



Assessment of Extreme Temperature in the Qinghai-Xizang Plateau and Surrounding Areas

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Abstract

This study utilizes hourly temperature data from the China Meteorological Administration to assess extreme temperatures on the Qinghai-Xizang Plateau. The annual and seasonal variations of extreme temperatures from 2005 to 2020 are analyzed using methods such as the climate tendency rate, T-test, and Mann-Kendall mutation test. Additionally, the study explores the impact of meteorological factors on sudden changes in extreme temperature indices. The results show that the frequency of warm weather increases at a rate of 12 days per decade. The earliest occurrence of high-temperature weather has advanced to the end of March and is expected to continue advancing. The minimum value of the maximum temperature (TXn) shows a decreasing trend, whereas the maximum value of the minimum temperature (TNx) shows an increasing trend, with annual variation rates of -2.5°C per decade and 2°C per decade, respectively. These trends are consistent with their seasonal variations. The number of warm nights (TX90p) and cold nights (TN10p) shows positive annual growth trends, with rates of 11.2 days per decade and 19.9 days per decade, respectively. Both indices exhibit positive growth trends across all seasons. The annual growth rates of frost days (FD) and summer days (SU) are 27 days per decade and 6.8 days per decade, respectively. Notably, the growth rate of frost days (FD) is significantly higher than that of summer days (SU) in both annual and seasonal variations.

Subject Areas

Atmospheric Sciences

Keywords

Qinghai-Xizang Plateau, Extreme Temperature, M-K Test

1. Introduction

Global climate change is one of the most significant challenges facing the world

today, with profound impacts on human society, the economy, and ecosystems [1]-[4]. Since the 20th century, greenhouse gas emissions and surface temperatures have continuously risen. Extreme temperature events, a primary manifestation of climate change, have attracted significant global attention. Over the past few decades, the frequency, intensity, and duration of these events have increased, posing substantial challenges to human society and the natural environment.

Extreme temperature events include both extreme high- and low-temperatures, each exhibiting distinct characteristics across various regions and seasons. Extreme high-temperature events lead to natural disasters, such as heatwaves, droughts, and forest fires, directly impacting human health, agricultural production, and water resource management. Extreme low-temperature events can cause cold waves, heavy snowfall, and frost damage, affecting crops, livestock, infrastructure, transportation, and energy supply. The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) in 2023 highlighted that the continuous rise in global temperatures over the past century, now 1.1°C higher than pre-industrial levels, is due to fossil fuel burning and unsustainable energy and land use [1]. This increase has made extreme weather events more frequent and intense, further endangering natural and human populations worldwide.

The Qinghai-Xizang Plateau, located in southwestern China, is the world's highest and one of its largest plateaus. Its complex terrain, with altitudes ranging from 4000 to 8000 meters, creates a unique climate and geographical environment. Extreme temperature events on the plateau, including extreme cold and heat, profoundly affect local ecosystems, water resource distribution, and the climate and environment of surrounding regions [5]. According to Wang and Ma [4], the land surface energy changes significantly impact the local climate at Zhufeng Station on the Qinghai-Xizang Plateau. The Qinghai-Xizang Plateau is the source of major rivers in Asia and is crucial for water supply in China and surrounding areas. Its ecological environment significantly impacts global ecosystems, with issues such as accelerated glacier melting and grassland degradation receiving widespread attention.

Studying extreme temperature events on the Qinghai-Xizang Plateau holds significant scientific and practical value for disaster forecasting, early warning, and prevention. Numerous studies have shown that extreme weather phenomena, such as heatwaves and severe cold, significantly impact human health, ecosystems, and socio-economic development. Research analyzing the spatial and temporal characteristics of extreme temperatures in China from 1956 to 2005 found that both extreme high- and low-temperatures show warming trends, especially from 1986 to 2005, when the warming trend was three times that of the period from 1956 to 2005 [6]. Other studies have analyzed changes in extreme temperature indices on the Qinghai-Xizang Plateau from 1961 to 2018, showing a significant increase in extreme warm indices and a significant decrease in extreme cold indices over the past 58 years.

