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Spatial and Temporal Characteristics of Rainstorm Events in Southwest China from 1961 to 2021

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Abstract: The rainfall distribution in southwest China is uneven, and the rainstorm threshold cannot use in a unified standard. This paper synthesizes a calculation method for the extremely heavy precipitation threshold and the provision of the rainstorm threshold in meteorological operation. It calculates the daily precipitation rainstorm threshold at 400 national ground stations in southwest China. The rainstorm events from 1961 to 2021 were statistically analyzed using the rainstorm threshold and analyzing the spatial-temporal variation characteristics. The results show that the number of single-station rainstorm events and the average precipitation of single-station rainstorm events in southwest China decreased from east to west. The number and frequency of single-station rainstorm events in Guizhou, Sichuan, Tibet, and Chongqing are increasing, while the number of single-station rainstorm events in Yunnan is decreasing. There is no apparent spatial distribution pattern for the continuous rainstorm events in the southwest region. From 1961 to 2021, the number and frequency of rainstorm events at a single station in southwest China followed an upward trend. The number of rainstorm events at a single station increased by 16.7 times · $(10a)^{-1}$, and the frequency of rainstorms increased by 9.9% · $(10a)^{-1}$. The continuous rainstorm events show an increasing trend, with an increase of 0.1 times · $(10a)^{-1}$. Using the rainstorm threshold in southwest China, the early warning threshold for rainstorm disasters can be adjusted. The temporal and spatial characteristics of rainstorm events since 1961 can analyze the changes occurring in rainstorm events under global warming and provide data to support the response of southwest China to climate change.

Keywords: rainstorm events; rainstorm threshold; spatial and temporal change; Southwest China

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1. Introduction

Burning fossil fuels and carbon emission causes environmental and climate change [1,2]. When precipitation occurs continuously over time, it increases the likelihood of severe meteorological disasters such as debris flow, landslide, floods, etc. [3,4]. The geomorphic structure of southwest China is complex. It is an area of China that is sensitive and vulnerable area to climate change. It is also one of the regions where extreme weather, climate events, and meteorological-induced secondary disasters occur most frequently. The spatial distribution of precipitation in southwest China presents a morphological distribution that is high in the east and low in the west [5–8]. Due to the intense sensitivity of precipitation to global warming [9], scholars in many countries and regions have reflected on the specific performance and impact of global climate change by studying the temporal and spatial characteristics of rainstorms or extreme precipitation events [10–12]. In the past ten years, based on the analysis of the long-term series of extreme precipitation events in China, it is concluded that continuous extreme precipitation events in southwest China have followed an insignificant downward trend [13,14]. After analyzing the temporal and spatial distribution of summer precipitation at ground stations in southwest China for nearly 60 years before 2017, the total number of days of summer precipitation in southwest China was generally found to decrease [15,16]. In the past five years, extreme weather events have occurred frequently. According to the sixth assessment report of IPCC Working Group I, the assessment results of cities' impact on severe weather and climate events under climate warming indicate that urbanization has increased extreme precipitation in many urban areas and downwind directions [17]. The results of spatiotemporal changes in excessive rainfall in southwestern China have also changed. In 2020, the summer precipitation in southwest China was abnormally high [18], and the ongoing regional rainstorm events in the east of southwest China increased [19]. The analysis of the evolution of extreme precipitation in China's significant watersheds over the past 60 years has also enhanced extreme rainfall in the southwestern rivers [20].

The annual precipitation in southwest China varies by thousands of millimeters from southeast to northwest; it has extremely uneven spatial and temporal distribution. Using a 24-hour precipitation value of not less than 50 mm as the rainstorm threshold specified in the precipitation classification (GB/T 28592-2012) [21] will ignore the extreme precipitation in Tibet, southern Sichuan, and other areas with less precipitation. In meteorological operations, some stations in Tibet use 25 mm as a rainstorm threshold to collect statistics on precipitation levels at stations [22]. Due to the sparse distribution of surface meteorological stations in Tibet, the unified 25 mm or 20 mm rainstorm threshold is not applicable in Tibet. The rainstorm threshold should be calculated based on the precipitation sequence of the stations [23]. Therefore, considering the calculation results of the extreme precipitation index and the commonly used 24-hour precipitation exceeding 50 mm in business, calculating the rainstorm threshold in southwest China is conducive to determining the statistics of solid precipitation in the case of uneven precipitation distribution in southwest China.

The above research on southwestern China mainly focuses on a specific region or period. There needs to be more than the distribution of ground stations used for a rainstorm or extreme precipitation statistics to represent the actual situation of the whole southwest region. In the statistical analysis of rainstorm events, there still needs to be more research on recalculating the rainstorm threshold at each station for uneven precipitation in southwest China. This paper intends to use the daily precipitation from national ground stations in southwest China from 1961 to 2021, for more than 60 years, to calculate the rainstorm threshold of each station, extract rainstorm events through the threshold, and analyze spatial and temporal characteristics. The analysis results will help to obtain the spatial and temporal distribution of rainstorm events in southwest China over the last 61 years, provide a historical basis for climate change impact and disaster monitoring in southwest China, and improve the operational capacity of southwest China relating to heavy rainfall forecasting, disaster prevention, and mitigation. The second chapter of this paper introduces the data used and the method for calculating the rainstorm threshold of a single station; the third chapter introduces the calculation results for a single station rainstorm threshold in southwest China and analyzes the temporal and spatial distribution of rainstorm events in southwest China; the fourth chapter summarizes and discusses the research results. The framework of the study is shown in Figure 1.

