Postprint: Variation Characteristics and Influencing Factors of Compound Day-Night High Temperature Events in Xi' an Based on MF-DFA

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Abstract

Using multifractal detrended fluctuation analysis (MF-DFA) and extreme-point symmetric mode decomposition (ESMD), the variation characteristics of compound day-night high temperature events in Xi' an from 1955 to 2019 were analyzed. The results show that: (1) Meteorological station relocation caused an underestimation of the extreme high temperature trend in Xi' an. Specifically, the maximum temperature threshold for raw data is identical to that for the corrected series; after correction, the minimum temperature threshold is relatively lower by 0.2–0.5°C. (2) The MF-DFA, 90.0% and 95.0% threshold schemes exhibit similarity in identifying interdecadal variations of high temperature events, whereas the 99.0% threshold and relative threshold schemes constitute the main sources of uncertainty in the conclusions. (3) Regarding variation characteristics, compound day-night high temperature events in Xi' an exhibit both interannual fluctuations of 3.3–3.8 years and trend changes; since the mid-1980s, the number of compound day-night high temperature days has shown a significant increase. (4) Sea surface temperature anomalies in the equatorial western Pacific can serve as a key oceanic region for early warning of compound day-night high temperature events in Xi' an. That is, when sea surface temperature anomalies in the equatorial western Pacific are abnormally high, they often correspond to periods of frequent compound day-night high temperature events in Xi' an. It is also indicated that the northward shift of the South Asian high and the westward extension of the western Pacific subtropical high are the circulation mechanisms affecting persistent compound day-night high temperature events in Xi' an.

Full Text

Variation Characteristics and Influencing Factors of Compound Hot Extremes at Daytime and Nighttime in Xi' an Based on MF-DFA

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Abstract: Refining extreme weather processes is crucial for improving research methods and regional adaptation measures. However, it remains challenging to classify historical warming into more sophisticated extreme event categories. Based on daily temperature data (Tmax and Tmin) from 22 meteorological stations in Xi' an City and surrounding areas, this study identifies three types of summertime hot extremes: independent hot days, independent hot nights, and compound hot extremes. Using multifractal detrended fluctuation analysis (MF-DFA) and extreme-point symmetric mode decomposition (ESMD), we analyze the variation characteristics of compound hot extremes at daytime and nighttime in Xi' an from 1955 to 2019 and examine their influencing factors.

The results show that: (1) The highest temperature threshold remains identical between original and homogenized data for Xi' an, while the minimum temperature threshold is 0.2–0.5°C lower after homogenization. Consequently, the relocation of Xi' an meteorological station between urban and suburban areas from 1959 to 2005 resulted in an underestimation of extreme temperature trends. (2) The MF-DFA, 90.0%, and 95.0% threshold schemes perform similarly in identifying high temperature events, whereas the 99.0% threshold and relative threshold schemes constitute the primary sources of uncertainty. (3) From 1955 to 2019, compound hot extremes exhibited both interannual fluctuations and trend changes with a periodicity of 3.3–3.8 years. The number of compound hot extreme days increased significantly after the mid-1980s, while normal days and independent hot days decreased, and independent hot nights and compound hot extremes increased. (4) Sea surface temperature (SST) anomalies in the equatorial western Pacific can serve as a key predictor for compound hot extremes in Xi' an. Circulation analysis of events lasting more than five days confirms the reliability of equatorial western Pacific SST anomalies as early warning information. Additionally, we find that the northward shift of the South Asian High and westward extension of the Western Pacific Subtropical High constitute the specific circulation mechanisms for regional compound hot extremes. This study provides a theoretical and methodological basis for urban climate adaptation by revealing the variation characteristics of compound hot extremes in Xi' an from 1955–2019 and the circulation features of events persisting more than five days.