Shigute *et al.* found that in four major cities in South Africa, except for some lower extreme temperature indices, all temperature indices analyzed showed significant annual variation trends under SSP2-4.5 and SSP5-8.5 scenarios, with coastal cities having slower growth in extreme weather indices compared to inland cities [7]. Patel *et al.* analyzed the annual and seasonal extreme temperature changes in the West Bengal basin from 1951 to 2020 and found that extreme high-temperatures showed a decreasing trend in winter and summer from 1951 to 2020, while an increasing trend was observed from 2001 to 2020 [8].

Van Der Woude *et al.* reported that severe droughts in the European continent could lead to a reduction in forest carbon absorption [9]. Alexander *et al.* observed global changes in daily climate extremes of temperature and precipitation, further underscoring the broad impacts of climate change [10]. Ning *et al.* reported changes in temperature and precipitation extremes in the Hengduan Mountains of the Qinghai-Xizang Plateau from 1961 to 2008 [11]. Jayasekara *et al.* investigated tropical cyclones in the North Indian Ocean and their linkage to extreme weather events in Sri Lanka [12]. Qiao *et al.* provided insights into adaptation to extreme environments on the Qinghai-Xizang Plateau through genome and transcriptome studies [13].

Studying extreme temperature changes on the Qinghai-Xizang Plateau can serve as an important indicator of the impacts of climate change. Extreme high- and low-temperature events on the plateau reflect trends in climate system changes, providing crucial references for understanding global climate change [14]. Additionally, studying these events can provide scientific evidence and policy recommendations for sustainable development and ecological protection in the Qinghai-Xizang Plateau region [15]. Therefore, investigating extreme temperature events on the Qinghai-Xizang Plateau is of great importance. It not only helps to understand the mechanisms of global climate change impacts in depth but also provides crucial references for ecological environment protection, socio-economic development, and international cooperation in the Qinghai-Xizang Plateau region.

This study utilizes hourly temperature data from the China Meteorological Administration to assess extreme temperature variations on the Qinghai-Xizang Plateau from 2005 to 2020. The research employs methods such as climate tendency rate analysis, T-test, and Mann-Kendall mutation test to analyze annual and seasonal changes in extreme temperatures. This research aims to provide insights into the spatiotemporal characteristics of extreme temperature changes on the Qinghai-Xizang Plateau, offering scientific foundations for climate adaptation and disaster risk reduction strategies (see **Figure 1**).

2. Data and Methods

2.1. Data

This study primarily analyzes changes in extreme temperatures over the past 16 years on the Qinghai-Xizang Plateau. The data used in this research is sourced from

