# Spatiotemporal Variation Characteristics of Heat Waves in the Wei River Basin from 1980 to 2020: Postprint

**Authors:** Deng Tiantian, Geng Guangpo, Yang Rui, Bao Zhang, Geng Guangpo

**Date:** 2023-03-14T00:00:00+00:00

## Abstract

Based on daily maximum temperature data from 24 meteorological stations in the Wei River Basin from 1980 to 2020, the spatiotemporal variation characteristics of heat waves in the Wei River Basin over the past 40 a were investigated using the Sen+Mann-Kendall trend analysis method. The results indicate that: (1) The multi-year average number of high-temperature days in the Wei River Basin is 3.54 d, showing an extremely significant increasing trend at a rate of approximately 1 d · (10a)-1. The annual average number of high-temperature days exhibits a spatial distribution pattern of fewer in the northwest and more in the southeast, with the most significant increasing trend observed at stations in the Guanzhong Plain. (2) The earliest occurrence of the first high-temperature day is in late April, and the latest occurrence of the last high-temperature day is in early September. The first high-temperature day at most stations in the Wei River Basin shows a significant advancement of approximately 3-5 d · (10a)-1, while nearly half of the stations show a significant delay in the last high-temperature day of approximately 3 d · (10a)-1, indicating that the total duration affected by high temperatures in the Wei River Basin has become longer. (3) The proportion of severe heat wave events in the Wei River Basin is 10.32%, indicating that at least one out of every ten events is a severe heat wave. Stations with higher frequencies of different-grade heat waves and longer durations are all located in the Guanzhong Plain in the southeastern part of the Wei River Basin, indicating that the Guanzhong Plain is the focal area of heat waves in the Wei River Basin. (4) The intensity of heat waves in different periods shows a significant overall upward trend, and the intensity may further intensify in the future, posing a serious threat to human health and industrial and agricultural production in the Wei River Basin and requiring sufficient attention from relevant departments. The research results can provide references for mitigating heat wave disasters in the Wei River Basin.

ChinaRxiv

## Full Text

## Abstract

Based on daily maximum temperature data from 24 meteorological stations in the Weihe River Basin from 1980 to 2020, this study employs the Sen+Mann-Kendall trend analysis method to investigate the spatiotemporal variation characteristics of high temperature and heat waves over the past 40 years. The results indicate that: (1) The multi-year average of high temperature days in the Weihe River Basin was 3.54 days, showing an extremely significant increasing trend at a rate of 1 $d \cdot (10a)^{-1}$. The spatial distribution pattern exhibits fewer days in the northwest and more in the southeast, with stations in the Guanzhong Plain showing the most significant increasing trend. (2) The earliest first high temperature day occurred in late April, while the latest last high temperature day appeared in early September. Most stations showed a significant advance in the first high temperature day at approximately 3 $d \cdot (10a)^{-1}$, while nearly half of the stations exhibited a significant delay in the last high temperature day at about 3 $d \cdot (10a)^{-1}$, indicating that the total duration affected by high temperatures in the basin has become longer. (3) Severe high temperature and heat wave events accounted for 10.32% of the total, meaning at least one out of every ten events was severe. Stations with higher frequency and longer duration of different-grade heat waves were concentrated in the Guanzhong Plain in the southeastern part of the basin, demonstrating that this plain represents the epicenter of heat wave activity. (4) The intensity of high temperature and heat waves showed a significant upward trend across different periods, with potential for further intensification in the future, posing serious threats to human health and industrial-agricultural production in the Weihe River Basin that warrant adequate attention from relevant authorities. These findings provide valuable references for mitigating high temperature and heat wave disasters in the region.

