Besides, Jiang et al.[39] detected and reconstructed a regional average temperature series at the global level using multiple spectrum and claimed that there was quasi-10.3-year interdecadal variability in the northern region of China. All of these studies are consistent with our results in this paper, which clearly confirms that PE is reliable and scientific.

Figure 4 clearly showed that there were mainly 3 periods in every region from 1956 to 2008, which were quasi-7, quasi-10-13 and quasi-16-20 years. Besides, we also found that 7 years and 10—13 years correspond to the ENSO and solar activity period, respectively, both of which have great influence on global and Chinese climate change. Hou et al.[28] found that the period of AEHTF was related to solar activity periods and 10-year climatic variabilities. As a meteorological element, temperature is influenced by various factors, such as solar activity, earth rotation, and various teleconnection indices[16]. However, previous studies indicated that the frequency of high temperature and its progress were all impacted by atmospheric circulation[38, 40]. In addition, the high temperature becomes more intense and frequent and on larger scale during summer in China when the summer monsoon is strong[41, 42], because there is a significant relationship between the subtropical high and the intensity of tropical summer monsoon in East Asia. The cross-equatorial flow of Western Pacific Region that has an effect on the temperature in China presents oscillations of 10—11 years and quasi-20 years, the zonal wind of mid-level 500 hPa and low-level 850 hPa mainly shows a 17-year decadal oscillation, and the meridional wind reveals quasi-7-year and quasi-13-year periods in summer[43].

The mutations of every region mainly occurred in the 1960s, the end of 1970s and the early 1980s, which corresponds to the results of a climatic jump in Lin[44] and the spatio-temporal distribution of dynamic structure mutation for surface temperature in He[45]. The mutations widely happened during the 1960s in the Northern Hemisphere (NH). There were connections at the planetary scale between the mutation of every region: this was caused by the cooling at mid- and higher-latitudes and the warming at mid- and lower-latitudes in NH, and as a result thermal gradients at high latitudes increased rapidly in the early 1960s[46]. In response, the mutations of AFEHT appeared during the same period. Besides, it was also believed that the mutations during the end of 1970s and the early 1980s were related to the conditions of solar activity[45]. In addition, the mutations in this period well responded to the different trend of sunshine hours before and after this period in China[31-34] and the overall trend of global temperature around the 1980s.