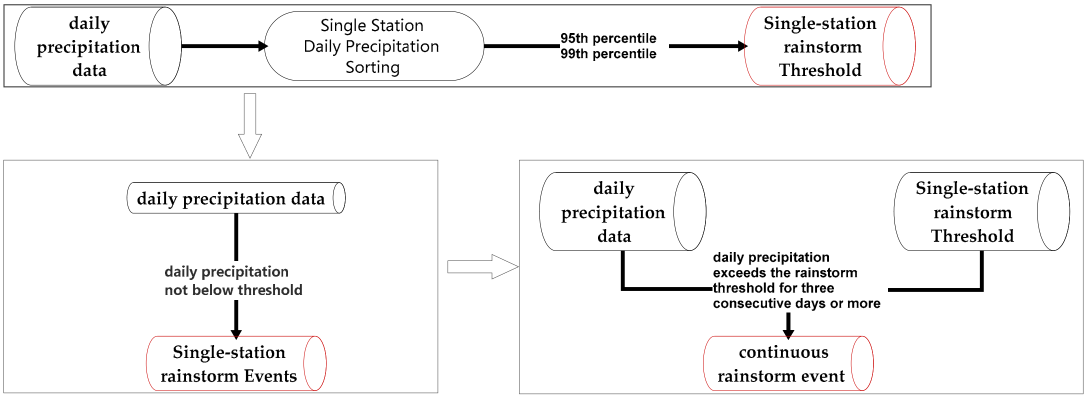

Figure 1. The framework of the study.

2. Data and Methods

According to China's natural geographical division, the southwest region divides into five provinces: Yunnan (YN), Guizhou (GZ), Sichuan (SC), Chongqing (CQ), and Tibet (XZ). The precipitation data are derived from the daily rainfall from 8 p.m. on the previous day to 8 p.m. on the current day (Beijing Time) from the "China Daily Surface Data (V3.0)", which was developed by the National Meteorological Information Center. The station is a national-level Auto Weather Station (NAWS). In the southwest region, there are 400 NAWSs with complete observation data from 1961 to 2021; their distribution is shown in Figure 2.

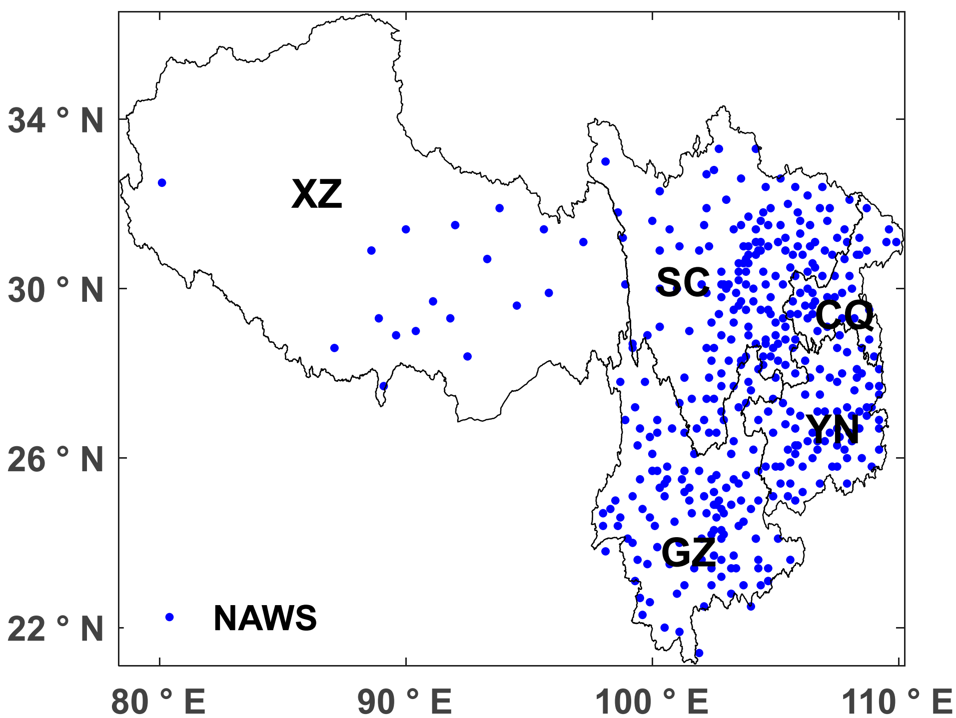

Figure 2. Distribution of NAWS in southwest China.

The daily precipitation data in "China Surface Daily Data (V3.0)" have undergone four quality control steps: format check, boundary value check, time consistency check, internal consistency check, and spatial consistency check, and it has been labeled with a quality control code [24]. Using quality control codes to determine statistics on the accuracy, suspicious rate, error rate, and missing measurement rate of daily precipitation at stations in southwestern China from 1961 to 2021 (Table 1). It shows that the daily precipitation of NAWS in the southwest region has no error data, and the accuracy rate is above 99.8%. The data used in the article are data with a quality control code of 0 or 1.

Table 1. Daily precipitation statistics of NAWS in southwest China (%).

