# Spatiotemporal Characteristics of Regional High-Temperature Processes in Shaanxi Province from 1971 to 2024

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## Abstract

Using daily maximum temperature data from 95 national meteorological observation stations in Shaanxi Province from 1971 to 2024, this study analyzed the spatiotemporal variation characteristics of regional high-temperature processes in Shaanxi Province by applying the operational assessment methods and indicators for regional high-temperature processes currently used by the Shaanxi Climate Center, together with statistical diagnostic methods including linear trend estimation, correlation coefficients, moving averages, and the Mann-Kendall test. The results show that high temperatures in Shaanxi Province are mainly concentrated in the central-eastern Guanzhong Plain and the Ankang river valley in southern Shaanxi. Both the number of high-temperature days and their intensity exhibit spatial distribution characteristics of fewer and weaker events in the north and more and stronger events in the south, as well as fewer and weaker events in the west and more and stronger events in the east. Regional high-temperature processes occur 4 times per year on average, mainly from mid-June to mid-August, with an average duration of 4 d, an average intensity mostly ranging from 36 to 37 ℃, and a wide impact area. With global climate warming, high temperatures in Shaanxi Province have become more frequent and stronger over the past 54 a. Regional high-temperature processes show changes characterized by increased frequency, earlier onset and later ending of high temperatures, longer duration, broader coverage, and enhanced average and comprehensive intensity. These changes began in the late 1990s and have been particularly significant since the 21st century.

## Full Text

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# Spatiotemporal Characteristics of Regional High-Temperature Processes in Shaanxi Province from 1971 to 2024

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**Abstract:** Using daily maximum temperature data from 95 national meteorological observation stations in Shaanxi Province during 1971–2024, and adopting the assessment methods and indicators for regional high-temperature processes stipulated in the current operational rules of the Shaanxi Climate Center, this study analyzed the spatiotemporal variation characteristics of regional high-temperature processes in Shaanxi Province based on statistical diagnostic methods including linear trend estimation, correlation coefficients, moving averages, and the Mann-Kendall test. The results show that high temperatures in Shaanxi

Province are mainly concentrated in the central and eastern Guanzhong Plain and the Ankang river-valley area in southern Shaanxi. Both the number of high-temperature days and intensity exhibit spatial distribution characteristics of fewer in the north and more in the south, and fewer in the west and more in the east. Regional high-temperature processes occur on average 4 times per year, mainly from mid-June to mid-August, with an average duration of 4 d; their average intensity is mostly 36–37 °C, and their influence range is extensive. With global climate change, high temperatures in Shaanxi Province have tended to intensify over the past 54 years. Regional high-temperature processes show changes such as increasing frequency, earlier onset and later termination, longer duration, wider coverage, and increases in both average intensity and comprehensive intensity. These changes began in the late 1990s and have been especially significant since the 21st century.

**Keywords:** climate change; high-temperature process; spatiotemporal characteristics; Shaanxi

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the current global mean temperature has risen by about 1.1 °C relative to the preindustrial level[1]. Against the background of continued global warming, high-temperature heat-wave events show trends of increasing frequency, strengthening intensity, and lengthening duration[2–4]. In recent decades, many regions around the world have frequently been struck by extreme high-temperature heat waves, posing serious threats to the ecological environment, agricultural production, and public health, while also aggravating the risk of natural disasters such as forest fires and rainstorm-induced flooding[5–12]. For example, the extreme heat wave in Europe in the summer of 2003 led to a significant increase in mortality among vulnerable populations and caused enormous economic losses[13]; in 2013, a historically rare regional high-temperature event occurred in southern China, affecting multiple provinces and municipalities in the middle and lower reaches of the Yangtze River and triggering widespread agricultural drought and difficulties in providing drinking water for livestock[14–18]; and the 2019–2020 high-temperature heat wave in Australia induced large-scale forest fires, causing severe damage to local ecosystems[19].

A deeper understanding of the spatiotemporal characteristics, formation mechanisms, and impact pathways of high-temperature heat waves is of great significance for mitigating their negative impacts, safeguarding social well-being, and promoting sustainable development. As the risks of global warming have intensified, research on high-temperature heat waves has received widespread attention over the past 20 years. Numerous studies have indicated that by the middle and late 21st century, global high-temperature heat waves will exhibit characteristics such as stronger intensity, higher frequency, and longer duration[20–22]. Analyses focused on China show that since the 1990s, extreme high-temperature events have increased and intensified markedly[23]. Regional studies further reveal that since 1961, the affected area, duration, and intensity of regional high-temperature processes in China have all shown increasing trends, and the risk of high-temperature disasters has tended to rise[24–26]. Among these, the increase in the regional persistent-high-temperature index has been particularly significant in North China, the Yangtze River basin, and South China[27]. Although important progress has been made in the identification methods, evolution patterns, causal mechanisms, and response strategies for high-temperature heat waves, the complexity and variability of such events have become increasingly prominent as the climate continues to warm and extreme events occur more frequently; related research therefore still needs to be further deepened.

