



Analysis and Evaluation of Extreme Precipitation Events over the Qinghai-Xizang Plateau

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Abstract

To explore the interannual variability and spatial distribution of extreme precipitation events on the Qinghai-Xizang Plateau, this study employs percentile threshold methods to determine extreme precipitation thresholds based on three-hourly weather data from 215 meteorological stations on the Qinghai-Xizang Plateau. Additionally, extreme precipitation indices are calculated, and their spatial distribution characteristics are investigated. The main findings are as follows: 1) From 2005-2020, the annual precipitation on the Qinghai-Xizang Plateau exhibited an upward trend, with the Mann-Kendall trend test indicating a significance level greater than 99%. Notably, around 2017, there was a significant abrupt change in the annual average precipitation, showing a decreasing trend from southeast to northwest in spatial distribution. The monthly average precipitation on the Qinghai-Xizang Plateau ranged from 1.86 to 72.86 mm, with the highest monthly average precipitation occurring in July and the lowest in December. Seasonal precipitation characteristics were similar to those of the monthly averages, with the highest precipitation in summer and the lowest in winter. 2) The extreme precipitation threshold values at stations on the Qinghai-Xizang Plateau ranged from 4.81 to 41.26 mm, with an average of 14.96 mm. The spatial distribution of these thresholds resembled that of annual precipitation, decreasing from southeast to northwest. The highest extreme precipitation threshold was observed in Liangshan Yi Autonomous Prefecture, while the lowest was near the Qandam Basin. 3) From 2005 to 2020, extreme precipitation amounts, extreme precipitation days, and extreme precipitation intensities at all stations on the Qinghai-Xizang Plateau showed upward trends, but the extreme precipitation contribution rate declined. This suggests that the frequency or intensity of non-extreme precipitation events (such as light or moderate rain) may be increasing, thus contributing more to the total precipitation. Although the Tarim Basin and Qilian Mountains did not exhibit high

levels of extreme precipitation amounts or days, their extreme precipitation contribution rates were relatively high, indicating that precipitation in these regions tends to occur in extreme forms.

Subject Areas

Atmospheric Sciences

Keywords

Qinghai-Xizang Plateau, Extreme Precipitation, Spatiotemporal Distribution, Trend Analysis, Percentile Threshold Method, Mann-Kendall Test

1. Introduction

The latest assessment by the Intergovernmental Panel on Climate Change (IPCC) makes it clear that human-induced greenhouse gas emissions have significantly increased global temperatures, indicating the severity of future climate change. In this context, extreme weather events are becoming more frequent and intense, and natural disasters such as rainstorms, floods, droughts and wildfires are emerging one after another [1]. The IPCC report also further emphasizes that the impact of climate change on socio-economic and human life is gradually deepening. As global temperatures continue to rise, extreme hydrological events such as extreme precipitation and floods have caused huge damage and casualties worldwide, which not only directly threaten human security and well-being, but also pose serious challenges to social and economic stability and sustainable development [2].

The acceleration of the water cycle on a global scale has changed the original spatial distribution pattern of precipitation. The research results of extreme precipitation events on the global scale show that the heavy precipitation events in most regions show an increasing trend, while the heavy precipitation events in a small part of regions are decreasing [3]. In an in-depth analysis of global climate data in the second half of the 20th century, Frich *et al.* found that the long-term change trend of global total precipitation was not obvious, but the number of days and intensity of extreme precipitation events showed a significant increase, which revealed an important shift in climate change patterns [4]. Similarly, Klein Tank *et al.* found in their study on precipitation trends in Europe that although the consistency of spatial trends was low, the wet-extreme index in Europe generally increased during the study period [5]. Roust *et al.* have observed a notable increase in the precipitation associated with extreme rainfall events in the central plateau region of Iran over the past several decades. This increase manifests itself in both the intensified intensity of individual precipitation events as well as in the overall frequency of extreme rainfall occurrences [6].

In China, Cao *et al.* conducted an in-depth spatio-temporal analysis of summer extreme precipitation in the central and eastern regions of the Qinghai-

Xizang Plateau, and found that the northern part of the plateau mainly increased, while the southern part increased or decreased, and the extreme precipitation index showed an obvious decadal transition in the 1970s [7]. The study of Wei *et al.* revealed the complexity and periodicity of precipitation changes in different regions of the Qinghai-Xizang Plateau [8]. Ma *et al.* pointed out that the extreme precipitation over the Qinghai-Xizang Plateau showed a decreasing trend from southeast to northwest [9]. In addition, he also proposed a method for estimating the critical rainfall of flood disasters on the Qinghai-Xizang Plateau [10]. Yao *et al.* studied the spatio-temporal variation of extreme precipitation in the central and eastern Qinghai-Xizang Plateau, and explored the contribution of different precipitation levels to total precipitation [11].

As the world's highest plateau, the Qinghai-Xizang Plateau holds a pivotal position in climate change research due to its unique terrain and ecosystem. Particularly in the realm of extreme precipitation studies, the significance of the Qinghai-Xizang Plateau cannot be overstated. Its glaciers serve as crucial regulators of the Asian and even global water cycle, not only providing a continuous source of water for numerous rivers, but also playing a pivotal role in stabilizing and modulating both global and regional climates. Consequently, a thorough investigation into extreme precipitation events over the Qinghai-Xizang Plateau is of paramount importance for understanding the water cycle and climate change across Asia and beyond.