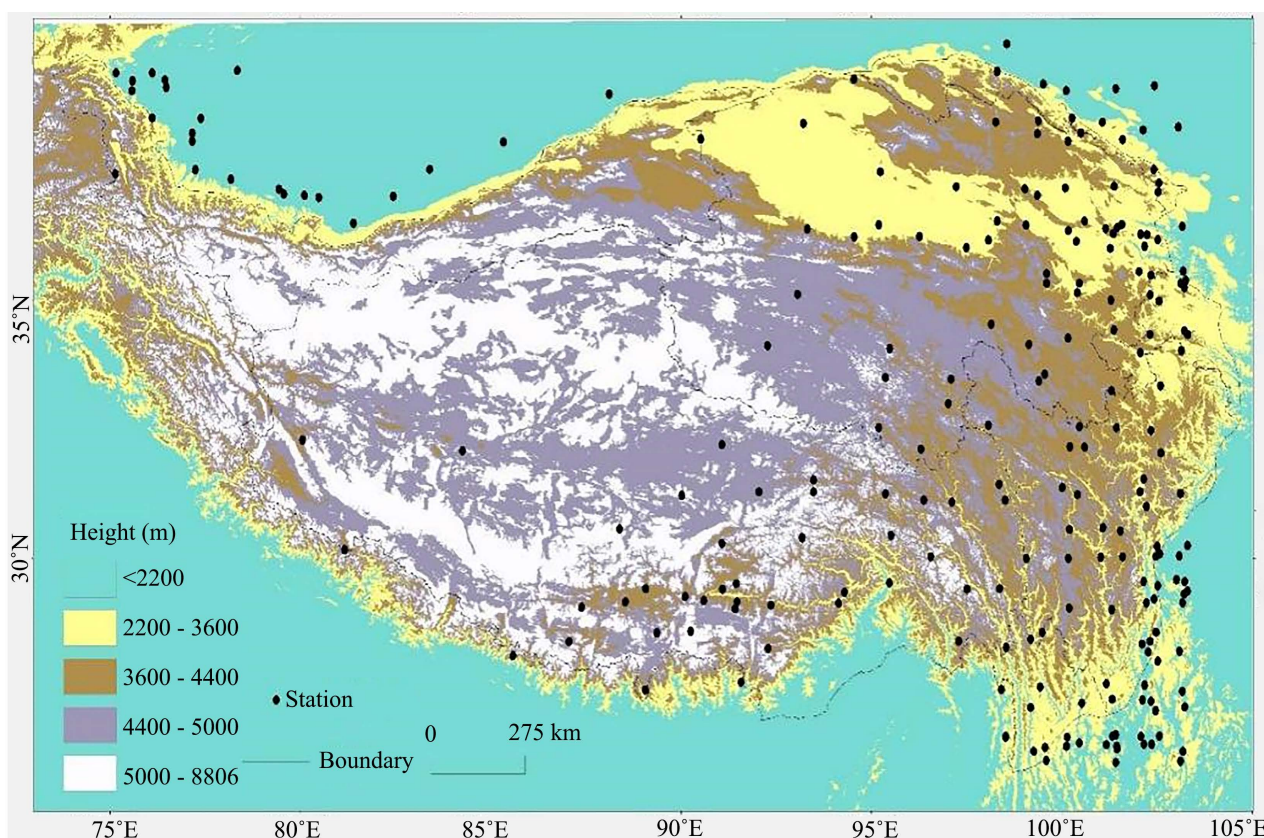


Figure 1. Distribution of sites on the Qinghai-Xizang Plateau.

the meteorological station observations of the National Climate Center in the Qinghai-Xizang Plateau region. The selected data covers the period from 2005 to 2020, during which the distribution of ground meteorological observation stations in China was dense, ensuring that the measured data is highly reliable and scientifically valid. The study area ranges in longitude from $26^{\circ}03'$ to 40° and in latitude from $75^{\circ}14'$ to $103^{\circ}3'$.

The extreme indices (**Table 1**) selected in this paper are defined for both annual and seasonal scale studies. For convenience in seasonal division, this paper defines March to May as spring, June to August as summer, September to November as autumn, and December to February as winter. It has been confirmed that there are no instances where the minimum value of the maximum temperature (TXn) equals the maximum value of the minimum temperature (TNx).

Table 1. Definition of the extreme temperature index for the Qinghai-Xizang Plateau.

	Extreme Temperature Index	Abbreviation	Definition	Unit
Extreme Indices	Maximum Temperature Minimum	TXn	The lowest value of the maximum temperature in a year (season)	$^{\circ}\text{C}$

Continued

	Minimum Temperature Maximum	TNx	The highest value of the minimum temperature in a year (season)	°C
	Frost Days	FD	Number of days with minimum temperature below 0°C in a year (season)	d
	Summer Days	SU	Number of days with maximum temperature above 25°C in a year (season)	d
Relative Indices	Warm Day Count	TX90p	Number of days with maximum temperature above the 90 th percentile in a year (season)	d
	Cold Night Count	TN10p	Number of days with minimum temperature below the 10 th percentile in a year (season)	d