	Accuracy Rate	Suspicious Rate	Error Rate	Missing Measure Rate
TOTAL	99.9708	3.20×10^{-3}	1.30×10^{-5}	2.56×10^{-2}
YN	99.9922	7.31×10^{-4}	0	7.00×10^{-3}
GZ	99.9456	4.48×10^{-2}	0	9.70×10^{-3}
SC	99.9883	2.06×10^{-4}	2.93×10^{-5}	1.15×10^{-2}
XZ	99.9056	2.30×10^{-2}	1.17×10^{-4}	7.13×10^{-2}
CQ	99.9861	4.10×10^{-3}	0	9.80×10^{-3}

Calculation method for rainstorm threshold: Sort the precipitation of no less than 0.1 mm observed by each NAWS in southwest China since 1961 from small to large, and calculate the precipitation values at the 95th percentile and 99th percentile, respectively. At the same time, considering the provisions that the 24-hour precipitation commonly used in business exceeds 50 mm and 25 mm, the rainstorm threshold is judged comprehensively. The specific method is as follows:

(1) Extract precipitation data from China's surface daily value dataset.

(2) The precipitation data of ≥ 0.1 mm at each station is arranged in ascending order, and the precipitation values for the 99th percentile and 95th percentile are calculated, respectively.

(3) Determine the rainstorm threshold at each station according to the following rules:

(a) When the precipitation values of the 99th percentile is <50 mm, the precipitation value of the 95th percentile is taken as the rainstorm threshold of the station.

(b) When the 99th percentile of a station is ≥50 mm, 50 mm is taken as the rainstorm threshold of the station.

According to the definition in the meteorological industry standard "Persistent Rainstorm Event (QXT 442-2018)" of the China Meteorological Administration, a rainstorm event is defined as a precipitation event with a rainfall of 50 mm or more in 24 h (from 08:00 on the day to 08:00 on the next day or from 20:00 on the previous day to 20:00 on the day) [25]. In this paper, after the comprehensive judgment of the rainstorm threshold of a single station in southwest China, the rainstorm event of a single station is defined as a single rainstorm event when the daily precipitation of the station is not lower than the rainstorm threshold of the station. A continuous rainstorm event is defined as if the statistical station's precipitation exceeds the station's rainstorm threshold for three consecutive days or more.

3. Results

3.1. Single-Station Rainstorm Threshold

Figure 3 and Table 2 show the results of the calculation of the rainstorm threshold (R_t) of NAWS in southwest China. The chart shows that the rainstorm thresholds of stations in XZ, western SC, central YN, and western GZ are lower than 50 mm. The threshold value of a rainstorm in XZ shall not exceed 25 mm. The rainstorm threshold of all stations in CQ is 50 mm. The minimum rainstorm threshold is at Shiquanhe Station in XZ (9.4 mm).

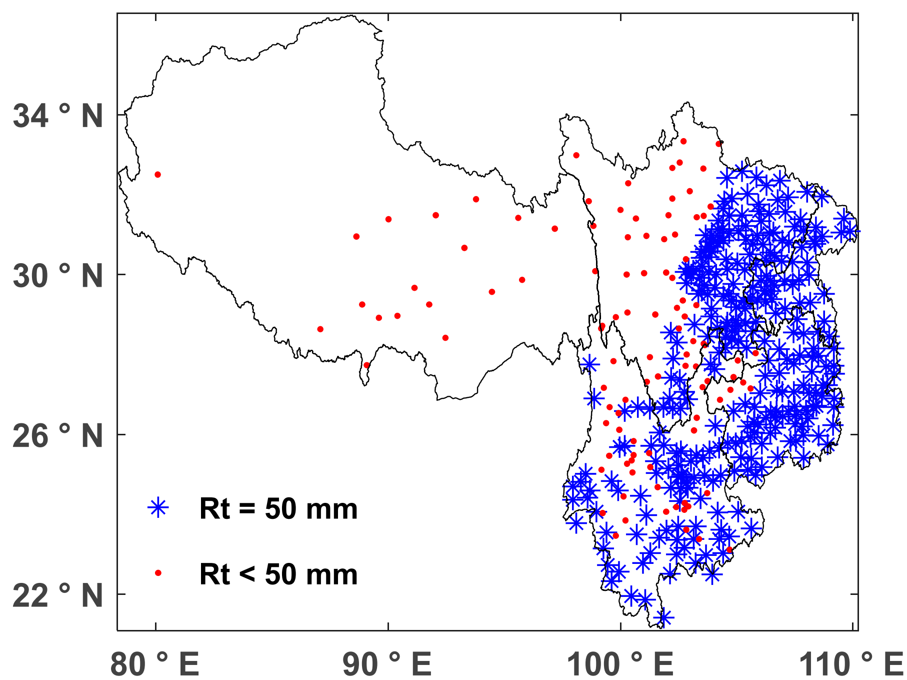

Figure 3. R_t distribution of NAWS in southwest China.