Furthermore, extreme precipitation events on the Qinghai-Xizang Plateau can have profound impacts on local ecosystems and human societies. Given its unique terrain and fragile ecosystem, extreme precipitation can trigger severe natural disasters, posing significant threats to the livelihoods of local residents and the safety of infrastructure. Therefore, a deep dive into extreme precipitation is instrumental in accurately predicting and effectively mitigating the risks associated with these disasters, thereby safeguarding the lives and property of the people.

2. Materials and Methods

2.1. Study Area and Data Overview

The Qinghai-Xizang Plateau occupies 26.80% of China's total land area, and its vast geographical area covers about 2.57×10^6 square kilometers. As shown in **Figure 1**, it is located between $26^{\circ}00'12''$ N and $39^{\circ}46'50''$ N, spanning 13 degrees of latitude from south to north, and covering a width of 1532 kilometers; at the same time, it extends between $73^{\circ}18'52''$ and $104^{\circ}46'59''$ east, covering a length of 2945 km across 31 longitudes of the Eastern Hemisphere from east to west [12].

In this study, three-hour meteorological data from 215 meteorological stations on the Qinghai-Xizang Plateau were used. The distribution of these sites can be seen in **Figure 2**. These data provide us with valuable meteorological information, which is helpful to further study the climate characteristics and changing trends of the Qinghai-Xizang Plateau.

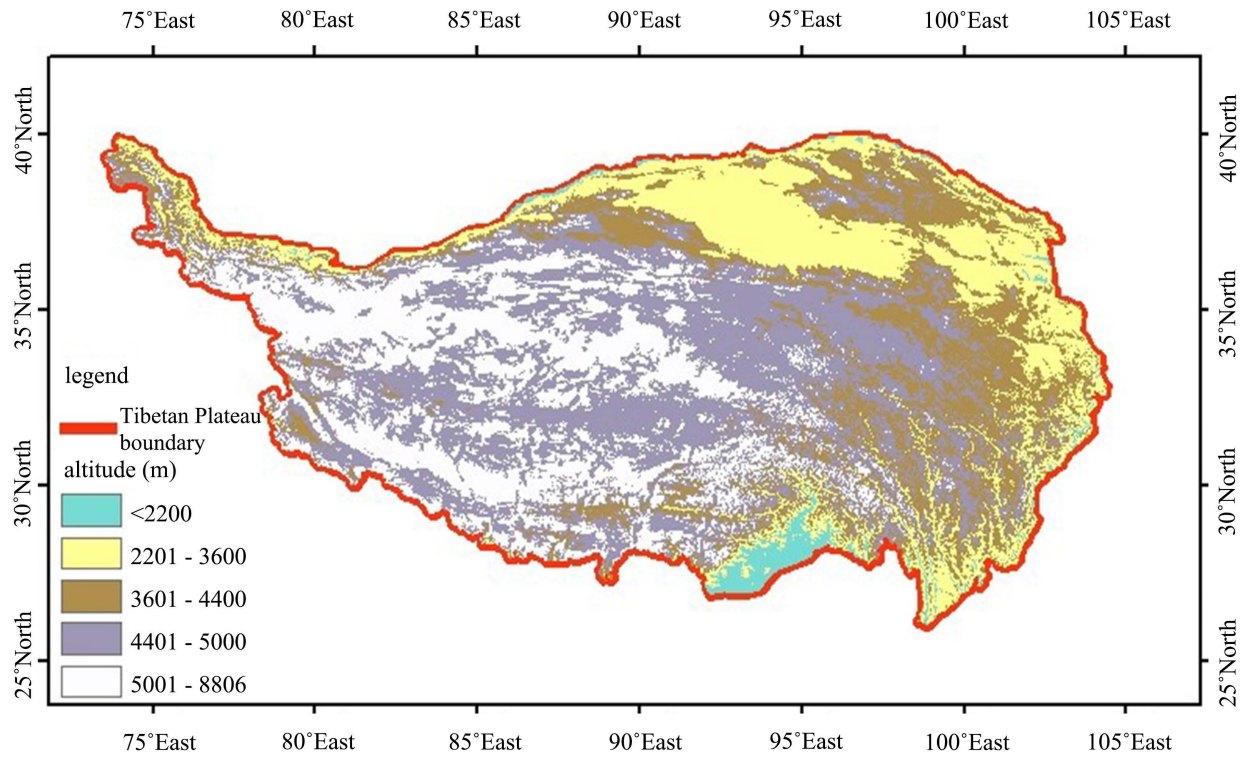


Figure 1. Topographic map of Qinghai-Xizang Plateau.