Shaanxi Province is located in inland China. Its terrain is high in the north and south and low in the middle, and the Qinling Mountains within the province, as an important climatic boundary in China, further strengthen the north–south climatic differences within the province. Observational data show that air temperature in Shaanxi Province has exhibited a significant upward trend in recent years[28], and extreme high-temperature events have also become more frequent and intense[29–30]. High-temperature events have likewise shown a trend of spatial expansion; for example, Yijun County recorded high-temperature weather for the first time in 2017[31]. These changes have attracted broad attention from the government and the public. Existing studies have carried out a series of analyses of extreme high-temperature events in Shaanxi Province[31–36], but most have focused on local high temperatures or the station scale. Systematic research on large-scale regional high-temperature processes remains relatively lacking; moreover, some datasets are insufficiently up to date, and the evaluation indicators are relatively singular. When regional high-temperature processes exhibit the characteristics of an expanding affected area and lengthening duration,

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when they occur, their disaster-causing risk will increase significantly, and their impacts on the socioeconomic system will also be more profound. Therefore, against the background of frequent extreme high-temperature events and continuously increasing intensity, systematically revealing the evolution patterns of regional high-temperature processes based on the latest observational data and carrying out quantitative assessment are of important scientific value and practical significance for improving short-term climate prediction and earlywarning capability and for supporting regional disaster prevention and mitigation decision-making

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# 1 Materials and Methods

## 1.1 Data

The meteorological data used are daily maximum temperature data from 95 national meteorological observation stations in Shaanxi Province released by the Shaanxi Provincial Meteorological Information Center (Fig. 1). The data period is 1971–2024. Before use, strict quality control was performed on the representativeness, accuracy, and consistency of the data to ensure that the data were accurate and valid.

## 1.2 Indicators and Methods

According to the method in the *Classification of Grades for Regional High-Temperature Weather Processes* (QX/T 228–2014)

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, and through localized applicability research, the Shaanxi Provincial Climate Center established assessment methods and indicators suitable for regional high-temperature processes in Shaanxi, focusing on objective identification of regional high-temperature processes, calculation of comprehensive intensity, and classification of intensity grades. The details are as follows:

(1) Identification of regional high-temperature processes

If, on a given day within the study area, high-temperature weather with daily maximum temperature \$ \$35 ℃ occurs over 20% or more of the area (number of stations), and persists for 2 d or longer, it is determined that one regional high-temperature process has occurred in the study area.

Fig. 1 Distributions of topography and meteorological stations in Shaanxi Province

(2) Comprehensive intensity index of regional high-temperature processes

Average intensity index: the mean daily maximum temperature at affected stations during one regional high-temperature process. The calculation formula is as follows:

$$I_a = \sum_{t=1}^{N} \sum_{m=1}^{M_t} S_{t,m} \Big/ \sum_{t=1}^{N} M_t \tag{1}$$

where $I_a$ denotes the average intensity index of the high-temperature process; $N$ denotes the duration, in days, of the high-temperature process; $S_{t,m}$ denotes the daily maximum temperature at station $m$ on day $t$ during the high-temperature process; and $M_t$ denotes the number of affected stations on day $t$ during the regional high-temperature process.

Average extent: the daily average number of affected stations during one regional high-temperature process. The calculation formula is as follows:

$$A_a = \sum_{t=1}^{N} M_t \Big/ N \tag{2}$$

where $A_a$ denotes the average extent of the high-temperature process; $M_t$ denotes the number of affected stations on day $t$ during the regional high-temperature process; and $N$ denotes the duration, in days, of the high-temperature process.

Comprehensive intensity index: an index that comprehensively considers the impact extent, duration, and average intensity of one regional high-temperature process. The calculation formula is as follows:

$$Z = I_a \times A_a^{0.5} \times T^{0.5} \tag{3}$$

where $Z$ denotes the comprehensive intensity index; and $T$ denotes the duration, in days, of the regional high-temperature process.

(3) Comprehensive intensity evaluation grades and criteria

According to current operational regulations, the climate period adopts the most recent 30 a (1991-2020). Based on the proportions of regional high-temperature processes in the latest climate period, the comprehensive intensity of regional high-temperature processes is divided into four grades: general, relatively strong, strong, and extremely strong (Table 1).