Keywords: climate change; compound hot extremes at daytime and nighttime; El Niño; Xi' an City

1 Introduction

Under global warming, extreme weather events occur frequently and exhibit characteristics of suddenness, difficulty in prediction, and early warning challenges. The statistical classic "Simpson' s Paradox" reveals that "conclusions satisfying group discussions under specific conditions may reverse when combined." Consequently, many climate researchers have attempted to subdivide extreme climate events to analyze the response relationship between regional warming and extreme weather events. For instance, based on extreme precipitation processes, events can be classified as forward-biased, backward-biased, balanced, and single-day types. According to diurnal anomaly characteristics of extreme heat, heatwaves can be categorized as day-hot/night-cool, day-cool/night-hot, and compound types. Evidently, refining extreme weather processes provides insights for improving research methods and designing regional adaptation strategies for global warming.

Currently, three primary methods exist for determining extreme events: absolute threshold, relative threshold, and standard deviation methods. Among these, the relative threshold method is most widely applied, using the 90.0%, 95.0%, or 99.0% percentile to define extreme weather events, thereby avoiding defects of absolute thresholds. However, different interpretations exist regarding threshold methods—whether thresholds should be derived from all temporal meteorological elements or from daily thresholds (e.g., all years for a specific date). As criteria for extreme temperatures, these two approaches yield different results. To enhance objectivity in threshold determination and integrate long-range correlations in climate systems, multifractal detrended fluctuation analysis (MF-DFA) has been proposed and applied to extreme temperature and precipitation events, providing new perspectives for identifying extreme weather events.

Xi' an City, located in the Guanzhong Plain, features a warm temperate semi-humid continental monsoon climate. The topographic conditions of the Weihe River Valley coupled with anthropogenic heat release from urbanization make extreme heat intensity significantly higher than surrounding areas. Quantitative assessments of anthropogenic heat emissions in major Chinese cities classify Xi' an as a strong heat island contribution area, second only to Shenzhen and Wuhan. Against the backdrop of global warming coupled with urban heat island effects, how do compound hot extreme events in Xi' an change? This requires further analysis. Therefore, this study selects Xi' an as the research object, analyzes variation characteristics of compound hot extremes from 1955 to 2019, and discusses circulation features of events lasting more than five days, aiming to provide theoretical and methodological references for scientific evaluation of urban extreme climate change.

2 Study Area and Data

2.1 Study Area

Xi' an is situated in central Guanzhong Plain and serves as the core of the Guanzhong urban agglomeration, playing an important role in regional economic development. The city had a population of 10.204 million and a GDP of 932.12 billion yuan in 2019. Due to urban expansion and other factors, Xi' an' s meteorological observation station has experienced multiple relocations since the founding of the People' s Republic of China. Specifically: in early 1950, the station was located in Xi' an Revolution Park; in July 1959, it moved to Xiguan Zheng Street; in July 1960, to Xiguan Airport; in July 1970, to Liuheyao Village at the east entrance of Ziqiang Road; in July 1995, to Taihua North Road; and in July 2005, to Xiaojiazhai outside the North Gate, where observations ceased. Evidently, against rapid urbanization, Xi' an' s meteorological station has relocated multiple times, with the final move stopping observations and connecting with Jinghe data, resulting in temperature data inhomogeneity.

[Figure 1: see original paper]

2.2 Data Sources

Daily temperature data from 22 meteorological stations in Xi' an and surrounding areas from 1955 to 2019 were obtained from the China National Ground Meteoration Station Basic Meteorological Elements Daily Dataset. Monthly mean SST data were sourced from the Hadley Centre Sea Surface Temperature dataset (HadISST) with 1.0° × 1.0° spatial resolution. Daily wind fields, pressure fields, and other reanalysis data were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) with 2.5° × 2.5° spatial resolution. Xi' an land use data were derived from the urban fringe land use dataset.