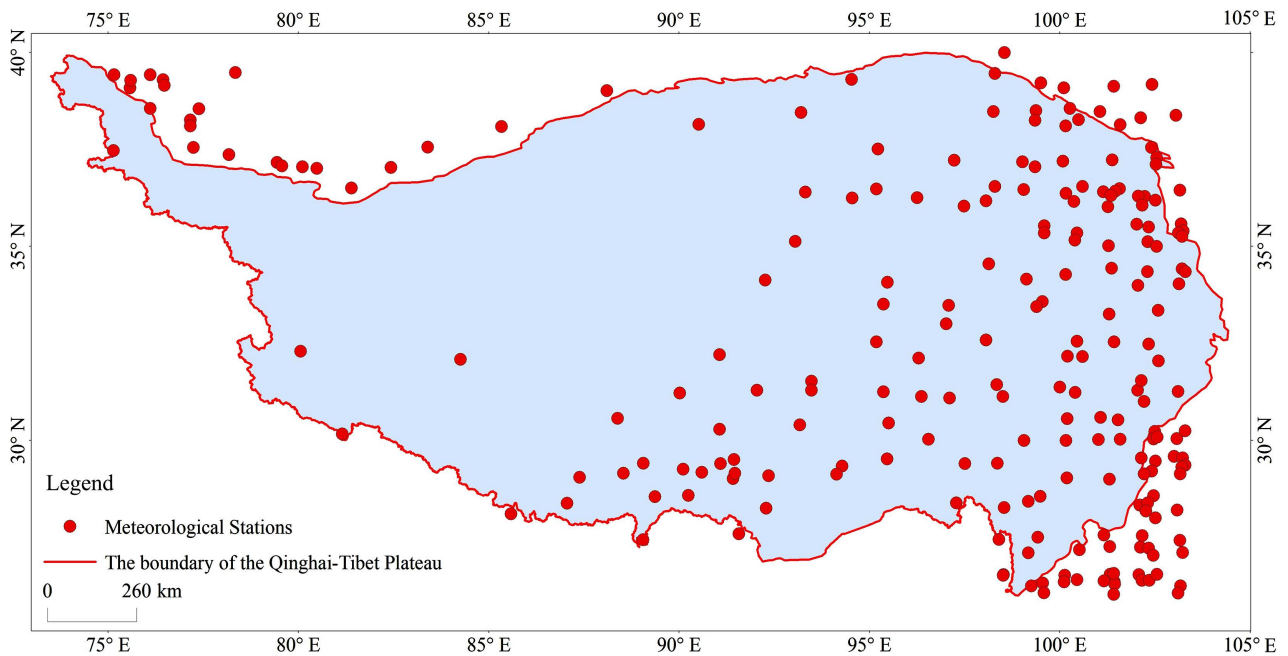


Figure 2. Distribution of research sites on the Qinghai-Xizang Plateau.

2.2. M-K Trend Test and M-K Mutation Test

Mann-Kendall trend test (M-K test for short) is a highly respected statistical tool, which is widely used to analyze the long-term evolution trend of meteorological data such as temperature, precipitation and barometric pressure [13]. As

a non-parametric test method, it is also called distribution-free test. Its advantage is that it does not require the data to conform to a normal distribution, and it has strong robustness for a few outliers in the data. The method has the characteristics of high quantification, wide detection range, low interference degree and simple calculation, so it is particularly suitable for analyzing the change trend that does not have the characteristics of normal distribution, such as the change of meteorological elements. In the specific implementation of M-K test, we set A_1, A_2, \dots, A_n is a time series variable where n represents the number of samples. To quantify the trend of this sequence, we introduce a statistic called S , which is defined as (1):

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sgn}(A_i - A_j) \quad (1)$$

In the formula, sgn represents the symbolic function, and the calculation method is shown in Formula (2) S stands for normal distribution, the mean is equal to 0, and its variance is calculated as shown in Equation (3):

$$\text{sgn}(A_i - A_j) = \begin{cases} 1 & A_i - A_j > 0 \\ 0 & A_i - A_j = 0 \\ -1 & A_i - A_j < 0 \end{cases} \quad (2)$$

$$\text{Var}(S) = n(n-1)(2n+5)/18 \quad (3)$$

The corresponding Z values of different S intervals in the Mann-Kendall statistic formula are as follows:

$$Z = \begin{cases} (S-1)/\sqrt{\text{Var}(S)} & S > 0 \\ 0 & S = 0 \\ (S+1)/\sqrt{\text{Var}(S)} & S < 0 \end{cases} \quad (4)$$

After the Mann-Kendall trend test is performed, we can continue to apply this method to the mutation analysis of time series. Mutation analysis is designed to detect the presence of significant transition points in the data series that might signal a change in a trend or pattern.

To sum up, in the trend test of M-K method, we judge whether there is a significant trend in the time series by calculating the statistic Z and comparing it with the critical value. Specifically, given the confidence level α , if the absolute value of the calculated Z value is greater than or equal to the critical value $|Z| \geq Z_{1-\alpha/2}$, we reject the null hypothesis and hold that there is a significant trend in the time series. The positive and negative values of Z indicate the direction of the trend: $Z > 0$ indicates an upward trend, and $Z < 0$ indicates a downward trend. In addition, we can also judge the significance level of the trend according to the absolute value of the Z value, for example, $|Z| \geq 1.28$, $|Z| \geq 1.64$, $|Z| \geq 2.32$, corresponding to 90%, 95% and 99% significance levels, respectively.