**Table 1 Comprehensive intensity classification and criteria for regional high-temperature processes**

| Intensity grade | Extremely strong | Strong | Relatively strong | General |
|---|---|---|---|---|
| Percentile of the comprehensive intensity index | >95% | 95%–80% | 80%–50% | \$ \$50% |

In addition, this paper also uses methods such as linear trend estimation and correlation coefficients to examine the variation trends of element series and the significance of those trends. The moving-average method is used for trend fitting; this method is equivalent to a low-pass filter and uses smoothed values of a specified time series to display the variation trend. Meanwhile, the Mann-Kendall (M-K) test is adopted to examine abrupt-change characteristics of the elements

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## 2 Results and Analysis

### 2.1 Basic Climatic Characteristics of High Temperatures in Shaanxi Province

The spatial distribution of the multi-year average number of high-temperature days in Shaanxi Province during 1971-2024

The distribution (Fig. 2) shows that, overall, the number of high-temperature days is lower in the north and higher in the south, and is greater in plains and river valleys than on plateaus and in mountainous areas. Among these areas, the central-eastern Guanzhong Plain and the Ankang valley in southern Shaanxi are centers with large numbers of high-temperature days, with a climatological mean of 12-27 d; in the remaining parts of the province, high-temperature days are relatively fewer, with a climatological mean of 0-11 d. Further analysis indicates that within the three different climatic regions of Shaanxi—northern Shaanxi, Guanzhong, and southern Shaanxi—the distribution of high-temperature days shows a pattern of fewer in the west and more in the east. In northern Shaanxi, the annual mean number of high-temperature days is generally low, but along the Yellow River in the east the number reaches 5-11 d, more than the 1-4 d in the western part. As the area with the largest number of high-temperature days in Shaanxi, the Guanzhong Plain also exhibits a distribution characterized by more days in the east than in the west: 16-26 d in the central-eastern part of the plain and 12-15 d in the west. In southern Shaanxi, Hanzhong and Shangluo have fewer high-temperature days than Ankang, but overall they also show a west-low/east-high spatial pattern. In the eastern part of the Ankang valley, the number of high-temperature days is 14-27 d; extending westward to the Hanzhong valley, it gradually decreases to 4-11 d. In Shangluo, high-temperature days are mostly 6-12 d, slightly higher than in Hanzhong.

**Fig. 2** Distribution of the climatological mean number of high-temperature days from 1971 to 2024
Legend: number of days/d: 0.0-5.5; 5.5-11.0; 11.0-16.5; 16.5-22.0; 22.0-27.5. Scale: 0-100 km.

From the annual variation series of high-temperature days in Shaanxi Province (Fig. 3), it can be seen that during 1971-2024 the provincial mean number of high-temperature days showed a marked increasing trend amid interdecadal oscillations. Before the mid-1990s, most years had negative anomalies; after the mid-1990s, most years had positive anomalies. The five years with the largest numbers of high-temperature days all occurred after the mid-1990s: 1997 (24 d), 2002 (18 d), 2017 (21 d), 2022 (25 d), and 2024 (19 d). The 5-a moving-average series further highlights the stable transition in 1997 from fewer to more high-temperature days: among the 22 a before 1997, 21 a had negative anomalies, whereas among the 28 a from 1997 onward, 26 a had positive anomalies, with only 2 a showing slight negative anomalies. From the linear trend, the increase rate of the provincial mean annual number of high-temperature days was 1.6 $\mathrm{d}\cdot(10\mathrm{a})^{-1}$, and this increasing trend exceeded the 99% significance level. The M-K test further indicates that an abrupt change in this increasing trend occurred in 2010, after which the increase in high-temperature days further strengthened. Based on the linear trend change, moving average, and M-K test of high-temperature days, it can be seen that over the past 54 a the number of high-temperature days in Shaanxi Province has shown a significant increasing trend, and that this increase has become more pronounced in the 21st century.

**Fig. 3** Time series of anomalies in the annual number of high-temperature days in Shaanxi Province from 1971 to 2024
Legend: 5-a moving average; linear trend; anomaly of high-temperature days. Axes: anomaly of high-temperature days/d; year.

The climatological mean high-temperature intensity in Shaanxi Province during 1971–2024 has spatial distribution characteristics similar to those of the number of high-temperature days (Fig. 4), generally showing a spatial pattern of lower values in the north and higher values in the south, and lower values in the west and higher values in the east. Among them, Guanzhong

**Fig. 4** Distribution of the climatological mean high-temperature intensity from 1971 to 2024
Legend: intensity/℃: 35.6–35.9; 35.9–36.2; 36.2–36.5; 36.5–36.8; 36.8–37.1. Scale: 0–100 km.