Table 2. R_t statistics of NAWS in southwest China.

num \ R_t (mm)	0~14.9	15~24.9	25~50	50
YN	0	14	25	82
GZ	0	4	0	75
SC	4	34	0	104
XZ	8	10	0	0
CQ	0	0	0	34

3.2. Temporal and Spatial Characteristics of Single-Station Rainstorm Events

According to the rainstorm threshold values from 400 NAWSs in southwest China, the daily precipitation from 1961 to 2021 was counted for single-station rainstorm events. Figure 3 shows the distribution of the number of single-station rainstorm events, the average precipitation of single-station rainstorm events, the linear trend in the number of single-station rainstorm events, and the linear trend in single-station rainstorm frequency in southwest China. Overall, the number of rainstorm events and the average precipitation distribution in southwest China have decreased from the east to the west in the past 60 years. As shown in Figure 4a, stations with more than 500 rainstorm events in southwest China from 1961 to 2021 are mainly located in the southern part of SC, GZ, and southern YN. Stations with fewer than 300 rainstorm events are mainly concentrated in XZ. The most single-station rainstorm events were in Yanjin Station in YN (1294 events). The least single-station rainstorm events is in Shiquanhe Station in XZ (89 events). In Figure 4b, the average precipitation of single-station rainstorm events at stations in eastern SC, CQ, YN, and GZ exceeds 25 mm, and the average precipitation of single-station rainstorm events at stations in eastern SC exceeds 60 mm. The average precipitation of rainstorm events at most stations in XZ and western SC is less than 25 mm. The maximum mean precipitation of single-station rainstorm events occurs at Beichuan Station in SC (78.3 mm) and the minimum precipitation at Shiquanhe Station in XZ (14.7 mm). Figure 4c,d show the rainstorm frequency at a single station. The rainstorm frequency is the ratio of the number of rainstorm events at a single station to the number of precipitation days at the station that is not less than 0.1 mm. In Figure 4c, the rainstorm frequency of single stations in southwest China from 1961 to 2021 is 5~5.1%, of which the rainstorm frequency of Xuyong Station in Sichuan is the largest, reaching 10.1%. Figure 4d shows the linear trend in single-station rainstorm event frequency from 1961 to 2021 in southwest China. The linear trend calculation adopts the formula $y = ax + b$. Here, y represents the variable's value, a represents the slope of the variable, and b represents the constant term of the linear function. The value of a can determine the trend in variable changes. Among them, 309 sites show an increasing trend, of which 52 passed the significance test, with an average growth trend of 0.37 mm · $(10a)^{-1}$. Ninety-one sites have a decreasing trend.

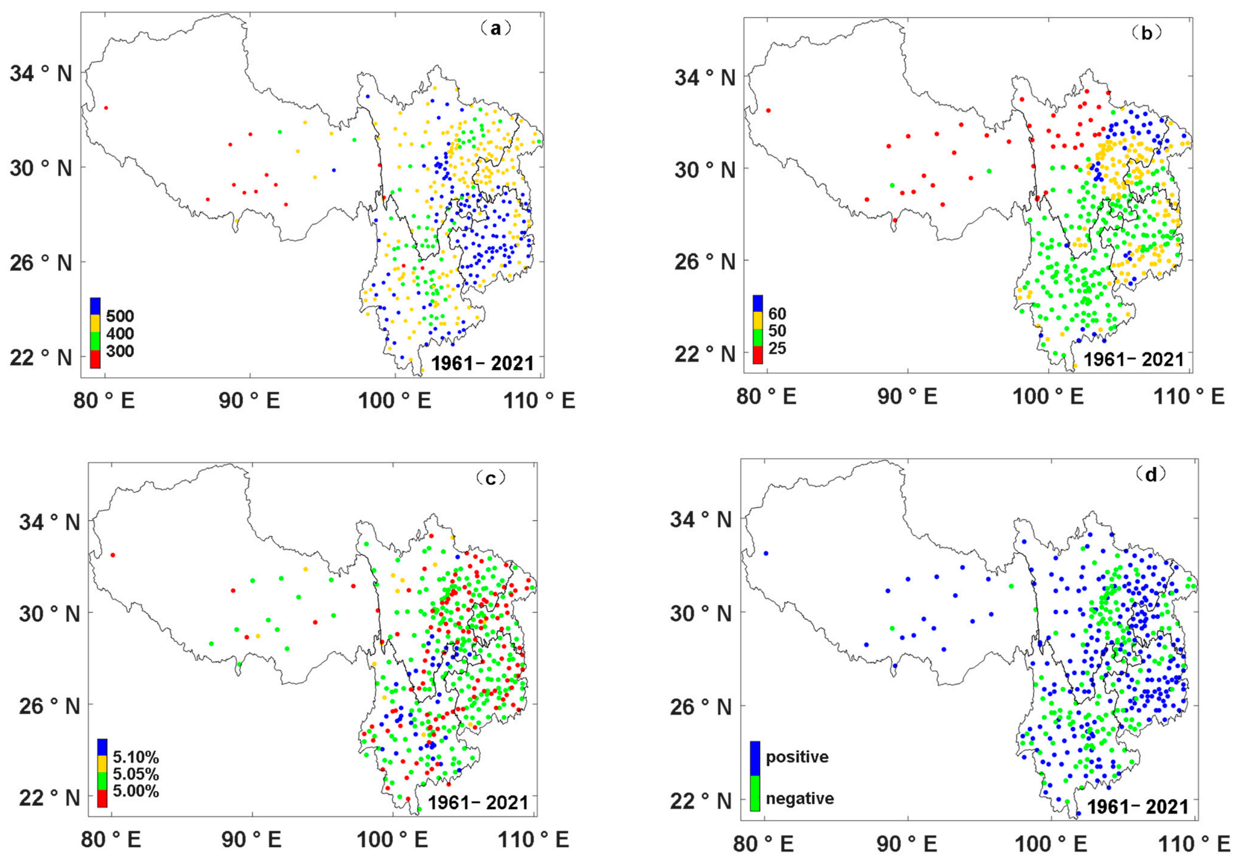

Figure 4. (**a**) Number of single-station rainstorm events. (**b**) Average precipitation of single-station rainstorm events (mm). (**c**) Single-station rainstorm frequency. (**d**) Trend in single-station rainstorm frequency (% · $(10a)^{-1}$).