Next, the mutation analysis of time series was performed using M-K test. The structure is as follows:

$$S = \sum_{i=1}^k \sum_{j=1}^{i-1} a_{ij} \quad k = 2, 3, 4, \dots, n \quad (5)$$

$$a_{ij} = \begin{cases} 1 & A_i > A_j \\ 0 & A_i < A_j \end{cases} \quad 1 \leq j \leq i$$

When doing mutation analysis, we usually calculate two statistical sequences: UF_k (the statistic of the forward sequence) and UF_k (the statistic of the reverse sequence). This method can help us identify abrupt points in time series data. Statistical calculation formula:

$$UF_k = \frac{|S_k - E(S_k)|}{\sqrt{Var(S_k)}} \quad k=1,2,3,4,\dots,n \quad (6)$$

where $E(S_k)$ represents the mean; $Var(S_k)$ represents the variance.

According to Equation (7):

$$E(S_k) = \frac{k(k+1)}{4} \quad Var(S_k) = \frac{k(k-1)(2k+5)}{72} \quad (7)$$

The time series follows A_n, A_{n-1}, \dots, A_1 in order, and according to the above method:

$$\begin{cases} UB_k \\ k = m+1-k \end{cases} \quad k=1,2,3,\dots,n \quad (8)$$

Drawing UB_k and UF_k curves, when we find an intersection of UF_k and UF_k curves in the confidence interval of $|U| \leq 1.96$ (corresponding to the confidence level of 0.95, or 95% confidence interval), this intersection is identified as a mutation point in the time series.

2.3. Precipitation Tendency Rate Method

The tendency rate of precipitation at a station X is usually expressed by a linear equation with one variable, as shown in Equation (9):

$$X = a_0 + a_1 t \quad (9)$$

where a_0 is a constant term; a_1 is the slope, the linear trend term; t indicates the number of the year. The value of a_1 is generally magnified by a factor of 10 to indicate the tendency rate of precipitation [14].

2.4. Percentile Threshold Method

In view of the significant spatial heterogeneity of precipitation distribution in China, especially the abundance of precipitation in the eastern monsoon region, and the scarcity of precipitation in the cold region of the Qinghai-Xizang Plateau and the arid region of Northwest China, if only specific precipitation such as heavy rain or rainstorm is used as the standard for determining extreme precipitation events, it may lead to incorrect data inclusion or omission. In addition, such a standard would make it difficult to effectively compare extreme precipitation thresholds in different regions. Zhai *et al.* proposed a new method to determine the extreme precipitation threshold [15] [16]: Firstly, the null values in the daily precipitation data were removed and arranged in ascending order. Then, a value with a cumulative percentage of 95% or 99% is selected as the extreme precipi-

tation threshold for this site. This method, the percentile threshold method, effectively avoids the limitations of the traditional “one-size-fits-all” threshold selection method, and makes the threshold values in different regions comparable. The key to this method is that it takes into account the overall distribution of the data, rather than simply applying a fixed standard to define extreme precipitation, which makes the method show good applicability in a variety of climatic and geographical conditions [17]. In order to further analyze the spatial heterogeneity of extreme precipitation events over the Qinghai-Xizang Plateau, four indexes R95P, R95D, R95I and R95C were used for research and analysis, as shown in **Table 1** for details.

Table 1. Extreme precipitation index and its corresponding abbreviation.

Index	Definition	Abbreviation	Units
Extreme precipitation	Total annual daily precipitation greater than the 95th percentile	R95P	mm
Frequency of extreme precipitation	The sum of the number of times the annual daily precipitation is greater than the 95th percentile	R95D	D
Extreme precipitation intensity	Ratio of R95P to R95D of the site	R95I	mm/d
Contribution rate of extreme precipitation	R95P as a percentage of total annual precipitation	R95C	%

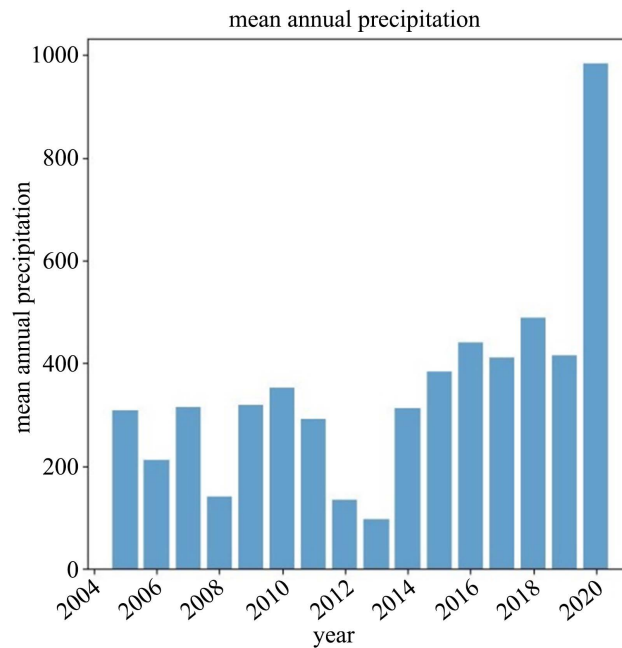
3. Analysis of Precipitation Characteristics, Extreme Precipitation Event Threshold, and Temporal Distribution of Extreme Precipitation in Qinghai-Xizang Plateau

The following is a detailed introduction from three aspects: 1) Time and space distribution of average precipitation from 2005 to 2020; 2) Threshold of extreme precipitation events over the Qinghai-Xizang Plateau; 3) Temporal and spatial distribution characteristics of extreme precipitation over the Qinghai-Xizang Plateau.