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3 Methods

3.1 Climate Series Homogenization

Currently, two approaches exist for constructing reference series in climate data homogenization: single-series and regional average methods. Regional average construction includes arithmetic mean and weighted average. Weighted average can eliminate influences of local climate anomalies on single-station series to some extent and is currently the widely accepted approach. This study employs weighted average to construct reference series using the formula:

$$T_{\text{ref}} = \frac{\sum_i k_i T_i}{\sum_i k_i}$$

where T_{ref} represents reference series temperature data; i is station index; k_i is the correlation coefficient between candidate station i and Xi' an temperature data at annual scale; and T_i is annual temperature data for station i.

For reference station selection, we selected stations within 100 km spatial distance, with elevation differences <200 m, observation duration >30 years, relocation times <2, and relocation distance <20 km, showing correlations with Xi' an's mean, maximum, and minimum temperatures higher than 0.80. Ultimately, Pucheng, Weinan, Yongshou, Lantian, and Qindu were used to construct the reference series. Using RHtestV4 software, we conducted breakpoint analysis on monthly and annual temperature series, repeatedly verifying and deleting insignificant breakpoints before performing homogenization correction on original series.

3.2 Definition of Compound Hot Extremes

Following existing research, we use maximum and minimum temperature anomalies as criteria to identify compound hot extremes, classifying summer extreme heat events into three types: day-hot/night-cool, day-cool/night-hot, and compound hot extremes, with others classified as normal days. Specific identification steps include: (1) determining thresholds for daytime and nighttime high temperatures in Xi' an; (2) counting annual occurrence days of compound hot extremes; and (3) focusing on persistence by counting events lasting more than five days to provide data foundation for analyzing circulation mechanisms of persistent extreme heat events.

For threshold determination, we primarily use the 95.0% percentile, supplemented by 90.0% and 99.0% relative threshold methods and absolute threshold methods (35.0°C daytime, 25.0°C nighttime) to construct different threshold analysis systems. To avoid redundancy, specific calculation methods can be referenced in existing literature.

3.3 Trend Statistical Diagnosis Methods

To better analyze variation characteristics of compound hot extremes in Xi' an, we employ ESMD for information decomposition of summer compound hot extreme time series, obtaining intrinsic mode functions (IMFs). Subsequently, harmonic analysis is applied to analyze periodic characteristics of IMFs, providing theoretical foundation for identifying influencing factors of compound hot extremes in Xi' an.

4 Results

4.1 Threshold Determination for Summer Compound Hot Extremes in Xi' an

We use the moving mean difference detection method proposed by Bao et al. to detect breakpoints in Xi' an' s maximum and minimum temperature series. Compared with sliding t-test, Yamamoto, Cramer, and Kendall methods, this approach has relatively simple structure, clear physical meaning, and can more accurately detect breakpoint locations. For corrected series, the 95.0% threshold for maximum temperature is 35.9°C and for minimum temperature is 23.1°C. The absolute threshold (35.0°C) is equivalent to the 95.0% threshold but lower than the 99.0% threshold (37.8°C). Regarding station relocation impacts, original maximum temperature thresholds are identical to corrected series thresholds, with main differences in minimum temperature. After correction, minimum temperature thresholds are 0.2–0.5°C lower, causing non-homogenized series to underestimate trends in extreme weather events in Xi' an.

[Figure 2: see original paper]

4.2 Impact of Different Threshold Schemes on Compound Hot Extreme Days

The 90.0% and 95.0% threshold schemes show similarity in identifying compound hot extreme events in Xi' an, while the 99.0% threshold scheme shows significant differences, representing the primary source of conclusion uncertainty. Comparing 90.0%, 95.0%, and 99.0% thresholds reveals that as extreme heat threshold conditions weaken, compound hot extreme days increase significantly. Common findings identify the mid-1980s as a turning point, with fluctuations decreasing in the earlier period and increasing trends in the later period. It is worth noting that while the 95.0% threshold scheme is applicable to Xi' an, this does not imply similar patterns for other regions. For example, Du et al.' s study on extreme heat thresholds in Dandong, Jilin, found an extreme heat threshold of 32.8°C at the 97.5% percentile, which does not correspond to the 95.0% threshold. Therefore, 95.0% thresholds should not be universally applied across regions.