**Keywords:** high temperature and heat wave; trend analysis; temporal and spatial variation; intensity; Weihe River Basin

## Introduction

The Sixth Assessment Report of the IPCC indicates that global surface temperature has risen by 1.09°C compared to the pre-industrial era and may exceed 1.5°C in the future. Against this background of climate change, high temperature and heat wave events are occurring more frequently and affecting larger areas. As an extreme weather phenomenon, heat waves not only threaten human life and health but also cause significant damage to industry, agriculture, ecological environments, and social stability. The severe heat wave that swept across Europe in the summer of 2003 caused over 70,000 deaths and agricultural losses exceeding 13 billion euros. In the summer of 2013, a rare extreme high temperature event occurred in the middle and lower reaches of the Yangtze River in China, resulting in thousands of heatstroke cases and severely impacting industrial and agricultural production.

Currently, there is no unified global standard for high temperature and heat waves. Identification methods can be broadly categorized into three types: (1) absolute threshold method, which defines heat waves when daily maximum temperature exceeds a specific value; (2) relative threshold method, which uses exceedance of a certain percentile of daily maximum temperature; and (3) methods based on the number of heatstroke or death cases caused by heat waves. Among these, the first two methods are most widely applied. The absolute threshold method is typically used at regional scales. For instance, Xing et al. used an absolute threshold of $ $35°C to define high temperature days in North China, classified heat waves into three grades, and found an overall increasing trend in annual high temperature days with similar spatial distribution patterns across different grades. Jiang et al. defined $ $35°C as high temperature weather in Shanghai and identified continuous 5 days $ $35°C as a heat wave process, revealing an intensifying trend in extreme high temperature weather, particularly after 2000 when both high temperature days and heat wave events reached maximum frequency.

The relative threshold method is suitable for larger spatial scales such as global and national levels. Jia et al. used the 90th percentile of temperature as the high temperature threshold and found that regional average high temperature days in China showed a decreasing-then-increasing trend, with weak heat waves more likely to occur in Northwest China. Keellings and Moradkhani defined heat waves using temperature exceedance above the 85th percentile, demonstrating significant increases in heat waves across the United States and a significant positive correlation between heat wave intensity, area, and duration.

While domestic research on heat waves has made substantial progress, studies have primarily focused on national scales and southern or northern regions. Under global warming, Northwest China has experienced particularly pronounced temperature increases, yet research on heat waves at the river basin scale in this region remains relatively scarce, with unclear spatiotemporal patterns and quantitative indicators. The Weihe River Basin, the largest sub-basin of the Yellow River Basin, features favorable geographical conditions and a distinct four-season climate, representing a traditional agricultural region in China. Its southeastern Guanzhong Plain is particularly important as a major grain production base and densely populated area. However, located in the transitional zone between arid and humid regions of the Loess Plateau, it represents a climate-sensitive area with fragile ecological environments. With intensifying global warming, the Weihe River Basin has become increasingly prone to high temperature and heat waves. Therefore, this study selects the Weihe River Basin as the research area, utilizing indicators including high temperature days, first/last high temperature day, duration, frequency, and intensity to comprehensively analyze spatiotemporal variation characteristics over the past 40 years. The results help scientifically identify basin-scale features of heat waves and provide references for implementing disaster prevention and mitigation measures.

### 1.2 Data Sources and Processing

The data used in this study were obtained from the China Meteorological Administration' s National Meteorological Information Center, specifically the China Surface Climate Data Daily Dataset (V3.0), covering the period 1980–2020. This dataset has undergone strict quality control. Based on station distribution and data completeness, 24 meteorological stations were selected within and around the Weihe River Basin, including 17 in Shaanxi Province, 5 in Gansu Province, and 2 in Ningxia Hui Autonomous Region.

### 1.3.1 High Temperature Days and First/Last Day

Following national meteorological regulations and the GB/T 27962-2011 "Graphical Symbols for Meteorological Disaster Warning Signals," a high temperature day is defined when daily maximum temperature $ $35°C. The first high temperature day refers to the date when maximum temperature first reaches $ $35°C each year, while the last high temperature day refers to the final date when maximum temperature reaches $ $35°C.