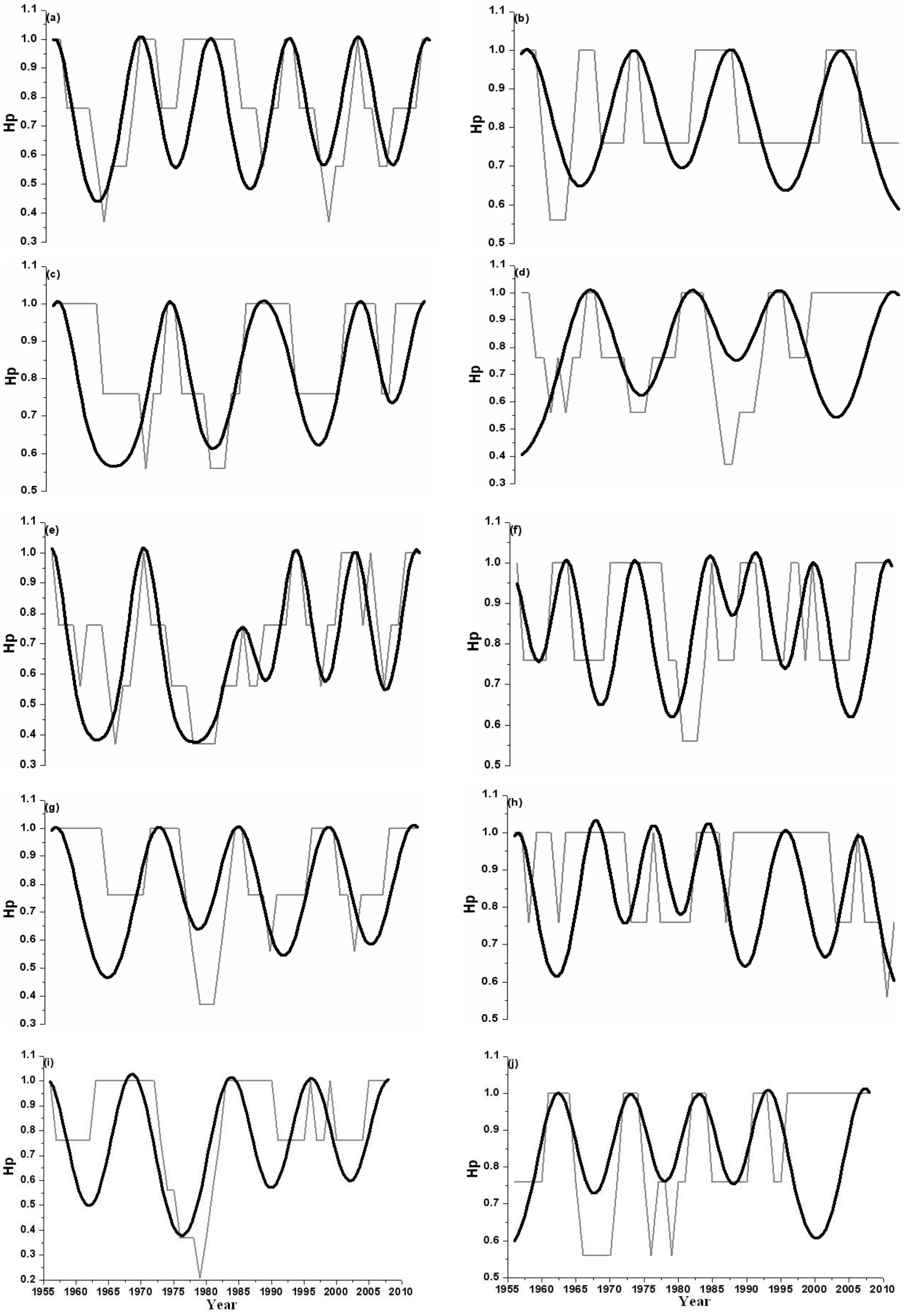

Figure 4. The variation of standardized H_p in the specific regions ((a) to (j) is for Junggar Region, Northeast Region, East of Junggar Region, East of Southwest Region, West of Southwest Region, Beijing-Tianjin-Hebei Region, Southeast Region, Central South Region, Taihang-Qinling mountains Region and South China Region, respectively.

4 CONCLUSIONS

(1) The annual average frequency of extreme high temperature presented a decreasing-increasing-decreasing trend from Southwest to Northeast China, and an increasing-decreasing trend from Southeast to Northwest China. The frequency was higher in the southern region than in the northern region. Besides, the maximum and minimum frequencies were relatively concentrated spatially.

(2) Quasi-7, quasi-10-13 and quasi-16-20 years were the three primary oscillation periods for the AEHTF from 1956 to 2008 in China. There are a number of possible reasons: the variation in meridional wind at mid- and lower-level from June to August, climate decadal variability, ENSO, solar activity and zonal wind of cross-equatorial flow in Western Pacific Region.

(3) The mutation of extreme high temperature mainly appeared in the 1960s, end of 1970s and early 1980s, which coincided with the extensive mutation of climate conditions during the 1960s in NH and the overall trend of sunshine hours and global temperature around the 1980s.

Acknowledgement: The authors are grateful to the National Meteorological Information Center of the China Meteorological Administration for providing daily maximum temperature data and thank two anonymous reviewers for their comments on an earlier version of the manuscript.

REFERENCES:

[1] IPCC. Summary for Policymakers. [R]// Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge: Cambridge University Press, 2007.

[2] LIN Xin, GUAN Zhao-yong. Temporal-spatial characters and interannual variations of summer high temperature in East China [J]. J. Nanjing Inst. Meteor., 2008, 31(1): 1-9.

[3] GAO Rong, WANG Ling, GAO Ge. The trend variation in high temperature days during 1956-2006 in China [J]. Adv. Clim. Change Res., 2008, 4(3): 177-181.

[4] NIU Ruo-yun, GUO Wen-hua. The characteristics analysis of high temperature in China in the summer of 1997 [J]. Meteor. Mon., 24(8): 44-49.

[5] SHI Jun, DING Yi-hui, CUI Lin-li. Climatic characteristics and their changing law during summer high temperature-times in East China [J]. Acta Geograph. Sinica, 2008, 63(3): 237-246.