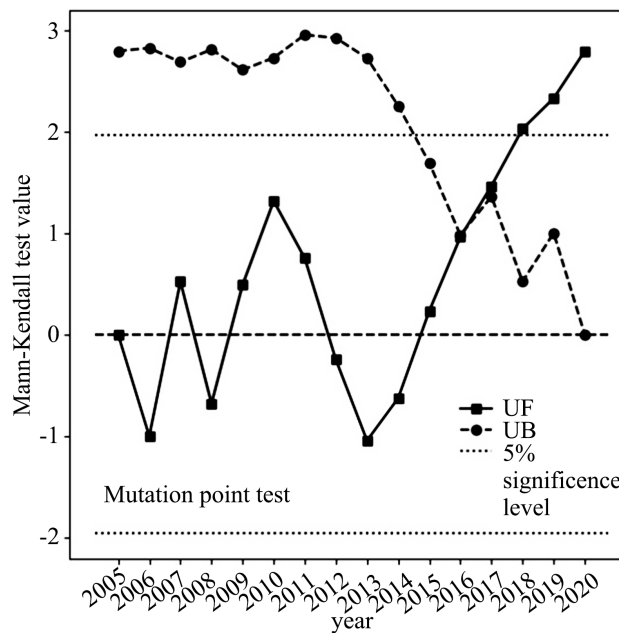
3.1. Spatial and Temporal Distribution Characteristics of Precipitation

As shown in **Figure 3(a)**, we can observe that the annual average precipitation of the Qinghai-Xizang Plateau is stable at 350.11 mm during the period from 2005 to 2020. In the 16-year record, years that were above the average accounted for 43.75 percent, while years that were below the average accounted for 56.25 percent. It is worth noting that the average precipitation in 2013 was significantly lower, only 96.75 mm, which became the lowest level in the past years. In contrast, the average annual precipitation in 2020 was 983.69 mm, the highest ever recorded. Through the M-K trend test, the annual precipitation can be calculated as an upward trend and $Z = 2.75$, indicating that the significance test of the up-

ward trend is greater than 99%. As shown in **Figure 3(b)**, M-K mutation test was conducted on the annual average precipitation of the Qinghai-Xizang Plateau from 2005 to 2020. Before 2017, the UF curve fluctuated between $-1.96 - 1.96$, indicating that the trend and mutation of the change curve were not obvious. After 2018, the UF curve exceeded the critical value, indicating an obvious increasing trend of annual precipitation. With a confidence level of 0.05, the average annual precipitation of the Qinghai-Xizang Plateau site suddenly changes around 2017.



(a)



(b)

Figure 3. Extreme precipitation threshold of Qinghai-Xizang Plateau.

As shown in **Figure 4**, the average monthly precipitation on the Qinghai-Xizang Plateau ranges from 1.86 mm to 72.86 mm. Among them, in terms of months, the average monthly precipitation in July is the highest, up to 72.86 mm, and the average monthly precipitation in August is second only to July, reaching 69.76 mm; the average monthly precipitation in December is the lowest, only 1.86 mm. In terms of seasons, the characteristics of seasonal precipitation and monthly precipitation are similar. Summer precipitation accounts for more than half of the annual precipitation, accounting for 57.00%. The proportion of autumn precipitation was 21.96%, second only to summer. Spring precipitation accounted for a small proportion of annual precipitation, accounting for 9.25%; the proportion of precipitation in winter is the least, only 2.92%. From the point of view of the stations, the average monthly precipitation of the stations in the Sichuan Basin maintained a high level, and the average precipitation of the stations in August was 316.84 mm. The stations in Gansu Province showed reduced levels, with the lowest station having an average monthly precipitation of less than 1 mm in March.

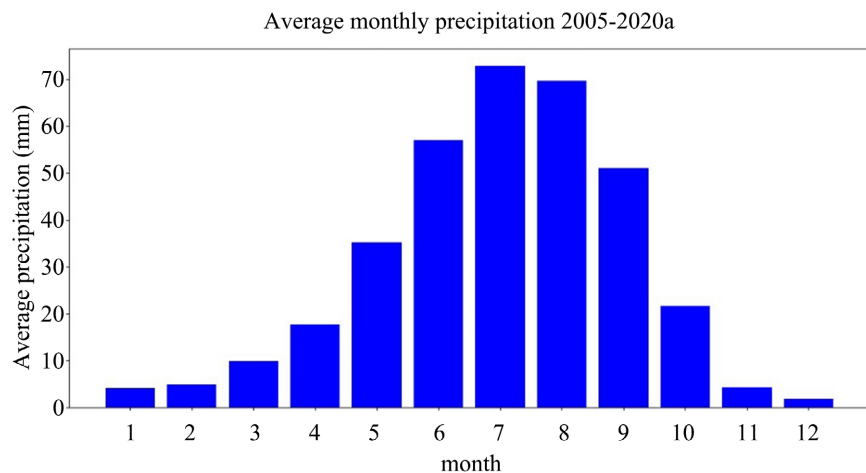


Figure 4. Average monthly precipitation over the Qinghai-Xizang Plateau from 2005 to 2020.