[Figure 3: see original paper]

4.3 Variation Characteristics of Compound Hot Extremes Based on MF-DFA

Using the ESMD method to decompose summer compound hot extreme time series in Xi' an yields four intrinsic mode functions (IMFs). Variance contribution analysis shows that the 3.3–3.8-year period contributes most significantly (35.3%). With the mid-1980s as a turning point, compound hot extreme days increased significantly at a rate of 2.7 d $\cdot$ (10a)$^{-1}$. In terms of decadal variation, before the 1980s, compound hot extremes were dominated by a 21.7-year period, forming three troughs and three peaks. After the 1980s, the 21.7-year component contribution gradually weakened while 16.3-year and 10.8-year components strengthened, with rapid increases after 2000. During the global warming hiatus (1998–2012), the increase in compound hot extremes slowed, mainly influenced by negative phases of decadal periodic fluctuations. After 2012, superimposed positive phases of decadal periodic fluctuations caused compound hot extremes in Xi' an to increase significantly again.

[Figure 4: see original paper]

4.4 Variation Characteristics of Different Heat Event Types

Analyzing compound hot extremes alone cannot systematically understand variation patterns of summer extreme heat in Xi' an. Therefore, we supplement the analysis with normal days, day-hot/night-cool events, and day-cool/night-hot events to illustrate the particularity of compound hot extreme trends. Results show: (1) Normal days, representing days when neither daytime nor nighttime temperatures exceed thresholds, first increased then decreased, with the mid-1980s as the boundary. Recently, non-extreme heat days in Xi'an have decreased while summer extreme heat days have gradually increased. (2) Day-hot/night-cool events, representing daytime high temperatures with rapid nighttime cooling, show a fluctuating decreasing trend, with positive anomalies before 2000 and persistent decline in high temperature days, followed by stable "W" -type fluctuations. (3) Day-cool/night-hot events, representing daytime temperatures below 35.9°C but slow nighttime cooling, show fluctuating decreases before the mid-1980s and rapid increases thereafter, with enhanced interannual fluctuations after 2000, indicating large interannual differences. (4) Compound hot extremes show an opposite trend to normal days, with fluctuating decreases before the mid-1980s followed by increasing trends. In summary, summer extreme heat in Xi'an from 1955–2019 has become more extreme, with the mid-1980s as a turning point, characterized by decreasing normal days and day-hot/night-cool events, and increasing day-cool/night-hot and compound hot events.

[Figure 5: see original paper]

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5 Discussion

5.1 Relationship with Sea Surface Temperature Anomalies

Given the nonlinear and non-stationary characteristics of climate systems, linear correlation analysis may underestimate or misjudge the influence of ocean-atmosphere anomalies on compound hot extremes in Xi' an. Moreover, early warning signals for extreme heat events are urgently needed. Whether 超前 (lead-time) SST information can be extracted is crucial for comprehensive risk prevention of compound hot extremes in Xi' an. Using events lasting more than five days as criteria, we screened 12 compound hot extreme events in Xi' an from 1955–2019 to identify key sea areas with pre-winter SST anomalies.

Results show: (1) Among the 12 events, 8 occurred after 2000, accounting for 66.7% of all events, indicating the frequent occurrence of extreme heat in recent years. (2) Composite analysis of these 12 events reveals that December–February SST anomalies in the equatorial Pacific show a consistent "west-high/east-low" pattern, indicating that abnormally high SSTs in the seas east of the Philippines correspond to frequent compound hot extremes in Xi' an. Notably, during three super El Niño events (1982/83, 1997/98, 2015/16), the pre-winter equatorial Pacific SSTs showed an obvious "east-high/west-low" cold tongue pattern, and no persistent compound hot extremes occurred in Xi' an during these summers. (3) Since El Niño events exhibit diversity, they can be divided into three types from pre-winter to spring to summer: persistent El Niño, decaying El Niño, and El Niño-to-La Niña transition types. This study provides preliminary statistical analysis of three super El Niño events, and future research should combine different El Niño-Southern Oscillation (ENSO) types to explore the ocean-atmosphere teleconnection mechanisms affecting compound hot extremes in Xi' an.