2.2. Analysis Methods

2.2.1. Linear Climate Propensity Rate Analysis

The linear climate tendency rate is an indicator used to describe climate change trends. It is typically used to analyze the trend of climate factors (such as temperature, precipitation, etc.) over a certain period. By performing linear fitting on climate data, it obtains the linear trend of climate factors over time, thus assessing the rate and direction of climate change. The univariate linear regression equation established using the linear climate tendency rate is:

$$x_i = b_0 + bt_i \quad (i = 1, 2, \dots, n) \tag{1}$$

where X_i is the i -th meteorological variable in the sample, t_i is the time corresponding to X_i , b is the linear regression coefficient, and b_0 is the linear regression constant. The relationship between b_0 and b is generally derived using the least squares method [16] [17]:

$$b = \frac{\sum_{i=1}^n x_i t_i - \frac{1}{n} \left(\sum_{i=1}^n x_i \right) \left(\sum_{i=1}^n t_i \right)}{\sum_{i=1}^n t_i^2 - \frac{1}{n} \sum_{i=1}^n (t_i)^2} \tag{2}$$

$$b_0 = \bar{x} - b\bar{t} \tag{3}$$

In the linear regression equation, the sign of the regression coefficient b reflects the trend of change: $b > 0$ indicates that the climate variable shows an upward trend over time, while $b < 0$ indicates a downward trend over time [16]. The magnitude of b also indicates the degree of the climate variable's tendency over time.

2.2.2. T-Test

The essence of the significance test of regression coefficients is to test whether the effect of the explanatory variable x_i on the dependent variable y is significant.

The steps of the test are as follows, the hypothesis of the first test is:

$$H_0 : \beta_i = 0 \quad (4)$$

$$H_1 : \beta_i \neq 0 \quad (5)$$

If H_0 holds, there is no true linear relationship between the dependent variable y and the explanatory variable x_i , *i.e.* changes in x_i do not have a significant linear effect on y . Otherwise, x_i is considered to have a significant linear effect on y .

Next, the test statistic t is calculated and the corresponding p-value is derived. Test statistic:

$$t = \frac{\hat{\beta}_i}{\sqrt{\text{Var}(\hat{\beta}_i)}} \sim t(n-k-1) \quad (6)$$

where $\sqrt{\text{Var}(\hat{\beta}_i)}$ is the standard deviation of the regression coefficient.

Finally, judgment is made based on the p-value. If the p-value is less than our pre-determined significance level α , the original hypothesis is rejected and it is considered that, *i.e.* the linear effect of the explanatory variable x_i on y is significant [18]. Otherwise, the original hypothesis cannot be rejected and the linear effect of x_i on y is considered insignificant.

2.2.3. Mann-Kendall (M-K) Test

The M-K test is an effective tool recommended by the World Meteorological Organization (WMO) for extracting the trend of sequence changes. Because the M-K test is not disturbed by individual outliers and can objectively reflect the trend of the time series, it is now widely used in the analysis of climatic parameters and hydrological sequences. Its calculation method is as follows.

Assume that the time series is X , and a sequence is listed as follows:

$$UF_k = \frac{s_k - E(s_k)}{\sqrt{\text{var}(s_k)}} \quad (k=1, 2, \dots, n) \quad (7)$$

where $UF_1 = 0$, $E(s_k)$ and $\text{var}(s_k)$ are the mean and variance of s_k , respectively, and x_1, x_2, \dots, x_n are independent of each other, they have the same continuous distribution, which can be introduced by the following equation:

$$E(s_k) = \frac{n(n+1)}{4} \quad (8)$$

$$\text{Var}(s_k) = \frac{n(n-1)(2n+5)}{72} \quad (2 \leq k \leq n) \quad (9)$$

where UF_k is a sequence of statistics calculated according to the order of the time series X , which is standard normal distribution, given the significance level α . In this paper, we take $\alpha = 0.05$. If $UF_i > UF_\alpha$, it indicates that there is a significant trend in the sequence. In accordance with the reverse order of the time series X , repeat the above process, so that:

$$UB_k = UF_k \quad (k = n, n-1, \dots, 1), \quad UB_i = 0 \quad (10)$$

3. Results and Analysis

3.1. Frequency Changes of High-Temperature Weather

Due to partially missing data on daily maximum temperatures, which could lead to errors, this study will not use the extreme high-temperature index (TXx). Instead, it redefines the number of high-temperature days reaching the threshold of 35°C as the high-temperature index. To facilitate a more intuitive comparison, this study calculates the average maximum, minimum, and mean temperatures across all years for 215 stations, using these values as a baseline for the high-temperature index. As shown in **Figure 2**, the annual average maximum and minimum temperature change rates on the Qinghai-Xizang Plateau are 0.7°C per decade and 2.3°C per decade, respectively, both indicating positive growth. This suggests that the temperature on the Qinghai-Xizang Plateau has been increasing over the years, becoming progressively warmer. Significant fluctuations occurred during 2007-2009 and 2010-2015, but temperatures rose following these fluctuations. According to **Figure 3**, the average maximum summer temperature on the Qinghai-Xizang Plateau is 23.2°C, and the average minimum summer temperature is 10.4°C. The temperatures in spring and autumn are similar, but autumn, being a transition period from warm to cold, has a slightly lower average temperature. The average minimum winter temperature is -10.7°C. Overall, the multi-year average temperature across the four seasons on the Qinghai-Xizang Plateau is around 8.2°C, making changes in high temperatures more noticeable. **Figure 4** shows that the number of days with temperatures reaching 35°C across all stations from 2005 to 2020 is gradually increasing, with an increase rate of 12 days per decade. In 2020, the number of high-temperature days reached 36, the highest in the past 16 years, and also the year with the greatest increase. This increasing trend in high-temperature days corresponds with the continuous growth in extreme warm temperature indices (TNx, TX90p, SU). Additionally, the occurrence of high-temperature days is advancing: in 2005, the earliest high temperature appeared on May 31, marking the beginning of summer; by 2020, high temperatures appeared as early as March 31, two months earlier than in 2005. This advancement in high-temperature occurrence indicates that extreme temperature events are becoming more frequent.

3.2. Trend Analysis of Extreme Temperature Event Indices

From 2005 to 2020, the seasonal and annual climate tendency rates of the minimum value of the maximum temperature (TXn) on the Qinghai-Xizang Plateau were $1.5^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $-0.3^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $0.006^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $-0.25^{\circ}\text{C}\cdot 10\text{a}^{-1}$, and $-0.25^{\circ}\text{C}\cdot 10\text{a}^{-1}$, respectively. The correlation coefficients for all four seasons and the entire year did not pass the significance test. The maximum value of the minimum temperature (TNx) increased at rates of $5.7^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $1.9^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $0.8^{\circ}\text{C}\cdot 10\text{a}^{-1}$, $3.9^{\circ}\text{C}\cdot 10\text{a}^{-1}$, and $2.0^{\circ}\text{C}\cdot 10\text{a}^{-1}$ for the four seasons and annually, respectively. These increases were significant at the 0.05 level in summer, winter, and annually, and even reached the 0.01 significance level in spring.