The central and eastern parts of the Guanzhong Plain and the Ankang river-valley area in southern Shaanxi are high-value areas of high-temperature intensity within Shaanxi Province, with a multi-year mean high-temperature intensity of 36.5–37.0 °C. Along the Yellow River in eastern northern Shaanxi, the western Guanzhong Plain, and the Hanzhong and Shangluo river-valley areas, the multi-year mean high-temperature intensity is 36.0–36.5 °C. In the remaining areas of the province, high-temperature intensity is relatively weak; in central and western northern Shaanxi, the southern margin of the Loess Plateau in northern Guanzhong, and the Qinba mountainous area in southern Shaanxi, the high-temperature intensity is 35.7–36.0 °C.

Similar to the interdecadal variation characteristics of the number of high-temperature days, high-temperature intensity in Shaanxi Province from 1971 to 2024 (Fig. 5) also shows an evident linear strengthening trend. Before the mid-1990s, high-temperature intensity was weaker than normal in most years, whereas after the mid-1990s it was stronger than normal in most years. The 5-a moving-average series shows that, beginning in 1997, high-temperature intensity steadily shifted from weak to strong: all 22 a before 1997 were weaker than normal, while among the 28 a from 1997 onward, 25 a were stronger than normal and only 3 a were slightly weaker. In terms of the linear trend, the province-wide mean annual high-temperature intensity increased at a rate of $0.076\,^{\circ}\mathrm{C}\cdot(10a)^{-1}$. This strengthening trend exceeded the 99% significance level, and the M-K test further indicates that a sudden strengthening of high-temperature intensity occurred in Shaanxi Province in 1999. Analysis of the linear trend, moving average, and M-K test of high-temperature intensity shows that, over the past 54 a, high-temperature intensity in Shaanxi Province has exhibited a significant strengthening trend.

## 2.2 Basic climatic characteristics of regional high-temperature processes in Shaanxi Province

In summary, under the background of climate warming, the number of high-temperature days in Shaanxi Province has increased and the intensity has strengthened, which is basically consistent with previous research conclusions[27-29]. Against this background, this study further analyzes the climatic change characteristics of large-scale regional high-temperature processes in Shaanxi Province, in order to objectively understand the evolution of regional high-temperature events over the past 54 a and to provide a scientific basis for heat prevention and cooling, agricultural disaster prevention, water-resource management, and related work.

### 2.2.1 Occurrence frequency

From 1971 to 2024, a total of 226 regional high-temperature processes occurred in Shaanxi Province, with an average of 4 occurrences per year. When calculating the occurrence frequency for each 10-day period, the principle of merging overlapping time periods was adopted: whenever a high-temperature process intersected with the time range of a 10-day period, it was counted in the occurrence frequency of that period. The occurrence frequency of regional high-temperature processes in Shaanxi Province by 10-day period shows a unimodal distribution. Regional high-temperature processes occurred in every month from April to September, but were mainly concentrated from mid-June to mid-August, accounting for 84% of the total annual frequency; during this interval, the high-temperature frequency in each 10-day period reached more than 20 occurrences (Fig. 6). Among them, the frequency was highest in early July, reaching 45 occurrences, followed by late June, with 39 occurrences.

### 2.2.2 Average intensity

During 1971–2024, the average intensity of a single regional high-temperature process in Shaanxi Province was 36.5 °C. Among the 226 processes, most had an average intensity between 36 and 37 °C, totaling 176 occurrences and accounting for 78% of all processes; 31 processes had an average intensity between 37 and 38 °C, accounting for 14%; 15 processes had an average intensity below 36 °C, accounting for 7%; and processes with an average intensity of 38 °C or above were the fewest, with only 4 occurrences, accounting for 2%. Among these, the regional high-temperature process that occurred on July 14–15, 2022 had the highest average intensity, reaching 39 °C. The three regional high-temperature processes that occurred on June 7–8, 1973, July 17–18, 1999, and June 9–10, 2023 had the lowest average intensity, all at 35.8 °C.