[6] ZHANG Tian-yu, CHENG Bing-yan, LIU Xiao-ran, et al. Variability of extreme high temperature and response to regional warming over Chongqing [J]. Meteor. Mon., 2008, 34(2): 69-76.

[7] LIN Xi. The temporal-spatial variations of hot summers in East China [D]. Nanjing University of Information Science & Technology, 2007: 1-63.

[8] ZOU Jin, WANG Qi. Interdecadal variability of summer high-temperature anomaly in Shandong province [J]. J. Shandong Meteor., 2005, 25(100): 5-8.

[9] SHI Zhen-bin, DONG Xu-guang, SHI Xing-wang, et al. Climatic characteristics of high temperature in past 50 years in jinan [J]. J. Meteor. Environ., 2007, 30(Suppl.): 95-97.

[10] WU Bin. The characteristics of the 50-year climate variaty in Fujian province [D]. Nanjing: Nanjing University of Information Science & Technology, 2005: 4-65.

[11] WANG Zuo-dong, YANG Qing, GONG Huan-sheng, et al. Analysis of summer temperature anomaly in 1999 and 2003 in northern China [J]. J. Meteor. Environ., 2006, 22(5): 6-9.

[12] YU Yue-fei. The study of the local climate in Xinjiang [D]. Zhejiang University, 2006: 1-56.

[13] HU Chun-li. Variations of temperature and precipitation in Xinjiang in past 45 Years [D]. Nanjing University of Information Science & Technology, 2007: 4-49.

[14] LI Qin. The analysis of last 50-year climate variability in Urumqi [D]. Xinjiang University, 2006: 1-49.

[15] WANG Yue-nan, HE Jin-hai, JIANG Ai-jun. A study on the climatic features of the summer persistence high temperature concentration in Jiangsu province [J]. J. Trop. Meteor., 2009, 25(1): 97-103.

[16] YANG Ping, HOU Wei, FENG Guo-lin. Determining the threshold of extreme event with Detrended Fluctuation Analysis [J]. Sci. Phys. Sinica, 2008, 57(8): 5333-5343.

[17] CAO Hong-xing. The self-memorization equation of atmospheric motion [J]. Sci. China (Ser. B), 1993, 23(1): 104-111 (in Chinese).

[18] SHUKLA J. Predictability in the midst of chaos: A scientific basis for climate forecasting [J]. Science, 1998, 282: 728-731.

[19] ZHENG Zuo-fang, ZHANG Xiu-li, CAO Hong-xing. Characteristics of climate change in Beijing with Detrended Fluctuation Analysis [J]. Chin. J. Geophys., 2007, 50(2): 420-424.

[20] GUO Yan-juan, YANG Xiu-qun. Temporal and spatial characteristics of interannual and interdecadal variations in the global ocean-atmosphere system [J]. Sci. Meteor. Sinica, 2002, 22(2): 127-139.

[21] YU Yi-ming, TIAN Ying. The application of entropy analysis on meteorology [J]. J. Guizhou Meteor., 1997, 21(5): 42-44.

[22] HAO Cheng-yuan, WU Shao-hong, LI Shuang-cheng. Measurement of climate complexity using permutation entropy [J]. Geograph. Res., 2007, 26(1): 46-52.

[23] WU Sheng-an, JIANG Zhi-hong, TU Qi-pu. Summer and winter temperature variability and their impacts on regional warming stability in China in recent 44 years [J]. J. Nanjing Inst. Meteor., 2002, 25(6): 830-836.

[24] WANG Qi-guang, ZHI Rong, ZHANG Zeng-ping. The research on long range correlation of Lorenz system [J]. Sci. Phys. Sinica, 2008, 57(8): 5343-5340.

[25] BANDT C, POMPE B. Permutation entropy: A natural complexity measure for time series [J]. Phys. Rev. Lett., 2002, 88(174102): 1-4.

[26] SCHWARTZ T U, WALCZAK R, BLOBEL G. Circular permutation as a tool to reduce surface entropy triggers crystallization of the signal recognition particle receptor β subunit [J]. Protein Sci., 2004(13): 2814-2818.

[27] PARDO E, TOVAR F, MAXENPER J R. A program for maximum entropy spectral estimation with assessment of statistical significance by the permutation test [J]. Comput. & Geosci., 2005(31): 555-567.