As shown in **Figure 5**, among the 215 observation stations selected, the annual average precipitation of 10 stations exceeded 800 mm, and these stations were mainly concentrated near the Hengduan Mountains at low latitude on the south-east side of the plateau. The average annual precipitation at Emei Mountain Station is as high as 1474.38 mm. There are 73 stations with annual precipitation between 400 and 800 mm, mainly distributed in the east, south and southeast of the plateau, and precipitation decreases further to the northwest, with 78 stations with annual precipitation between 200 and 400 mm. Finally, 54 stations on the north-west and northeast sides of the Qinghai-Xizang Plateau have annual precipitation of less than 200 mm. It can be seen that there is a significant spatio-temporal heterogeneity in the precipitation over the Qinghai-Xizang Plateau, and the precipitation shows a gradual decreasing trend from southeast to northwest. The plausi-

ble reasons for such spatial distribution of extreme precipitation may stem from the combined influences of atmospheric circulation, dynamics, thermodynamics, and moisture availability during years with high occurrences of extreme precipitation. Specifically, anomalous pressure patterns over the Plateau, coupled with the South Asian High and enhanced moisture transport, create favorable conditions for the generation and intensification of heavy precipitation. These factors, working in concert, contribute to the observed pattern of decreasing extreme precipitation from southeast to northwest across the Qinghai-Xizang Plateau [18].

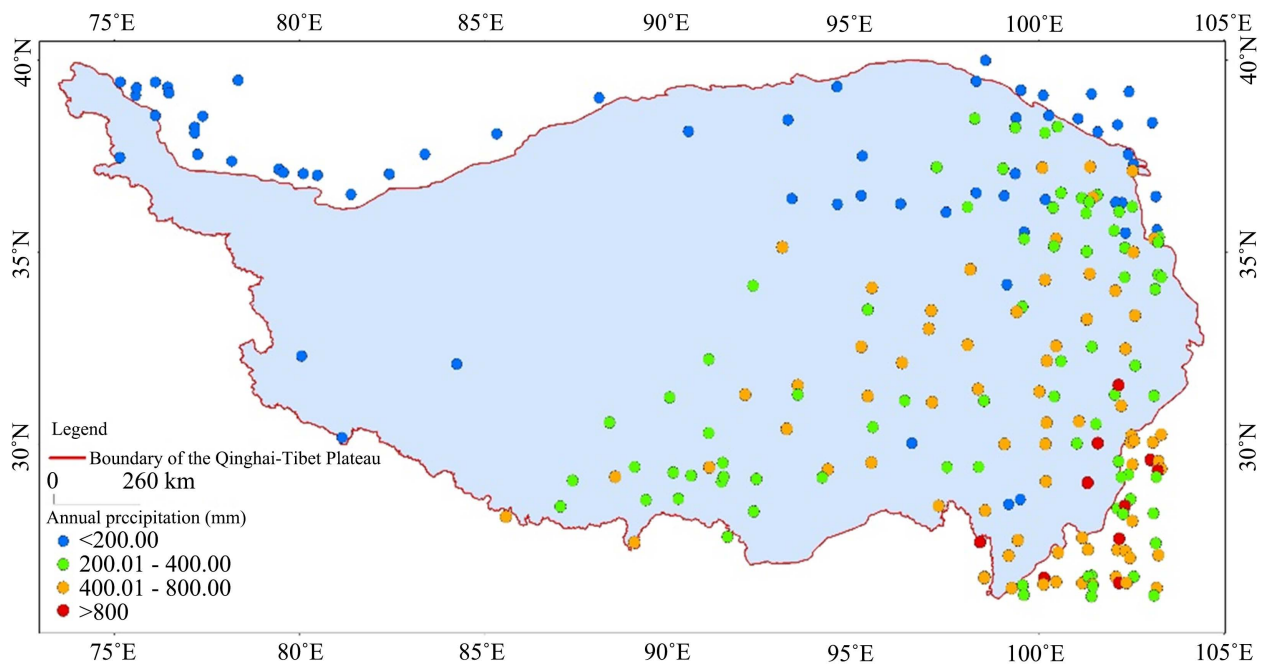


Figure 5. Spatial distribution of annual precipitation over the Qinghai-Xizang Plateau.

3.2. Threshold of Extreme Precipitation Events over the Qinghai-Xizang Plateau

The non-zero precipitation days of 215 stations on the Qinghai-Xizang Plateau from 2005 to 2020 are arranged in ascending order. We then selected precipitation values with a cumulative percentage of 95% per year and defined them as the extreme precipitation threshold for that year. In order to obtain a uniform reference standard, we calculated the average of the thresholds for all years as the threshold for determining extreme precipitation events at each site.