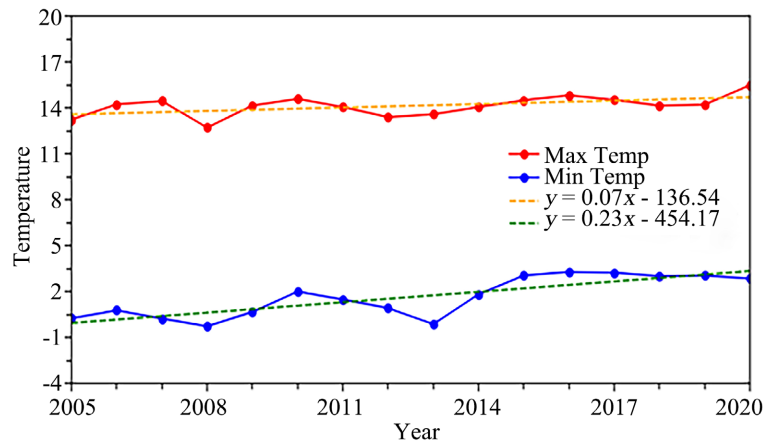


Figure 2. Average annual temperature of the Qinghai-Xizang Plateau.

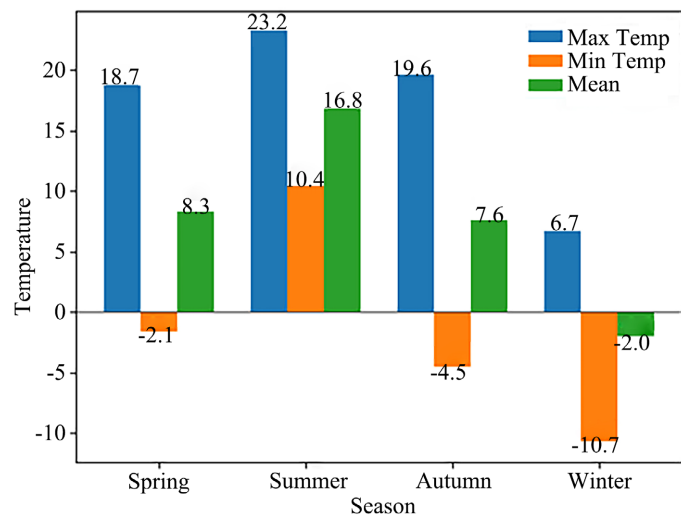


Figure 3. Multi-year seasonal average temperature of the Qinghai-Xizang Plateau.

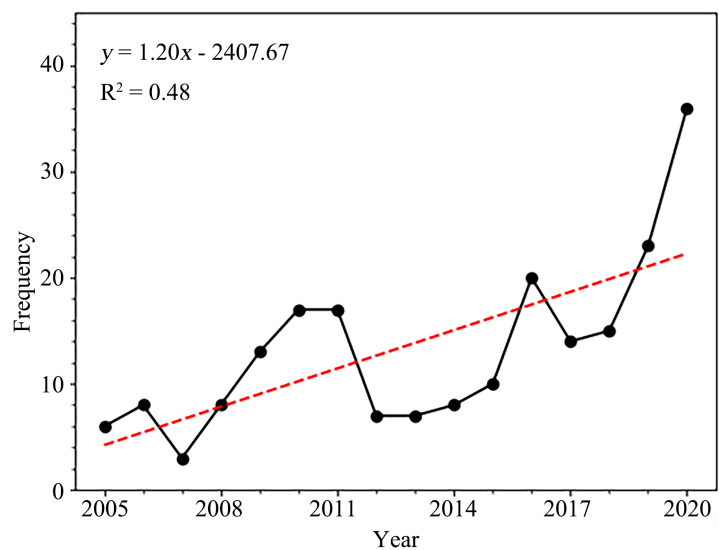


Figure 4. The frequency of high temperatures on the Qinghai-Xizang Plateau from 2005 to 2020.