Table 3 shows the statistics of single-station rainstorm events and rainstorm frequency trends in five provinces in southwest China. It can be seen from the table that the number of single-station rainstorm events and rainstorm frequency in GZ, SC, XZ, and CQ from 1961 to 2021 are increasing, while the number of single-station rainstorm events in YN is, on average, decreasing.

Table 3. Statistics of single-station rainstorm events at NAWS in Southwest China.

	YN	GZ	SC	XZ	CQ
Trend in rainstorm events at single station (times · $(10a)^{-1}$)	−0.03	0.10	0.07	0.17	0.11
Trend of single-station rainstorm frequency (% · $(10a)^{-1}$)	0.12	0.08	0.11	0.03	0.09

Figure 5 shows the number of single-station rainstorm events, rainstorm rate, and their distribution from 1961 to 2021 in southwest China. The rainstorm rate is the ratio of the number of single-station rainstorm events per year to the number of days with daily precipitation ≥0.1 mm at a single station per year. The number of rainstorm events and the frequency of rainstorms in southwest China are rising. The trend in the rainstorm events is 16.7 times · $(10a)^{-1}$, and the frequency of rainstorms is 9.9% · $(10a)^{-1}$. The 5-year moving average distribution shows that the rainstorm in southwest China has been increasing and decreasing periodically in the past 60 years, and prominent peaks appear in 1969, 1973, 1984, 1999, 2007, 2014, and 2020. The peak refers to the value at which the 5-year moving average curve periodically reaches its highest point. The anomaly of single-station rainstorm events in 1969 was -7.5×10^{-4}. Still, the rainstorm frequency anomaly reached 0.85%, indicating that there was more heavy precipitation in southwest China in that year, which is partially consistent with Sun and Zhang's conclusion (2017) on three periods of extreme precipitation in China: the 1960s, the late 1990s, and the early 21st century [26]. From 2013 to 2021, the trend in rainstorm events and rainstorm rate in southwest China increased, the change in the trend in single-station rainstorm events reached 42.4 times · $(10a)^{-1}$, and the change in the trend in rainstorm frequency reached 33% · $(10a)^{-1}$. Single-station rainstorm events and rainstorm frequency anomalies have been positive for nine consecutive years since 2013. The sliding *t*-test ($n_1 = n_2 = 10$) was used to test the rainstorm event number and frequency anomaly mutation. The formula for the sliding *t*-test is as follows:

$$t=\frac{\overline{x_2}-\overline{x_1}}{s\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \quad (1)$$

$$s=\sqrt{\frac{(n_1-1)s_1^2+(n_2-1)s_2^2}{n_1+n_2-2}} \quad (2)$$

where n_1 and n_2 are the sample lengths of the two sub samples, $\overline{x_1}$ and $\overline{x_2}$ are the mean value, and s_1 and s_2 are the variance.