The extreme precipitation thresholds of various stations on the Qinghai-Xizang Plateau show great differences and a wide range. The values ranged from a low of 4.81 mm to a high of 41.26 mm, while the overall average for all sites was 14.96 mm.

Its spatial distribution is consistent with the overall spatial characteristics of precipitation, showing a decreasing trend from southeast to northwest. It is worth noting that Huili Station has the highest extreme precipitation threshold, reach-

ing 41.26 mm, becoming the only station in the study area with an extreme precipitation threshold of more than 40 mm, followed by Xichang Station with a threshold of 35.28 mm.

3.3. Temporal Distribution Characteristics of Extreme Precipitation Index

According to the data shown in **Figure 6**, we have obtained multiple annual average indicators of extreme precipitation at various stations on the Qinghai-Xizang Plateau. First, as shown in **Figure 6(a)**, the average annual extreme precipitation of each station is 113.27 mm, indicating the overall level of extreme precipitation in this region. However, this average value fluctuates significantly from year to year, with the lowest mean value of 49.02 mm in 2008 and a peak value of 299.12 mm in 2020, which reveals a large annual variation in extreme precipitation.

As shown in **Figure 6(b)**, the annual average number of extreme precipitation days at each station is 4.51 days. Similarly, this indicator also shows inter-year differences, with the lowest number of extreme precipitation days in 2006, only 2.53 days, while the number of extreme precipitation days in 2020 increased to 6.17 days, the most in recent years.

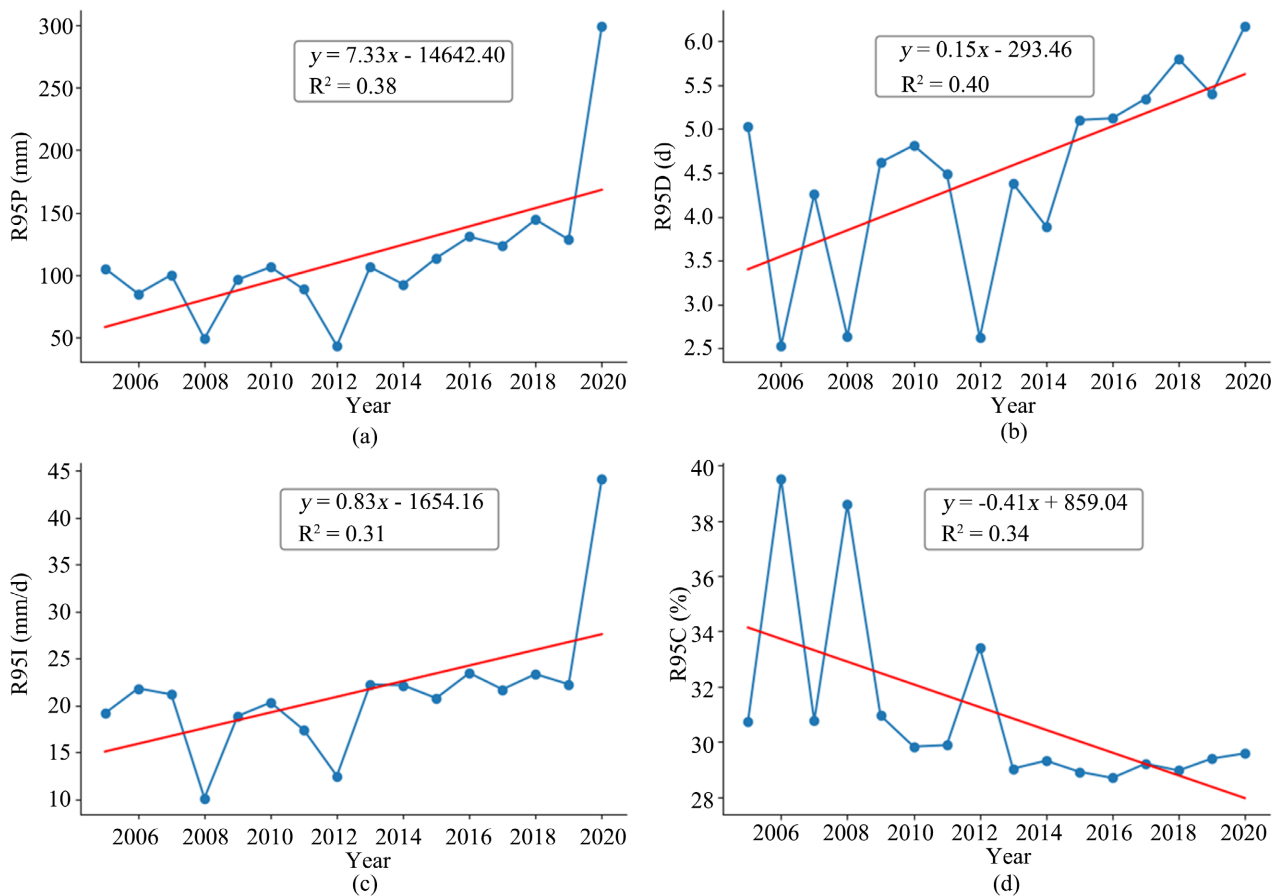


Figure 6. Interannual variation of four extreme precipitation indices.