[Figure 6: see original paper]

5.2 Circulation Mechanisms

Circulation field analysis of events lasting more than five days shows: (1) When persistent compound hot extremes occur in Xi' an, the South Asian High is abnormally northward, forming an anomalous high pressure over northern China that is unfavorable for moisture convergence. (2) At 500 hPa, the anomalous circulation pattern shows that during persistent compound hot extremes in Xi' an, the Western Pacific Subtropical High extends abnormally westward and northward, with northern China controlled by anomalous high pressure. Simultaneously, easterly anomalies in southern China are unfavorable for northward transport of southwest monsoon moisture, resulting in less rainfall in Xi' an and intensifying persistent hot weather. (3) Analysis of vertical velocity fields at 32°–35°N shows prevailing subsidence over Xi' an and its eastern regions. In summary, when persistent compound hot extremes occur in Xi' an, the northward extension of the South Asian High and westward extension of the Western Pacific Subtropical High, coupled with low-level wind field divergence in China' s north-south transition zone and strong easterly anomalies preventing northward moisture transport, collectively contribute to the formation of persistent day-night hot weather.

[Figure 7: see original paper]

6 Conclusions

Based on daily temperature data from 22 meteorological stations in Xi' an and surrounding areas from 1955–2019, this study analyzes variation characteristics of compound hot extremes and discusses circulation features of events lasting more than five days. The main conclusions are:

(1) Regarding threshold determination, the highest temperature thresholds are identical between original and homogenized sequences in Xi' an, with main differences in minimum temperature. After correction, minimum temperature thresholds are 0.2–0.5°C lower, leading to non-homogenized sequences underestimating trends in extreme weather events. The 90.0% and 95.0% threshold schemes show similar identification capabilities for high temperature events, while the 99.0% threshold and relative threshold schemes are primary sources of conclusion uncertainty. Artificially defined absolute thresholds and stringent relative thresholds significantly affect conclusions about compound hot extremes and hinder understanding of climate extremes in colder regions north of Xi' an.

(2) In terms of variation characteristics, compound hot extremes in Xi' an from 1955-2019 exhibited both interannual fluctuations and trend changes. With the mid-1980s as a turning point, compound hot extremes showed small fluctuations and decreases in the earlier period, followed by sustained increases, indicating the extremization of summer compound hot extremes in Xi' an in recent years.

(3) SST anomalies in the equatorial western Pacific can serve as a key predictor for compound hot extremes in Xi' an. When SSTs are higher in the seas east of the Philippines, compound hot extremes in Xi' an are more frequent. Conversely, when SSTs are lower in this region, particularly during super El Niño events, compound hot extremes in Xi' an tend to be less frequent. Additionally, when persistent compound hot extremes occur, the South Asian High is abnormally northward and eastward, the Western Pacific Subtropical High extends westward, low-level wind fields diverge in China' s north-south transition zone, and strong easterly anomalies prevent northward moisture transport, collectively intensifying the formation of persistent compound hot weather in Xi' an.

References

[1] Diffenbaugh N S, Singh D, Mankin J S, et al. Quantifying the influence of global warming on unprecedented extreme climate events[J]. Proceedings of the National Academy of Sciences, 2017, 114(19): 4881-4886.

[2] Power S B, Delage F P D. Setting and smashing extreme temperature records over the coming century[J]. Nature Climate Change, 2019, 9(7): 529-534.

[3] Wehrli K, Guillod B P, Hauser M, et al. Identifying key driving processes of major recent heat waves[J]. Journal of Geophysical Research: Atmospheres, 2019, 124(22): 11746-11765.

[4] Chuang J S, Rivoire O, Leibler S. Simpson' s paradox in a synthetic microbial system[J]. Science, 2009, 323(5911): 272-275.