[28] HOU Wei, FENG Guo-lin, DONG Wen-jie, et al. Regional characteristics of the decadal and interdecadal variations for global temperature field during the last century [J]. Sci. Phys. Sinica, 2006, 55(5): 2663-2668.

[29] CHEN Long-xun, ZHU Wen-qin, WANG Wen. Study on

climate change of China over the past 45 years [J]. Acta Meteor. Sinica, 1998, 56(3): 257-271(in Chinese).

[30] ZHANG Xian-gong, LI Xiao-quan. Some features of air temperature change over China [J]. Acta Meteor. Sinica, 1982, 40(2): 198-208.

[31] CHEN Zhi-hua. Study on surface solar radiation during 1957-2000 over China [D]. Institute of Atmospheric Physics, Chinese Academy of Sciences, 2005: 1-72.

[32] WEN Xiao-hang, SHANG Ke-zheng, WANG Shi-gong, et al. A primary study on characteristics of solar radiation region during 1961-2000 in China [J]. J. Desert Res., 2008, 28(3): 554-561.

[33] WANG Ya-jie, HUANG Yao, ZHANG Wen. The change trend of surface global radiation during 1961-2003 in mainland China [J]. Clim. Environ. Res., 2009, 14(4): 405-413.

[34] ZHANG Shang-yin, WANG Shou-rong, ZHANG Yong-shan, et al. Climatic character of high temperature and the prediction in large cities of east of China [J]. J. Trop. Meteor., 2004, 20(6): 750-760.

[35] XIANG Xun, WANG Ji, WANG Xu-xin, et al. Research of temporal-spatial variation and distribution of extreme temperature index in China [J]. Meteor. Mon., 2008, 34(9): 73-80.

[36] GONG Zhi-qiang, FENG Guo-lin. Regional Characteristics of Temperature Changes in China During the Past 58 Years and Its Probable Correlation With Abrupt Temperature Change [C]// Chinese Meteorology Society Annual Meeting, 2007: 775-768.

[37] DONG Man-yu, WU Zheng-fang. Analysis of temporal and spatial characteristics of temperature change over the last 50 years in northeast China [J]. Res. Sci., 2008, 30(7): 1093-1099.

[38] LIU Yan, CHENG Zheng-quan, CAI An-an. Analysis of mid-summer high temperature frequency anomaly in Guangzhou [J]. J. Trop. Meteor., 2006, 22(6): 553-559.

[39] JIANG Zhi-hong, LI Jian-ping, TU Qi-pu, et al. Regional characteristics of the decadal and interdecadal variations for global temperature field during the last century [J]. Chin. J. Atmos. Sci., 2004, 28(4): 545-548.

[40] SHI Jun, CUN lin-li, ZHOU Wei-dong. Characteristics of atmospheric circulation in association with high temperature over east China [J]. J. Trop. Meteor., 2009, 25(6): 753-759.

[41] GAO Hui, ZHANG Fang-hua. The Comparison about East Asian Monsoon Indices [J]. J. Trop. Meteor., 2003, 19(1): 79-86.

[42] LU Jun-mei, REN Ju-xin, JU Jian-hua. Interdecadal variation of East-Asian summer monsoon and its impact on rainfalls of China [J]. J. Trop. Meteor., 2004, 20(1): 73-80.

[43] GU Ze. Approaches to several problems about the abnormal features of the global wind fields climatic change [D]. Nanjing University of Information Science & Technology, 2006: 1-77.

[44] LIN Xue-chun. The Climate Jump in the Late 70's and Early 80's and Its Effect//East-Ascian Monsoon and China Rainstorm [M]. Beijing: China Meteorological Press, 1998.

[45] HE Wen-ping. The Research and application of the abrupt detecting methods in dynamical structures [D]. Lanzhou University, 2008: 1-134.

[46] YAN Zhong-wei, JI Jin-jun, YE Du-zheng. The summer climate jump in the Northern Hemisphere in the 1960s—I. Change of rainfall and temperature [J]. Sci. China (Ser. B), 1990(1): 97-103 (in Chinese).

Citation: YIN Ji-fu, ZHENG You-fei, WU Rong-jun et al. Investigation of the spatial and temporal distribution of extreme high temperature in China with detrended fluctuation and permutation entropy. *J. Trop. Meteor.*, 2013, 19(4): 349-356.