### 1.3.2 Heat Wave Grading Standards

Referencing relevant research, heat waves are classified into three grades: mild, moderate, and severe. The specific criteria are as follows: - **Mild heat wave:** Continuous 3–4 days with temperature $ $35°C, or continuous 5–7 days $ $35°C with at least one day $ $38°C - **Moderate heat wave:** Continuous 5–7 days with temperature $ $35°C, or continuous 3–4 days $ $38°C - **Severe heat wave:** Continuous $ $8 days with temperature $ $35°C, or continuous $ $5 days $ $38°C

### 1.3.3 Heat Wave Intensity

Heat wave research must reflect both frequency and intensity, with duration and daily maximum temperature during events serving as key indicators. To better characterize heat wave intensity, we define it as the cumulative value of daily maximum temperature $ $35°C throughout the event. The calculation formula is:

$$Q = \frac{1}{n}\sum_{i=1}^{n}(\bar{T}_i - 35) \times d_i$$

where $Q$ represents heat wave intensity, $n$ is the total frequency of heat wave events in a given year, $\bar{T}_i$ is the average daily maximum temperature during the $i$-th heat wave process, and $d_i$ is the duration in days of the $i$-th heat wave process.

### 1.3.4 Sen+Mann-Kendall Trend Analysis

This study employs the Sen+Mann-Kendall method to analyze spatiotemporal variation characteristics of high temperature days and heat wave events. Sen' s slope estimator calculates the median slope of the time series, offering strong noise resistance though without significance testing capability. For a time series with $n$ samples $x_1, x_2, ..., x_n$, the Sen' s slope is calculated as:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall i < j$$

where $\beta$ represents the average change rate and trend of the time series. $\beta > 0$ indicates an upward trend, $\beta = 0$ suggests no obvious trend, and $\beta < 0$ indicates a downward trend.

The Mann-Kendall test is a non-parametric method widely used for analyzing trends in precipitation, runoff, temperature, and other hydrometeorological variables. It compares the relative magnitudes of data and is less sensitive to outliers. The test statistic $S$ is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i)$$

where sgn is the sign function. For $n \geq 10$, the standardized test statistic $Z$ is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

where $\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$. At the 95% confidence level, $|Z| \geq 1.96$ indicates the trend is statistically significant.

## 2.1 Temporal and Spatial Variation of High Temperature Days

Figure 2 shows that annual average high temperature days in the Weihe River Basin fluctuated considerably from 1980 to 2020 but exhibited an extremely significant increasing trend at a rate of 0.92 $\text{d} \cdot (10\text{a})^{-1}$, indicating that high temperature days have gradually increased at approximately 1 $\text{d} \cdot (10\text{a})^{-1}$ over the past 40 years. Statistical results reveal that the annual average of high temperature days was 3.54 days, with the maximum of 10.8 days occurring in 1997 and the minimum of 0.3 days in 1983. When dividing the study period into three sub-periods (1980–1990, 1991–2005, and 2006–2020), the average high temperature days show a progressive increase: 1.71 days, 3.52 days, and 5.24 days, respectively.

High temperature days in the Weihe River Basin display a clear spatial gradient, gradually increasing from northwest to southeast (Figure 3). Areas with more high temperature days are concentrated in the southeastern part of the basin, particularly at Pucheng, Longxian, Fengxiang, Wugong, Yaoxian, Qindu, and Shangzhou stations. Pucheng, Wugong, and Qindu show notably higher values of 20.0 days, 18.6 days, and 15.7 days, respectively. Tianshui and Dingbian stations also exceed 10 days, while other stations record fewer than 10 days.