### 2.2.3 Coverage range

In this study, the coverage range of a regional high-temperature process is represented by the number of stations experiencing high temperature during that process. From 1971 to 2024, the average coverage range of a single regional high-temperature process in Shaanxi Province was 54 stations, accounting for 57% of all observation stations in the province. Most regional high-temperature processes covered between 30 and 80 stations, with 195 occurrences, accounting for 86% of all processes and 32%–84% of the total number of observation stations in the province. Next, 19 processes had a coverage range greater than 80 stations, accounting for 8% of all processes and more than 84% of the province' s total observation stations. Processes covering fewer than 30 stations were the least frequent, with 12 occurrences, accounting for 5% of all processes. Among them, the two processes that occurred on June 15–19, 2006 and July 29–August 3, 2021 had the largest coverage range, each involving 93 stations and basically covering the whole province; during these two processes, 67 and 53 stations, respectively, recorded high temperatures above 38 °C, and 34 and 11 stations recorded high temperatures above 40 °C. The process that occurred on August 16–17, 2017 had the smallest coverage range, involving only 25 stations and mainly affecting eastern Guanzhong and central southern Shaanxi.

*In-figure labels for Fig. 5:* 5-a moving average; linear trend; high-temperature intensity anomaly; y-axis: high-temperature intensity anomaly/°C; x-axis: year.

**Fig. 5** Anomaly variation series of annual mean high-temperature intensity in Shaanxi Province from 1971 to 2024

**Fig. 5** Anomaly variation of average high temperature intensity in Shaanxi Province from 1971 to 2024

*In-figure labels for Fig. 6:* y-axis: number of processes/times; x-axis: time; late April, mid-May, early June, late June, mid-July, early August, late August.

**Fig. 6** Frequency of regional high-temperature processes by 10-day period in Shaanxi Province

**Fig. 6** Frequency of regional high temperature processes in every 10 days in Shaanxi Province

### 2.2.4 Duration

Duration is an indicator reflecting the persistence of a regional high-temperature process[36]. The longer a high-temperature process lasts, the greater its impacts on human health, water-use risk, and agricultural drought. From 1971 to 2024, the mean duration of a single regional high-temperature process in Shaanxi Province was 4 d. Among all 226 regional high-temperature processes, most lasted 2–4 d, totaling 174 events and accounting for 77% of the total. Specifically, processes lasting 2 d occurred most frequently, reaching 93 events and accounting for 41%; those lasting 3 d and 4 d occurred 45 and 36 times, respectively, accounting for 20% and 16%; processes lasting 5–10 d were relatively fewer, totaling 44 events and accounting for 20%; and processes lasting 11–14 d occurred least frequently, only 8 events, accounting for just 4% (Fig. 7). Among them, the process from 2 to 15 August 2022 had the longest duration, reaching 14 d. This event covered 78 stations, accounting for 82% of all stations, and its integrated intensity reached the exceptionally strong grade.

**Fig. 7** Frequency of the regional high-temperature process with different durations in Shaanxi Province

### 2.2.5 First start and last end dates

Overall, during 1971–2024, regional high-temperature processes in Shaanxi Province began as early as April and ended as late as September. The multi-year mean first-start date was 12 June. Among them, 29 April 2006 was the earliest first-start date in 54 a, 44 d earlier than the multi-year mean; 22 July 1976 was the latest first-start date, 40 d later than the multi-year mean. The difference between the earliest and latest first-start dates was 84 d. The multi-year mean last-end date was 5 August. Among them, 4 June 1984 was the earliest last-end date in 54 a, 62 d earlier than the multi-year mean; 10 September 1999 was the latest last-end date, 36 d later than the multi-year mean. The difference between the earliest and latest last-end dates was 98 d.

In this study, the time span from the first-start date to the last-end date of regional high-temperature processes in a year is defined as the high-temperature season[24]. The analysis shows that, during 1971–2024, the mean length of the high-temperature season in Shaanxi Province was 55 d. The shortest high-temperature season occurred in 1984: regional high temperatures began on 3 June, 9 d earlier than the multi-year mean, and ended on 4 June, 62 d earlier than the multi-year mean; thus, the high-temperature season lasted only 2 d. The longest high-temperature season occurred in 2024: the first regional high-temperature process began on 23 May, and the last ended on 9 September. The high-temperature season lasted as long as 110 d; 13 regional high-temperature processes occurred during the year, indicating a pronounced persistence of high temperatures.