Figure 6(c) further analyzes the intensity of extreme precipitation, and we find that the average annual extreme precipitation intensity of each station is $21.33 \text{ mm}\cdot\text{d}^{-1}$. Among them, the extreme precipitation intensity in 2008 was the lowest at $10.13 \text{ mm}\cdot\text{d}^{-1}$, while the intensity in 2020 reached the highest at $44.12 \text{ mm}\cdot\text{d}^{-1}$, which indicates that the extreme precipitation intensity changes significantly with the year.

Finally, as shown in **Figure 6(d)**, the average contribution rate of annual average extreme precipitation is 31.05%, which means that extreme precipitation accounts for a considerable proportion of total precipitation. In terms of each year, the contribution rate of extreme precipitation in 2016 was the lowest, which was 28.69%, while the contribution rate in 2006 was as high as 39.52%, indicating that the impact of extreme precipitation on total precipitation in different years was significantly different.

From the perspective of long-term change trend, the annual extreme precipitation at each station on the Qinghai-Xizang Plateau shows an obvious upward trend, with a tendency rate of $73.3 \text{ mm}/10\text{a}$, which indicates that the extreme precipitation will increase year by year at a relatively stable rate from 2005 to 2020. At the same time, the annual number of extreme precipitation days is also increasing at a rate of $1.5 \text{ d}/10\text{a}$, which means that the frequency of extreme precipitation is increasing. The intensity of extreme precipitation also showed an upward trend, with a specific rate of $8.3 \text{ (mm/d)}/10\text{a}$, indicating that not only the number of extreme precipitations was increasing, but also the intensity of each extreme precipitation was gradually increasing. However, it is worth noting that although the amount, frequency and intensity of extreme precipitation are increasing, the contribution rate of extreme precipitation is decreasing at a rate of $4.1\%/10\text{a}$. This suggests that although extreme precipitation events are increasing and intensifying, their share is actually decreasing relative to total precipitation, which may be related to an increase in non-extreme precipitation or complex changes in precipitation patterns due to climate change.

4. Result

1) Data analysis from 2005 to 2020 shows that the annual precipitation of the Qinghai-Xizang Plateau presents a significant upward trend, and this trend has passed the M-K significance test with a confidence of more than 99%. Through M-K mutation test, we found that the annual mean precipitation of the Qinghai-Xizang Plateau site had a sudden change around 2017. From the perspective of spatial distribution, the annual precipitation gradually decreases from southeast to northwest, which is closely related to the topography and climatic conditions of the Qinghai-Xizang Plateau.

2) The spatial distribution of extreme annual precipitation is similar to that of annual precipitation, showing a gradual decline from southeast to northwest. Specifically, the highest point of the extreme precipitation threshold occurs in Liangshan Yi Autonomous Prefecture, while the lowest point is located near Qaidam

Basin. This spatial distribution feature helps us to better understand the precipitation pattern over the Qinghai-Xizang Plateau.

3) In terms of extreme precipitation index, from 2005 to 2020, the extreme precipitation, the number of extreme precipitation days and the extreme precipitation intensity of each station on the Qinghai-Xizang Plateau showed an obvious upward trend. However, the contribution rate of extreme precipitation to total precipitation showed a downward trend. This could mean that non-extreme precipitation events, such as light or moderate rain, have increased in frequency or intensity, and thus the contribution to total precipitation is rising.

5. Conclusions

In conclusion, this paper offers a comprehensive and nuanced examination of extreme precipitation on the Qinghai-Xizang Plateau by employing the percentile threshold method to establish thresholds, integrating the Mann-Kendall trend test to analyze annual precipitation trends, and calculating extreme precipitation indices to investigate their temporal distribution characteristics. This multifaceted approach provides a more holistic and profound perspective on extreme precipitation research in the region. However, there are limitations and avenues for future improvement. Potential directions for future research include:

1) Model Validation and Prediction: The study primarily focuses on analyzing existing data, with no mention of utilizing models for validating or predicting extreme precipitation events. This could potentially limit the applicability and predictive capacity of the findings. Incorporating model-based approaches to validate past trends and forecast future extreme precipitation scenarios would enhance the practical relevance and forward-looking nature of the research.

2) Insufficient Analysis of Precipitation Mechanisms and Causes: While the paper provides a detailed description of the spatio-temporal distribution and trends of extreme precipitation on the Qinghai-Xizang Plateau, it lacks an in-depth exploration of the underlying mechanisms and causes. A more thorough investigation into the key factors influencing extreme precipitation events, such as the interplay between large-scale atmospheric circulation patterns, local topography, and climate change dynamics, would significantly contribute to our understanding of this complex phenomenon.

In summary, this study represents a significant contribution to the understanding of extreme precipitation on the Qinghai-Xizang Plateau. Nevertheless, there is room for further advancements through model validation and prediction efforts, as well as a deeper analysis of precipitation mechanisms and causes, which could lead to even more comprehensive and actionable insights into this critical aspect of climate research.

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Conflicts of Interest

The authors declare no conflicts of interest.

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