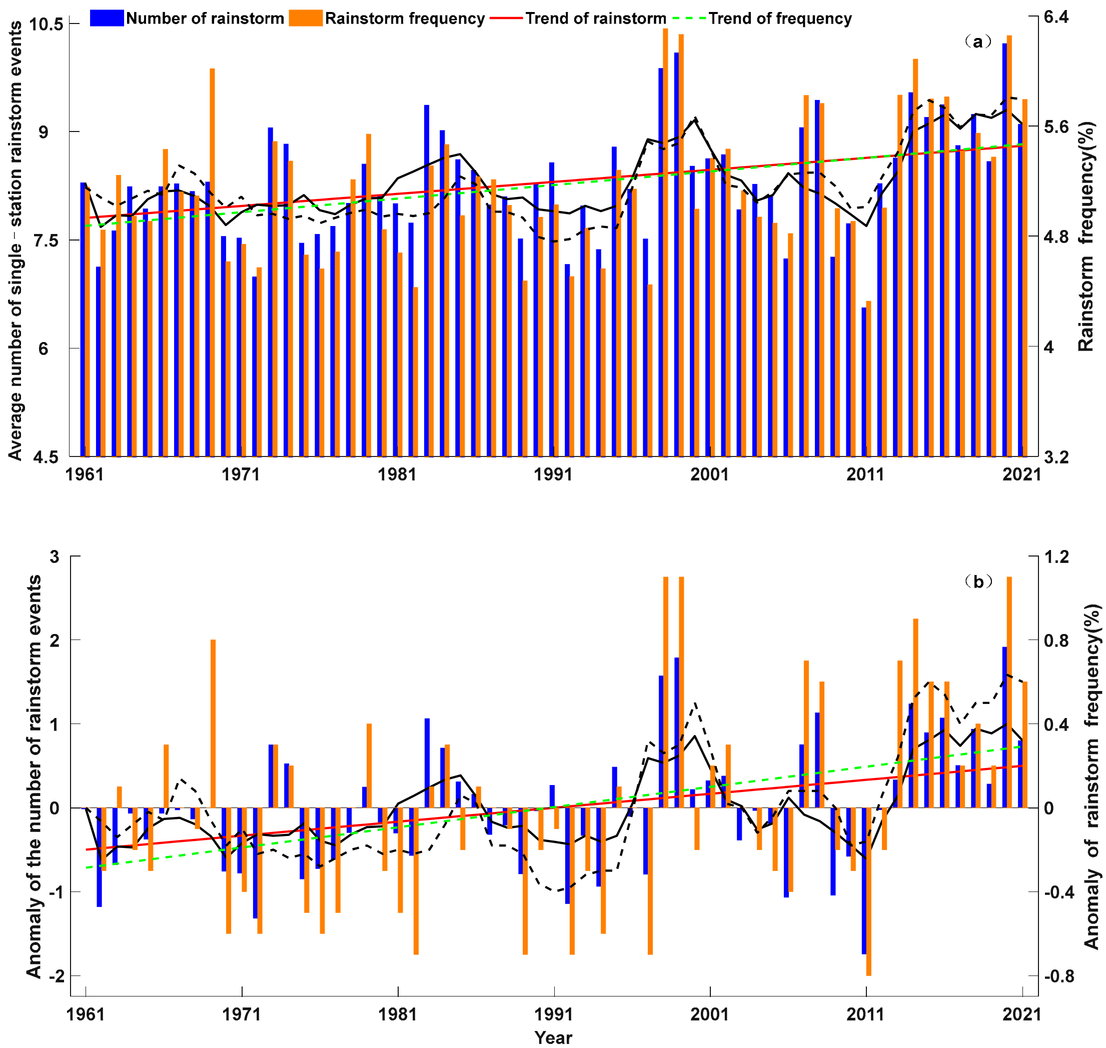

Figure 5. (**a**) Number of single–station rainstorm events and frequency from 1961 to 2021. (**b**) Anomaly of the number of single–station rainstorm events and rainstorm frequency from 1961 to 2021. (Solid line is trend and 5–year moving average of rainstorm events, dotted line is trend and 5–year moving average of rainstorm frequency).

The results verified that the rainstorm frequency anomaly had a decreasing mutation (more than 0.05 significance level) in 1997 and 2011. The changes in extreme heavy rainfall events in China are closely related to the El Nino Southern Oscillation (ENSO) [27]. According to climate analysis, 1997–1998 was a strong El Nino year, 1997 was at the beginning of a cyclical change; and 2010–2011 was a strong La Nina year, and 2011 was the end of a change. Since 1998, rainstorm events, frequency, and anomaly in southwest China have increased significantly; since 2010, rainstorm events and frequency have decreased significantly, which is consistent with the analysis by Chen Zifan et al. on the relationship between extreme precipitation and strong ENSO events in the southwest region, namely that in strong El Nino years, extreme precipitation events increase, and in strong La Nina years, extreme precipitation events decrease [28]. The year with the highest number of rainstorm events was 2020, with 4087 events. The year with the lowest occurrence was 2011, with 2624 occurrences. The year with the highest annual average rainstorm rate is 1998, and the rainstorm rate is 6.31%. The year with the lowest annual average rainstorm rate was 2011, and the rainstorm rate is 4.33%.

3.3. Seasonal Variation in Single-Station Rainstorm Events

The spatial-temporal variation characteristics of single-station rainstorm events in southwest China are analyzed seasonally. March to May of each year is spring, June to August is summer, September to November is fall, and December to February of the next year is winter. According to statistics, there was no rainstorm event in the winter of 1961–2021 in southwest China. Figure 6 shows the spatial distribution of rainstorm frequency change trends in spring, summer, and autumn at a single station in southwest China. Overall, from 1961 to 2021, the number of stations with an increasing trend of single-station rainstorm events in summer is the most, and the number of stations with an increasing trend in autumn is the least. There are 229 stations with an increasing trend in single-station rainstorm events in spring, mainly distributed in XZ, western SC, and southern, with significant increase at 21 stations. There are 239 stations with an increasing trend in single-station rainstorm events in summer, mainly distributed in most areas of SC, GZ, and CQ, with 25 stations showing a significant increase. There are 209 stations with an increasing trend in single-station rainstorm events in autumn, mainly distributed in CQ, GZ, and other regions, with 16 stations showing a significant increase.