## 2.3 Long-term trends of regional high-temperature processes in Shaanxi Province

### 2.3.1 Trend in occurrence frequency

From 1971 to 2024, the annual frequency of regional high-temperature processes in Shaanxi Province showed an overall significant increasing trend, with an increase rate of 0.6 events $\cdot(10a)^{-1}$, exceeding the 99% significance level (Fig. 8). The changes in the decadal mean frequency indicate that, although the frequency of regional high-temperature processes exhibited obvious interdecadal fluctuations, it also showed a clear increasing tendency. The mean frequency was 4 events in the 1970s and 2 events in the 1980s, increased to 5 events after the 1990s, was 4 events in the first decade of the 21st century, and has reached an annual mean of 6 events since 2010, the highest period in nearly 54 a. In particular, during the most recent 5 a, the mean annual frequency was as high as 7 events. Of the 6 years with the highest frequencies over the past 54 a, all occurred after the 1990s, and 4 occurred after 2005; among them, 2024 had the highest frequency, reaching 13 events. Thus, under the background of climate warming, regional high-temperature events in Shaanxi Province show a significant tendency toward more frequent occurrence.

**Fig. 8** Interannual variation of the regional high-temperature process frequency in Shaanxi Province from 1971 to 2024

### 2.3.2 Trend in mean intensity

As shown in Fig. 9, during 1971–2024, the annual mean intensity of regional high-temperature processes in Shaanxi Province showed a slight increasing trend at a rate of $0.04\,^{\circ}\mathrm{C}\cdot(10a)^{-1}$. However, the M-K test results show that the annual mean intensity of regional high-temperature processes in Shaanxi Province over the past 54 a

**Fig. 9** Interannual variation of the regional high-temperature process mean intensity in Shaanxi Province from 1971 to 2024

The intensity showed an abrupt strengthening in 2001, close to the timing of the abrupt change in the mean intensity of regional high-temperature processes in China in 2002 [24]. Judging from the year-to-year variation in mean intensity, the strongest year was 2022, followed by 2005, both occurring since the beginning of the 21st century. The mean intensity of high-temperature processes has increased markedly since the 21st century: before the 21st century, the annual mean intensity of high-temperature processes was 36.5 °C, whereas since the 21st century it has reached 36.6 °C, a difference of 0.1 °C.

### 2.3.3 Variation trend in duration

From 1971 to 2024, the annual maximum duration of regional high-temperature processes in Shaanxi Province showed an increasing trend at a rate of 0.6 d · $(10a)^{-1}$, exceeding the 95% significance level (Fig. 10). Since the late 1990s, the interannual amplitude of the maximum duration of these processes has increased markedly. Before 1997, the average was 5 d, with a maximum of 9 d; in and after 1997, the average was 7 d, clearly longer than before 1997, with a maximum of 14 d, and interannual fluctuations intensified. This feature is closely related to the frequent occurrence of extreme high-temperature events under climate warming, increasing the probability that regional high-temperature processes become extreme. Further analysis shows that, over the past 54 a, all regional high-temperature processes lasting 10 d or longer occurred in and after 1997, totaling as many as 13 events; the longest occurred in 2022 and lasted 14 d. The M–K test indicates that, over the past 54 a, the annual mean duration and annual maximum duration of regional high-temperature processes in Shaanxi Province underwent abrupt increases in 2010 and 2014, respectively.

**Fig. 10** Interannual variation of the maximum duration of regional high-temperature processes in Shaanxi Province from 1971 to 2024

### 2.3.4 Variation trend in spatial extent

With the frequent occurrence of extreme high-temperature events, the area covered and affected by high-temperature processes has also changed. For example, Fugu County in Shaanxi Province had no high-temperature events above 39 °C before 2005; on 22 June 2005, high-temperature weather above 39 °C occurred there for the first time, and subsequently such weather occurred repeatedly in July 2005, July 2010, and July 2024.

The year-to-year variation in the annual mean coverage extent of regional high-temperature processes in Shaanxi Province from 1971 to 2024, measured by the number of high-temperature stations, shows that over the past 54 a the coverage extent of regional high-temperature processes increased at a rate of 2.3 stations $\cdot(10a)^{-1}$, exceeding the 99% significance level (Fig. 11).

**Fig. 11** Interannual variation of the mean extent of regional high-temperature processes in Shaanxi Province from 1971 to 2024

Since the late 1990s, the coverage extent of regional high-temperature processes has shown a clear increasing trend. Before 1997, the average annual coverage extent was 48 stations; in and after 1997, it was 58 stations. After 1997, the annual mean coverage extent was mostly above 55 stations, and exceeded 60 stations in 9 a; before 1997, by contrast, only 3 a had a coverage extent above 55 stations, while the remaining 22 a were all below 55 stations. The M–K test further indicates that, over the past 54 a, the annual mean coverage extent of regional high-temperature processes in Shaanxi Province underwent an abrupt increasing trend in 1997, and this increasing trend has become more pronounced since the 21st century. This suggests that the regional response to climate warming has become increasingly evident: under the background of climate change, some areas that had not previously experienced high temperatures have begun to experience high-temperature weather, leading to a higher probability of large-scale regional high-temperature events and an increasing trend in the coverage extent of high temperatures.