[5] Wu X S, Guo S L, Yin J B, et al. On the event based extreme precipitation across China: Time distribution patterns, trends, and return levels[J]. Journal of Hydrology, 2018, 562: 305-317.

[6] Shang W, Li S S, Ren X M, et al. Event based extreme precipitation in central eastern China: Large scale anomalies and teleconnections[J]. Climate Dynamics, 2020, 54(3-4): 2347-2360.

[7] Li Shuangshuang, Wang Chengbo, Yan Junping, et al. Variability of the event based extreme precipitation in the south and north Qinling Mountains[J]. Acta Geographica Sinica, 2020, 75(5): 989-1007.

[8] Hou Wei, Zhang Daquan, Qian Zhonghua, et al. Research about the extreme high temperature events and its composite index based on stochastic re-sort detrended fluctuation analysis[J]. Plateau Meteorology, 2012, 31(2): 329-341.

[9] Yang Weitao, Sun Jianguo, Kang Yongtai, et al. Temporal and spatial changes of extreme weather indices in the Loess Plateau[J]. Arid Land Geography, 2020, 43(6): 1456-1466.

[10] Wang S S, Hu D Y, Chen S S, et al. A partition modeling for anthropogenic heat flux mapping in China[J]. Remote Sensing, 2019, 11(9): 1132-1151.

[11] Shaanxi Meteorological Administration. History of meteorological stations in Shaanxi Province[M]. Beijing: China Meteorological Press, 2012.

[12] Wang Bo, Huang Xiaojun, Wang Chen, et al. Land use dataset of the suburban area in Xi' an (2015)[J]. Journal of Global Change Data & Discovery, 2019, 3(4): 382-386.

[13] Zhu B, Sun B, Wang H. Dominant modes of interannual variability of extreme high temperature events in eastern China during summer and associated mechanisms[J]. International Journal of Climatology, 2020, 40(2): 841-857.

[14] Yin H, Sun Y. Detection of anthropogenic influence on fixed threshold indices of extreme temperature[J]. Journal of Climate, 2018, 31(16): 6341-6352.

[15] Wang J, Chen Y, Tett S, et al. Anthropogenically driven increases in the risks of summertime compound hot extremes[J]. Nature Communications, 2020, 11(1): 528-538.

[16] Bao Weimin, Shen Dandan, Ni Peng, et al. Proposition and certification of moving mean difference method for detecting abrupt change points[J]. Acta Geographica Sinica, 2018, 73(11): 2075-2085.

[17] Yang Ping, Hou Wei, Feng Guolin. Determining the threshold of extreme events with detrended fluctuation analysis[J]. Acta Physical Sinica, 2008, 57(8): 5333-5342.

[18] Du Q Q, Zhang M J, Wang S J, et al. Changes in air temperature over China in response to the recent global warming hiatus[J]. Journal of Geographical Sciences, 2019, 29(4): 496-516.

[19] Wang Jinliang, Li Zongjun. Extreme point symmetric mode decomposition: The new way of data analysis and scientific exploration[M]. Beijing: Higher Education Press, 2015.

[20] Du Haibo, Wu Zhengfang, Zhang Na, et al. Characteristics of extreme temperature and precipitation events over Dandong during the last six decades[J]. Scientia Geographica Sinica, 2013, 33(4): 473-480.

[21] Wang X L, Chen H, Wu Y, et al. New techniques for the detection and adjustment of shifts in daily precipitation data series[J]. Journal of Applied Meteorology and Climatology, 2010, 49(12): 2416-2436.

[22] Chen Y, Zhai P. Revisiting summertime hot extremes in China during 1961–2015: Overlooked compound extremes and significant changes[J]. Geophysical Research Letters, 2017, 44(10): 5096-5103.

[23] Ji Wenhui, Zhang Bo, Ma Bin, et al. Temporal and spatial changes of extreme temperature and its influencing factors in northern China in recent 58 years[J]. Arid Land Geography, 2020, 43(5): 1220-1230.

Note: Figure translations are in progress. See original paper for figures.