Regarding spatial trends (Figure 3), all stations except Hualing, Xiji, Liupanshan, Guyuan, Minxian, Taibai, and Huashan (which have no high temperature records) show increasing trends. Pucheng, Wugong, and Qindu exhibit increases exceeding 3 $d \cdot (10a)^{-1}$, with Wugong showing the largest increase at 4 $d \cdot (10a)^{-1}$. Stations with strong increasing trends are mainly located in southern Weihe River Basin, with Lintao, Longxian, Fengxiang, Xifeng, Wuqi, Luochuan, Yaoxian, and Shangzhou passing the 95% significance test, while Tianshui, Kongtong, Qindu, Pucheng, and Yongshou pass the 99% significance test. Southern stations show particularly significant increasing trends, mostly passing the 95% significance test, while northern stations show relatively significant increases, generally passing the 90% significance test, and central stations show non-significant trends.

## 2.2 Characteristics of First and Last High Temperature Day Changes

The first high temperature day in the Weihe River Basin typically occurs in late April, with the earliest instances in early April at Dingbian, Pucheng, Fengxiang, and Qindu stations in Shaanxi Province. The latest first high temperature day appears in early June at Minxian station. In extreme cases, high temperatures occurred as early as March 29 at Huanxian, Wugong, Yaoxian, and Shangzhou stations. Spatially, all stations except Dingbian, Wuqi, Huanxian, and Yaoxian show advancing trends in the first high temperature day. The largest advance occurs at Kongtong station (-8.16 $d \cdot (10a)^{-1}$), while Shangzhou shows the smallest advance (-0.60 $d \cdot (10a)^{-1}$). No clear spatial differentiation is observed in these trends.

The last high temperature day typically occurs in early September, though some stations extend to late September at Lintao, Kongtong, Xifeng, and Changwu. In the northern part of the basin, Dingbian, Wuqi, and Huanxian stations record final high temperature days in October. In extreme cases, the latest high temperature days occurred on October 20 at Wugong and Qindu, and October 21 at Shangzhou. Spatial trend analysis reveals both advancing and delaying patterns (Figure 5). Advancing trends are concentrated in central basin stations including Lintao, Kongtong, Xifeng, Changwu, Luochuan, and Yongshou, while other stations show delaying trends. Lintao, Wuqi, Huanxian, Kongtong, Xifeng, Changwu, Luochuan, Pucheng, Tianshui, Fengxiang, Yaoxian, and Shangzhou pass the 95% significance test, and Qindu passes the 99% test. Kongtong and Luochuan show the strongest advancing trends (-8.28 and -8.15 $d \cdot (10a)^{-1}$, respectively), while Huanxian shows the strongest delaying trend (7.99 $d \cdot (10a)^{-1}$). Dingbian, Wuqi, Wugong, Qindu, and Shangzhou also show notable delaying trends exceeding 3 $d \cdot (10a)^{-1}$.

## 2.3 Characteristics of High Temperature and Heat Wave Events

### 2.3.1 Frequency of Different-Grade Heat Waves

From 1980 to 2020, 24 stations in the Weihe River Basin recorded 341 heat wave events, including 220 mild events (64.52%), 86 moderate events (25.16%), and 35 severe events (10.32%). This indicates that mild heat waves dominate, followed by moderate events, while severe heat waves are least frequent but occur at a rate of at least one in ten events.

Spatial distribution of cumulative frequency shows that 10 stations (Hualing, Guyuan, Xiji, Liupanshan, Kongtong, Minxian, Luochuan, Taibai, and Huashan) recorded no mild heat waves. Pucheng, Wugong, and Qindu recorded the most mild heat wave occurrences (16, 14, and 12 events, respectively). Eleven stations had no moderate heat waves, with Pucheng, Wugong, and Qindu again recording the most (6, 5, and 5 events). Seventeen stations recorded no severe heat waves, while Dingbian, Pucheng, Longxian, Fengxiang, Wugong, Yaoxian, and Qindu recorded severe events, with Pucheng, Wugong, and Qindu showing the highest frequencies (3, 3, and 2 events, respectively). The spatial patterns of frequency across different grades are consistent, with the highest-frequency stations all located in the Guanzhong Plain in southeastern Shaanxi Province.