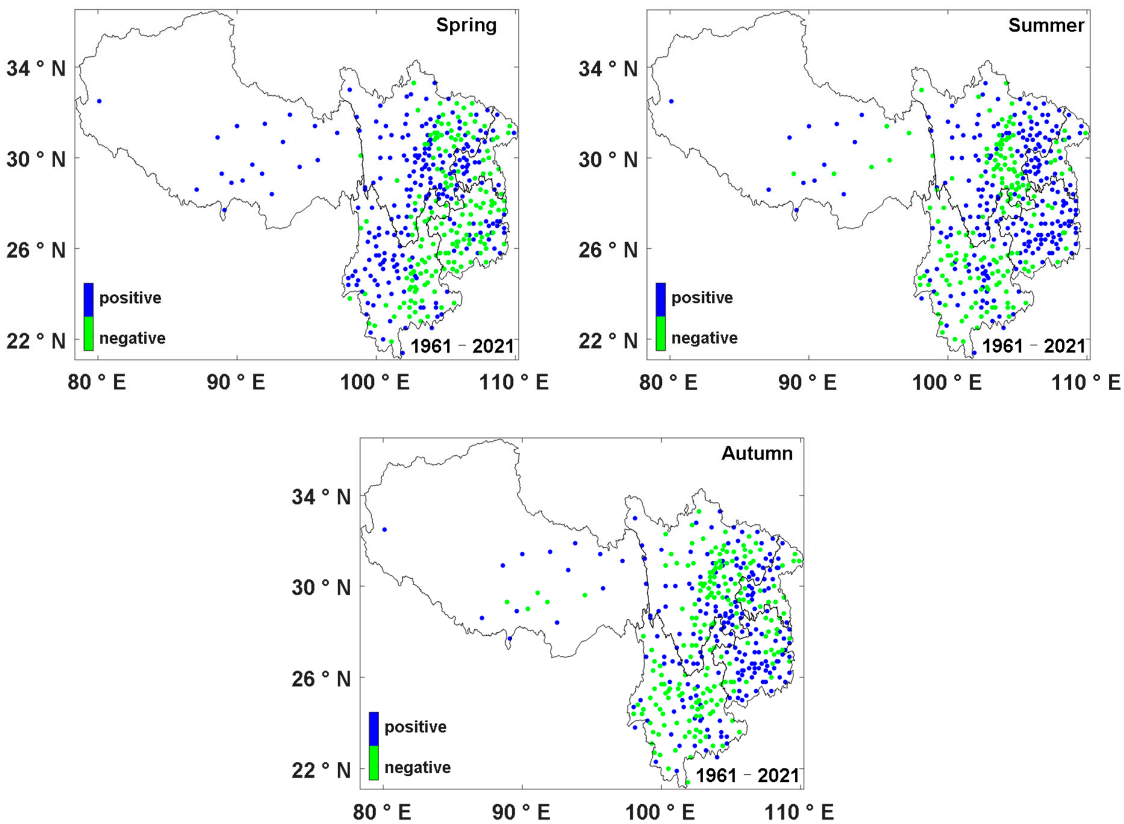

Figure 6. Trends in single–station rainstorm events in seasons.

From 1961 to 2021, the trend in single-station rainstorm events in spring, summer, and autumn in southwest China was 6.1 times · $(10a)^{-1}$, 14.8 times · $(10a)^{-1}$, 1.8 times · $(10a)^{-1}$, respectively. The increase in single-station rainstorm events in summer is the largest. The year with the highest number of single–station rainstorm events in spring, summer, and autumn is 2004, 2020, and 2008.

3.4. Temporal and Spatial Characteristics of Persistent Rainstorm Events

Figure 7 shows the frequency distribution of persistent rainstorm events of NAWS in southwest China from 1961 to 2021. Overall, there is no obvious spatial distribution law of persistent rainstorm events in southwest China. Among the 400 NAWS involved in the statistics, 303 stations had sustained rainstorm events. During 1961–2021, Fugong Station in YN, which had 15 continuous rainstorm events, had the most. The two places with the longest duration of persistent rainstorm events are Fugong Station in YN from 3 October 1979 to 8 October 1979 and Midu Station in YN from 5 October 1986 to 10 October 1986, with a duration of 6 days. After searching for disaster information, the result shows that from late September to early October 1979, continuous heavy rain occurred in the Nujiang region of YN, causing floods and mudslides. From 7 September to 15 October 1986, some areas of YN experienced heavy rain and floods [29]. These two continuous rainstorm events both triggered floods.

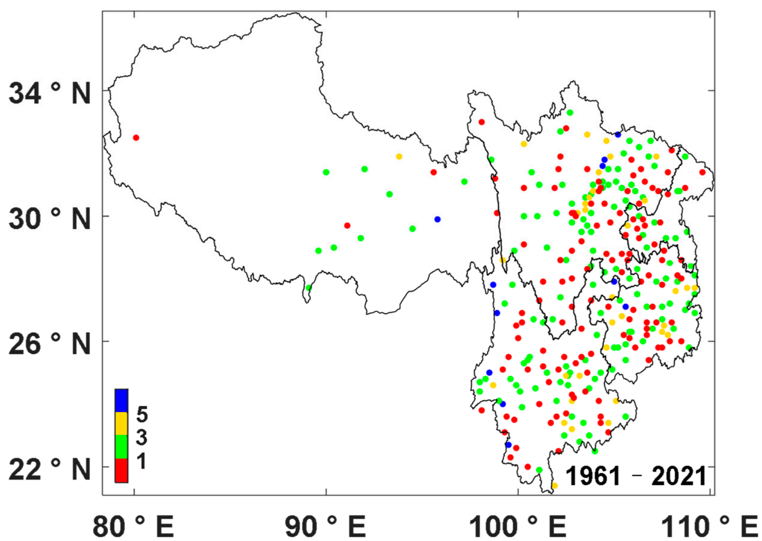

Figure 7. Number of continuous rainstorm events.

Figure 8 shows the annual distribution of persistent rainfall events in the southwestern region. From 1961 to 2021, the continuous rainstorm events in southwest China followed an increasing trend (the increase was 0.1 times · $(10a)^{-1}$), with periodic increases and decreases. The year with the highest sustained rainfall events was 1983 (93 times) and the lowest was 2002 (6 times). After sliding *t*-test ($n_1 = n_2 = 10$), no significant mutations were observed.

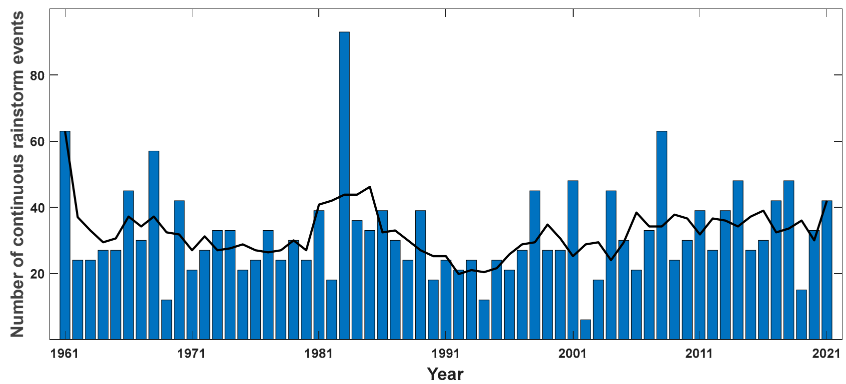

Figure 8. Number of continuous rainstorm events from 1961 to 2021 (solid line designates 5–year moving average of continuous rainstorm events).