The number of warm days (TX90p) showed a slight increase across the four seasons, but the annual rate of change significantly increased, reaching the 0.01 significance level for the entire year. The number of cold nights (TN10p) increased at rates of $1.7 \text{ d}\cdot 10\text{a}^{-1}$, $1.2 \text{ d}\cdot 10\text{a}^{-1}$, $2.2 \text{ d}\cdot 10\text{a}^{-1}$, $0.5 \text{ d}\cdot 10\text{a}^{-1}$, and $1.9 \text{ d}\cdot 10\text{a}^{-1}$ for the four seasons and annually, respectively. Except for winter, which did not pass the 0.05 significance test, the entire year all reached the 0.01 significance level. The number of frost days (FD) increased the least in summer, at $0.6 \text{ d}\cdot 10\text{a}^{-1}$, while the other three seasons and the entire year saw increases of over $14 \text{ d}\cdot 10\text{a}^{-1}$. The winter season had the largest climate tendency rate and correlation, with frost days reaching significance levels of 0.05 in summer and 0.01 in spring, autumn, and winter.

The number of summer days (SU) increased at rates of $3.7 \text{ d}\cdot 10\text{a}^{-1}$, $10.6 \text{ d}\cdot 10\text{a}^{-1}$, $2.8 \text{ d}\cdot 10\text{a}^{-1}$, $0.3 \text{ d}\cdot 10\text{a}^{-1}$, and $6.8 \text{ d}\cdot 10\text{a}^{-1}$ for the four seasons and annually, respectively, with all four seasons reaching the 0.01 significance level. In summary, the minimum value of the maximum temperature (TXn) shows a decreasing trend with no significant cooling. The maximum value of the minimum temperature (TNx) shows an increasing trend, with a significant increase in spring. Both the number of warm days (TX90p) and cold nights (TN10p) show increasing trends, with the number of cold nights increasing most significantly in spring, summer, and autumn. The number of frost days (FD) and summer days (SU) also show increasing trends, with significant increases in all four seasons (see **Table 2**).

Table 2. Trend analysis of extreme temperature indices.

Extreme Temperature Index	Spring		Summer		Autumn		Winter		Annual	
	Trend Rate	Correlation Coefficient	Trend Rate	Correlation Coefficient	Trend Rate	Correlation Coefficient	Trend Rate	Correlation Coefficient	Trend Rate	Correlation Coefficient
TXn	1.5	0.04	-0.3	-0.03	0.006	0	-2.5	-0.15	-2.5	-0.15
TNx	5.7	0.61**	1.9	0.3*	1.3	0.08	3.9	0.31*	2	0.35*
TX90p	0.3	0.06	0.2	0.02	0.4	0.07	0.7	0.11	11.2	0.63**
TN10p	1.7	0.61**	1.2	0.42**	2.2	0.42**	0.5	0.04	1.9	0.72**
FD	16.2	0.6**	0.6	0.3*	14.8	0.51**	39.9	0.66**	27	0.11
SU	3.7	0.48**	10.6	0.48**	2.8	0.51**	0.3	0.44**	6.8	0.1

Note: * indicates significance at the 0.05 level; ** indicates significance at the 0.01 level. Units: $^{\circ}\text{C} (\text{d})\cdot 10\text{a}^{-1}$.

3.3. M-K Test for Extreme Temperature Indices

The results of the MK mutation test (**Table 3**) indicate that among the six selected extreme temperature indices, only the maximum value of the minimum temperature, the number of frost days, and the number of summer days experienced mutations across all four seasons. The other three indices did not experience mutations in at least one season. The mutation years of the extreme warm indices (maximum value of the minimum temperature, number of warm days,

and number of summer days) show that the earliest mutation point for these indices occurred in spring, while the latest occurred in winter. Conversely, the mutation patterns for the extreme cold indices (TXn, TN10p, FD) are opposite to those of the warm indices. The mutation points for the warm indices occurred between 2011 and 2014, while those for the cold indices occurred between 2005 and 2008, indicating that the period from 2005 to 2014 was a transition period from cold to warm.

Table 3. Mutation years and differences before and after mutation for extreme temperature indices across seasons and annually.