Cumulative heat wave frequency trends (Figure 7) show increasing patterns at all stations except those without heat wave events. Yaoxian and Qindu pass the 99% significance test, while Lintao passes the 95% test. Qindu shows the most significant increasing trend at 4.8 $d \cdot (10a)^{-1}$, while Lintao shows the smallest increase at 0.5 $d \cdot (10a)^{-1}$. Longxian, Fengxiang, Yaoxian, and Shangzhou also show relatively high frequencies of mild and moderate heat waves.

### 2.3.2 Duration and Intensity of Heat Waves

The average duration of heat waves at each station (Figure 8) shows longer durations in the southeastern basin, consistent with spatial patterns of heat wave frequency. Most stations record total average durations of 1–5 days, while Pucheng, Qindu, and Wugong show the longest durations (12.9, 12.9, and 10.0 days, respectively), matching the stations with highest event frequencies. Longxian, Fengxiang, Yaoxian, and Shangzhou record durations exceeding 2 days (2.8, 3.7, 2.3, and 2.0 days, respectively), while other stations record less than 2 days.

All stations with heat wave events show increasing duration trends, particularly in the southern basin. Dingbian, Changwu, and Shangzhou pass the 95% significance test, while Qindu passes the 99% test. Wugong shows the most significant increasing trend at 2.8 $d \cdot (10a)^{-1}$.

Heat wave intensity, which integrates duration and maximum temperature information, shows marked spatial variation (Figure 9). High-intensity stations are mainly distributed in the southern basin with values generally >1.0, while northern stations show moderate intensity (0.5–1.0) and central stations show lower intensity (0.0–0.5). Pucheng and Qindu exhibit the highest intensities at 2.0 and 1.8, respectively. Temporal analysis reveals a significant upward trend in heat wave intensity of 4.8 $d \cdot (10a)^{-1}$, with particularly dramatic increases after 2000 (Figure 10). This suggests that intensifying global warming may further strengthen heat wave intensity in the Weihe River Basin, posing serious threats requiring urgent attention.

Heat waves significantly impact human health, with studies showing excess mortality rates increasing by over 10% during heat wave periods, particularly affecting infants under 5 years and elderly over 60 years. Heat waves also accelerate the progression of respiratory, digestive, and cardiovascular diseases. The Weihe River Basin' s population is concentrated in the Guanzhong Basin in the southeast (Figure 11), where high population density overlaps with high heat wave hazard areas, threatening vulnerable populations. Therefore, enhanced early warning and prevention systems for high-risk heat waves are essential.

## 3 Discussion

Overall, most areas of the Weihe River Basin have experienced significant increases in high temperature days and heat wave events since the 1980s, with pronounced spatial heterogeneity. Cheng et al. found that high temperature frequency and intensity in Shaanxi Province increased significantly over the past half-century, with spatial patterns showing more events in southern and eastern regions, and the first high temperature day advancing while the last day delayed. Ji et al. reported increasing daily maximum temperatures in the Weihe River Basin from 1960–2017, consistent with global warming trends and particularly accelerated after the 1990s, aligning with our findings.

The spatial heterogeneity of heat waves in the Weihe River Basin arises from multiple factors. First, geographical location and topography play crucial roles. The basin' s terrain is higher in the west and lower in the east, with the Qinling Mountains to the south, Loess Plateau to the north, and Guanzhong Plain to the southeast. Several high-altitude stations such as Taibai and Huashan recorded no high temperatures. Second, the urban heat island effect has intensified with rapid urbanization and industrialization since the 1990s, with heat island-induced temperature changes consistent with regional and global warming trends. Our results show high heat wave intensity concentrated in the Guanzhong urban agglomeration, where urban heat islands likely exacerbate heat waves. Additionally, heat wave variations are closely related to precipitation days, atmospheric circulation patterns, and soil moisture at interannual and decadal scales.