### 2.3.5 Variation trends in the first start time and last end time

With climate warming, the onset of high temperatures in Shaanxi Province has become increasingly earlier, and their ending time increasingly later [27]. As shown by the year-to-year variation in the first start time and last end time of regional high-temperature processes in Shaanxi Province from 1971 to 2024, over the past 54 a the first start time of regional high-temperature processes in Shaanxi Province advanced at a rate of $3.9\,\mathrm{d} \cdot (10\mathrm{a})^{-1}$, exceeding the 95% significance level (Fig. 12). The M-K test further shows that the first start time underwent an abrupt advance in 1999. Before the 21st century, the first day of regional high-temperature processes mostly occurred after June, with the latest date on 22 July; after the 21st century, the first day advanced significantly, with 9 a having the first day before late May. In 2006, it advanced further to 29 April, the earliest date in the past 54 a, while the latest occurrence also advanced to 13 July, 9 d earlier than before the 21st century. Over the past 54 a, the last end time of regional high-temperature processes has generally shown a delayed trend at a rate of $2.7\,\mathrm{d} \cdot (10\mathrm{a})^{-1}$. Its interdecadal fluctuations are marked, and after the 1990s the last end time showed a clear delayed trend. The M-K test results show that the last end time underwent an abrupt delay in 2016. Year-by-year analysis indicates that, during 1971–1990, the last end time of regional high-temperature processes occurred after early August in 6 a, accounting for

*In-figure labels for Fig. 12:* Legend: first start date; linear trend of first start date; last end date; linear trend of last end date; high-temperature season; linear trend of high-temperature season. Axes: date/month-day; year; high-temperature season/d.

**Figure 12** Interannual variation in the first start date, last end date, and high-temperature season of regional high-temperature processes in Shaanxi Province from 1971 to 2024

*Fig. 12 Interannual variation of the regional high temperature process first start date, last end date, and high-temperature season in Shaanxi Province from 1971 to 2024*

was 32%. During 1991–2024, there were 16 years in which the last ending date occurred after early August, accounting for 47%. In particular, since the beginning of the 21st century, the last ending date of high-temperature processes has shown a stable delaying trend. Especially in the 15 years after 2010, the last ending date occurred after early August in 10 years, accounting for as much as 67%.

Affected by the earlier first start date and the delayed last end date of high-temperature processes, the length of the high-temperature season in Shaanxi Province over the past 54 years has shown a significant lengthening trend at a rate of 6.8 d $\cdot$ $(10a)^{-1}$, exceeding the 99% significance level (Fig. 12). The M–K test results show that an abrupt increase in the high-temperature season occurred in 2011. The multi-year average high-temperature season over the past 54 years was 55 d; however, before the 21st century the multi-year average high-temperature season was 45 d, whereas after the 21st century it was 66 d. In particular, since 2010, only 2 years were below 55 d, while all other years were above 55 d; in 2024, the high-temperature season reached 110 d, the longest in the past 54 years.

### 2.3.6 Trends in comprehensive intensity

Comprehensive intensity is an evaluation index that comprehensively considers the effects of factors such as the duration, coverage, and mean intensity of a regional high-temperature process. An analysis of the comprehensive intensity index of regional high-temperature processes occurring year by year and event by event in Shaanxi Province from 1971 to 2024 shows that, over the past 54 years, the annual mean comprehensive intensity of regional high-temperature processes in Shaanxi Province has exhibited a significant strengthening trend, exceeding the 95% significance level; this strengthening trend has been especially pronounced since the 21st century (figure omitted). The M–K test results show that the annual mean comprehensive intensity underwent an abrupt change in 2000, shifting from a weakening trend to a strengthening trend, and underwent another abrupt change in 2008, with the intensity further increasing. Over the past 54 years, the comprehensive intensity index of the single strongest high-temperature process within each year has also shown a significant strengthening trend, exceeding the 99% significance level (Fig. 13). The M–K test results indicate that, during the past 54 years, the annual maximum comprehensive intensity index of regional high-temperature processes in Shaanxi Province showed an abrupt enhancement in 2000, and another abrupt change occurred in 2009, with the intensity further increasing. This indicates that, since the 21st century, the extremity of regional high-temperature processes has increased, consistent with the climatic-change characteristics of more frequent and stronger extreme climate events under the background of intensified climate change. The abrupt strengthening trends in annual mean comprehensive intensity and annual maximum comprehensive intensity around 2000 and 2010 are related to abrupt changes in mean intensity, duration, coverage, and other factors during the same period.