Extreme Temperature Index	Spring		Summer		Autumn		Winter		Annual	
	Mutation Year	Difference	Mutation Year	Difference	Mutation Year	Difference	Mutation Year	Difference	Mutation Year	Difference
TXn	2012	7.3	\	\	\	\	2005	-2.4	2005	-2.4
TNx	2011	1.1	2014	0.7	2017	2.7	2015	-3.6	2011	1
TX90p	2011	0.4	\	\	2010	0.7	2019	1.7 d	2019	11.7 d
TN10p	2015	0.3	2017	1.7	2019	-1.4	\	\	2014	12.2
FD	2019	0.7	2014	1.5	2014	5.2	2014	32.5	\	\
SU	2019	5.9	2019	21.6	2019	3.8	2019	0.32	2008	-24

Note: \ indicates no mutation. Units: °C (d).

From **Table 3**, it is evident that the earliest mutation year for the maximum value of the minimum temperature occurred in spring, and the latest mutation year occurred in autumn. Compared to the minimum value of the maximum temperature, the spring mutation year for the maximum value of the minimum temperature was later, and the increase was much smaller. The number of warm days and cold nights experienced mutations in spring, autumn, and annually. In spring and autumn, the number of warm days mutated earlier and increased, while the number of cold nights decreased after mutating in autumn. Overall, although the mutation years for the number of warm days and cold nights differ significantly, their overall averages increased to varying degrees after the mutations.

Although the number of frost days experienced mutations in all four seasons, it was the only index among the six selected that did not mutate annually. The number of frost days increased to varying degrees in all four seasons after the mutations, with the largest increase occurring in winter. The number of summer days started mutating in 2019 across all four seasons, showing increases after the mutations. However, annually, the number of summer days began mutating in 2008 and decreased by 24 days after the mutation, which was the largest decrease.

The mutation points for the extreme temperature indices mostly occurred between 2011 and 2015 and 2017 and 2019. The period from 2011 to 2015 coincides with significant fluctuations in the annual average maximum and minimum tem-

peratures on the Qinghai-Xizang Plateau. After this period, temperatures increased, corresponding to the previously mentioned transition period. The mutation years for the cold indices were earlier than those for the warm indices, and all six extreme temperature indices mutated in spring, which may be related to the variable spring temperatures leading to changes in ground temperature.

4. Conclusions

This paper uses observational data from 225 stations in the Qinghai-Xizang Plateau region to calculate six extreme temperature indices. By analyzing both annual and seasonal variations, the following conclusions were drawn:

1) The frequency of high-temperature weather has been increasing over the years, with a rate of change of 12 days per decade ($12 \text{ d}\cdot 10\text{a}^{-1}$). Additionally, the earliest occurrence of high-temperature weather has advanced to the end of March, and this trend may continue in the future.

2) The minimum value of the maximum temperature (TX_n) shows a decreasing trend, while the maximum value of the minimum temperature (TN_x) shows an increasing trend, with annual rates of change of -2.5°C per decade and 2°C per decade, respectively. These trends are consistent with their seasonal trends.

3) The number of warm days (TX90p) and cold nights (TN10p) both show positive annual trends, with rates of change of 11.2 days per decade ($11.2 \text{ d}\cdot 10\text{a}^{-1}$) and 19.9 days per decade ($19.9 \text{ d}\cdot 10\text{a}^{-1}$), respectively. These indices also show positive trends across all four seasons, indicating that the number of warm days and cold nights will continue to increase in each season over the years.

4) The annual growth rates of frost days (FD) and summer days (SU) are 27 days per decade ($27 \text{ d}\cdot 10\text{a}^{-1}$) and 6.8 days per decade ($6.8 \text{ d}\cdot 10\text{a}^{-1}$), respectively. However, the growth rate of frost days is much higher than that of summer days both annually and seasonally.

The data used in this paper are derived from Chinese meteorological observations. Since the data are obtained from both instruments and manual observations, some stations may have missing or anomalous values, which could introduce biases in the study results. Additionally, some errors are inevitable during the data processing.

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Conflicts of Interest

The authors declare no conflicts of interest.

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