This study has several limitations. The results are based on station data, which may have limited regional representativeness. Future research should consider using gridded meteorological data to improve reliability. Moreover, this study focuses solely on spatiotemporal variation characteristics without addressing heat wave mechanisms, causes, or impacts on economy and ecological environment, which require further investigation.

## 4 Conclusions

1. High temperature days in the Weihe River Basin from 1980–2020 showed an extremely significant increasing trend at a rate approaching 1 $d \cdot (10a)^{-1}$, with a multi-year average of 3.54 days. The year with most high temperature days was 1997 (10.8 days). Spatially, high temperature days increased from northwest to southeast, with high-value stations concentrated in the southeastern basin, particularly in the Guanzhong Plain where the increasing trend was most significant.

2. The earliest first high temperature day occurred in late April, while the latest last high temperature day appeared in early September, with a maximum interval of about 5 months. Trend analysis shows that most stations exhibited significant advancement of the first high temperature day at approximately 3 $d \cdot (10a)^{-1}$, while nearly half of stations showed significant delay of the last day at about 3 $d \cdot (10a)^{-1}$, indicating that the total duration affected by high temperatures has become longer.

3. From 1980–2020, mild, moderate, and severe heat waves accounted for 64.52%, 25.16%, and 10.32% of total events, respectively. Stations with higher frequency and longer duration across all grades were located in the Guanzhong Plain in the southeastern basin, consistent with spatial patterns of heat wave duration and intensity. The stations with highest cumulative frequency, longest duration, and greatest intensity were all located in the Guanzhong Plain (Pucheng, Wugong, and Qindu), confirming this plain as the epicenter of heat wave activity in the Weihe River Basin.

4. Heat wave intensity showed a significant upward trend across different periods, with particularly dramatic increases after 2000, suggesting further intensification may occur with ongoing global warming. This poses serious threats to human health and industrial-agricultural production in the basin, requiring adequate attention from relevant departments. The study provides valuable references for disaster prevention and mitigation efforts in the Weihe River Basin.

## References

[1] Zhou Botao. Global warming: Scientific progress from AR5 to AR6[J]. Transactions of Atmospheric Sciences, 2021, 44(5): 667-671.

[2] Huang Xiaomei, Shi Renrui, Liu Sijia, et al. Spatial temporal characteristics and causes of summer heat waves in southwest China[J]. Plateau and Mountain Meteorology Research, 2020, 40(3): 59-65.

[3] Alizadeh M R, Adamowski J, Nikoo M R, et al. A century of observations reveals increasing likelihood of continental scale compound dry hot extremes[J]. Science Advances, 2020, 39(6): eaa24571, doi: 10.11261/sciadv.aa24571.

[4] Zhang Jiayi, Qian Cheng. Linear trends in occurrence of high temperature and heat waves in China for the 1960–2018 period: Method and analysis results[J]. Climatic and Environmental Research, 2020, 25(3): 225-239.

[5] Keellings D, Moradkhani H. Spatiotemporal evolution of heat wave severity and coverage across the United States[J]. Geophysical Research Letters, 2020, 47(9): e2020GL087097, doi: 10.1029/2020GL087097.

[6] Conti S, Meli P, Minelli G, et al. Epidemiologic study of mortality during the summer 2003 heat wave in Italy[J]. Igiene E Sanita Pubblica, 2005, 60(3): 121-139.

[7] Zhang Shangyin, Song Yanling, Zhang Dekuan, et al. The climate characteristics of high temperature and the assessment methods in the large cities of northern China[J]. Acta Geographica Sinica, 2004, 59(3): 383-390.

[8] He Linyan, Jian Maoqiu. Temporal variations of extreme heat days in Guigang of Guangxi and related circulation background[J]. Journal of Tropical Meteorology, 2019, 35(5): 694-708.

[9] Peng Jingbei, Liu Ge, Sun Shuqing. An analysis on the formation of the heat wave in southern China and its relation to the anomalous western Pacific subtropical high in the summer of 2013[J]. Chinese Journal of Atmospheric Sciences, 2016, 40(5): 897-906.