*In-figure labels for Fig. 13:* Legend: annual values; linear trend. Axes: comprehensive intensity index; year.

**Figure 13** Interannual variation in the annual maximum comprehensive intensity index of regional high-temperature processes in Shaanxi Province from 1971 to 2024

*Fig. 13 Interannual variation of the regional high temperature process maximum comprehensive intensity index in Shaanxi Province from 1971 to 2024*

## 3 Conclusion

Using daily maximum temperature data from 95 national meteorological observation stations in Shaanxi Province from 1971 to 2024, this study systematically analyzed the spatiotemporal variation characteristics of high-temperature days, high-temperature intensity, and regional high-temperature processes in Shaanxi Province, and obtained the following main conclusions:

(1) Both the number of high-temperature days and high-temperature intensity in Shaanxi Province show a pattern of fewer in the north and more in the south, fewer in the west and more in the east, and more in plains and valleys than in plateau and mountainous areas. The central-eastern Guanzhong Plain and the Ankang valley in southern Shaanxi are the core high-value areas for both high-temperature days and intensity. In these areas, the multi-year average number of high-temperature days is 12–27 d, and the average high-temperature intensity is 36.5–37.0 ℃. Over the past 54 years, both the number of high-temperature days and the intensity have shown significant increasing trends. In the late 1990s, the number of high-temperature days shifted from below normal to above normal, and the intensity shifted from weak to strong, especially into⋯

Since entering the 21st century, the characteristics of more frequent and more intense high temperatures have become even more pronounced.

(2) Shaanxi Province experiences, on average, 4 regional high-temperature episodes each year, mainly concentrated from mid-June to mid-August. The mean intensity of a single episode is 36.5 °C; 78% of episodes have mean intensities between 36 and 37 °C, and the maximum intensity is 39 °C. The average coverage is 54 stations; 86% of episodes cover 30–80 stations, and 2 episodes basically covered the entire province. The average duration of a single episode is 4 d; 77% of episodes last 2–4 d, with the longest duration reaching 14 d. The earliest episode begins in April, and the latest ends in September. The multi-year average first episode begins on June 12, the last episode ends on August 5, and the average high-temperature period is 55 d.

(3) Over the past 54 years, the first start date of regional high-temperature episodes in Shaanxi Province has advanced significantly, while the frequency of occurrence, coverage, duration, high-temperature period, and integrated intensity have all shown significant increasing and strengthening trends. These climate-change characteristics mostly began after the late 1990s. Against the background of climate warming, the first start date and the last end date of regional high-temperature episodes in Shaanxi Province underwent abrupt advances and delays in 1999 and 2016, respectively; the high-temperature period abruptly lengthened in

2011; average intensity, duration, and coverage abruptly strengthened or increased in 2001, 2010, and 1997, respectively. Meanwhile, under the combined influence of average intensity, duration, and coverage, both the annual mean integrated intensity and the annual maximum integrated intensity abruptly strengthened in 2000, and further abruptly strengthened in 2008 and 2009.

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# Spatiotemporal characteristics of regional high temperature processes in Shaanxi Province from 1971 to 2024

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**Abstract:** Based on daily maximum temperature data from 95 national meteorological stations in Shaanxi Province from 1971 to 2024, regional high temperature processes (RHTPs) in Shaanxi Province were objectively identified following the operational method adopted by the Shaanxi Climate Center. Subsequently, their spatiotemporal characteristics were investigated using methods such as linear trend estimation, correlation coefficients, moving averages, and the Mann–Kendall test. The following conclusions were drawn: high temperature events in Shaanxi Province are primarily concentrated in the central-eastern Guanzhong Plain and the Ankang River Valley of southern Shaanxi. Both the frequency and strength of high temperature events in Shaanxi Province are generally higher in the south and east and lower in the north and west. RHTPs occur at an annual average frequency of four times, predominantly between mid-June and mid-August. For each process, the mean duration reaches 4 days, and the average intensity typically ranges between 36 ℃ and 37 ℃. Against the backdrop of global climate warming, both the frequency and strength of high temperature events in Shaanxi Province have increased over the past 54 years. RHTPs in Shaanxi Province have exhibited pronounced climate change characteristics during this period. These include increased frequency, enhanced intensity, prolonged duration, expanded spatial coverage, advanced onset, delayed termination, and strengthened comprehensive intensity. These changing characteristics initially emerged in the late 1990s and have become particularly pronounced since the beginning of the 21st century.

**Keywords:** climate warming; high temperature processes; spatiotemporal characteristics; Shaanxi Province

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