[10] Yang Guiyu, Wang Hao. Interaction of grain yield with irrigated agriculture development in Weihe River Basin[J]. China Water Resources, 2015(5): 56-59.

[11] Yuan Meng, Chang Jianxia, Li Yunyun. Comprehensive evaluation index on temporospatial analysis of drought in Weihe River Basin[J]. Engineering Journal of Wuhan University, 2018, 51(5): 401-408.

[12] Zou Lei, Yu Jianguo, Xia Jun, et al. Temporal spatial variation characteristics of drought in the Weihe River Basin based on SPEI[J]. Arid Land Geography, 2020, 43(2): 329-338.

[13] Bu Fanrui, Sun Peng, Yao Rui, et al. High temperature heat waves in the Huaihe River Basin and relation to the Madden Julian oscillation: Spatio

temporal properties and causes[J]. Scientia Geographica Sinica, 2021, 41(4): 705-716.

[14] Shi Hongbo. Climatic characteristics and the spatio temporal variation of high temperature days in north China[J]. Scientia Geographica Sinica, 2012, 32(7): 866-871.

[15] Xing Caiying, Zhang Jinghong, Wu Shengan. Climatic characteristics of high temperature days and heatwaves: Hainan Island in recent 50 years[J]. Chinese Agricultural Science Bulletin, 2017, 33(22): 107-112.

[16] Huang Zhuo, Chen Hui, Tian Hua. Research on the heat wave index[J]. Meteorology Monthly, 2011, 37(3): 345-351.

[17] Xing Pei, Yang Ruozi, Du Wupeng, et al. Spatiotemporal variation of high temperature day and heat wave in north China during 1961‒2017[J]. Scientia Geographica Sinica, 2020, 40(8): 1365-1376.

[18] Wei Fengying. Modern climate statistics diagnosis and prediction technology[M]. Beijing: Meteorological Press, 1999: 69-71.

[19] Jiang Rong, Chen Liang, Xiang Weining. Characteristics of extreme high temperature weather in Shanghai[J]. Journal of Meteorology and Environment, 2016, 32(1): 66-74.

[20] Mann H B. Nonparametric test against trend[J]. Econometrica, 1945, 13(3): 245-259.

[21] Kendall M G. Rank correlation methods[J]. British Journal of Psychology, 1990, 25(1): 86-91.

[22] Xu Shenzhen, Zheng Youfei, Yin Jifu, et al. Characteristics of high temperature and heat wave in Nanjing City and their impacts on human health[J]. Chinese Journal of Ecology, 2011, 30(12): 2815-2820.

[23] Liu Jianjun, Zheng Youfei, Wu Rongjun. Impacts of heat waves disasters on human health and its research method[J]. Journal of Natural Disasters, 2008, 17(1): 151-156.

[24] Cheng Xiaoxia, Cai Xinling, Li Ming, et al. Temporal spatial features and quantitative evaluation of high temperature events in Shaanxi Province[J]. Arid Zone Research, 2020, 37(4): 956-965.

[25] Ji Lin, Duan Keqin. Variations of extreme temperature and its response on regional warming in the Weihe River Basin during 1960‒2017[J]. Scientia Geographica Sinica, 2020, 40(3): 466-477.

[26] Jie Z, Liu Z, Li C. Reduced soil moisture contributes to more intense and more frequent heat waves in northern China[J]. Advances in Atmospheric Sciences, 2015, 32(9): 1197-1207.

[27] Wang P, Tang J, Wang S, et al. Regional heatwaves in China: A cluster analysis[J]. Climate Dynamics, 2017(8): 1-17.

[28] Wu Ruixi, Zeng Gang, Yang Xiaoye, et al. Interdecadal variability of mid summer high temperature days in northern China and its association with soil moisture in Mongolian Plateau[J]. Progress in Geophysics, 2021, 36(1): 78-87.

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