4. Conclusions and Discussion

4.1. Conclusions

As the 50 mm rainstorm standard does not reflect the actual rainstorm events in southwest China, we aimed to display the spatial and temporal distribution of rainstorm events in southwest China more comprehensively and accurately. Based on the daily precipitation data of 400 NAWSs continuously observed in southwest China from 1961 to 2021, this paper calculates the rainstorm threshold of each station by comprehensively considering the extreme precipitation percentile method and the operational rainstorm threshold and analyzes the spatial and temporal characteristics of single-station rainstorm events and continuous rainstorm events in southwest China. We draw the following conclusions:

(1) Due to the uneven distribution of precipitation in southwest China, using a single rainstorm threshold is not suitable, and it should be considered comprehensively to determine the rainstorm threshold.
(2) The rainstorm threshold in southwest China is comprehensively judged according to the combination of 95th percentile, 99th percentile, and 50 mm rainstorm standards. The threshold value gradually decreases from east to west, and the minimum threshold value of rainstorms is at Shiquanhe Station in Tibet (9.4 mm).
(3) Using NAWS, we obtained the detailed spatial and temporal distribution of rainstorm events in southwest China: The number of single-station rainstorm events and the average precipitation of single-station rainstorm events in southwest China from 1961 to 2021 decreased from east to west. The station with the largest single-station rainstorm events is Yanjin Station in YN (1294 times), and the smallest number is Shiquanhe Station in XZ (89 times). The number and frequency of single-station rainstorm events in GZ, SC, XZ, and CQ increased from 1961 to 2021, while the number of single-station rainstorm events in YN Province decreased. There is no obvious spatial distribution law for persistent rainstorm events in southwest China. The continuous rainstorm events at Fugong Station and Midu Station in YN Province, lasting for six days, triggered the rainstorm and flood disaster.
(4) From 1961 to 2021, the number of rainstorm events and the frequency of rainstorms in southwest China followed an upward trend. The number of rainstorm events at a single station increased by 66.6 times · $(10a)^{-1}$, and the frequency of rainstorms increased by 9.9% · $(10a)^{-1}$. The sliding *t*-test ($n_1 = n_2 = 10$) is used to test the mutation of rainstorm frequency anomaly at a single station, and the results show a decrease in mutation (more than 0.05 significance level) in 1997 and 2011. The year with the largest single-station rainstorm events is 2020, with 4087 events. The year with the least occurrence was 2011, with 2624 occurrences. The year with the highest annual

average rainstorm frequency is 1998 (6.31%), and the year with the lowest annual average rainstorm frequency is 2011 (4.33%). From 1961 to 2021, the continuous rainstorm events in southwest China showed an increasing trend (the increasing trend was 0.1 times · $(10a)^{-1}$) and a periodic increase and decrease. The year with the highest sustained rainfall events was 1983 (93 times), and the year with the lowest was 2002 (6 times).

(5) Using the rainstorm threshold in southwest China, the early warning threshold of rainstorm disasters can be adjusted, which combines more closely with the local weather and climate characteristics. Using the temporal and spatial characteristics of rainstorm events since 1961, the changes in rainstorm events under global warming can be analyzed to provide data to support the response of southwest China to climate change.

4.2. Discussion

Compared with previous studies, the results of this paper on the spatial distribution of rainstorm events in southwest China are consistent with the earlier results showing that these events are high in the east and low in the west. However, due to more NAWS data, this paper obtained a more detailed spatial distribution of rainstorm events. It was found that the number and frequency of single-station rainstorm events in GZ, SC, XZ, and CQ showed an increasing trend from 1961 to 2021, while the number of single-station rainstorm events in YN showed a decreasing trend. Yang, J.H. et al. (2015) analyzed the daily precipitation of 44 NAWS from 1951 to 2012 and believed extreme precipitation events were decreasing [13]. Lu, S. et al. (2020) studied the ongoing extreme precipitation events in Southwest China from 1961 to 2016 and thought they formed an insignificant downward trend [14]. Those results are different from this paper. According to the research results of Li, Y.H. et al. (2022), summer rainstorm events in Southwest China have increased since 2020. It is also mentioned in this paper that the increasing trend in rainstorm events and rainstorm rates in southwest China from 2013 to 2021 has become more significant [18]. The single-station rainstorm event and rainstorm frequency anomaly have been positive for nine consecutive years since 2013. The continuous rainstorm events in southwest China showed an increasing trend from 1961 to 2021. The above conclusions are consistent with the results of Zhou, J. et al. (2021) and Jiang, J. et al. (2022) showing that the number of persistent regional rainstorm events in southwest China is increasing and heavy rainfall is increasing [19,20].

This paper only uses the NAWS to determining the statistics of rainstorm events. In practical applications, there are a large number of regional AWS that need data quality control and statistical analysis. Regional AWS distribution is more intensive and more conducive to finding the spatial distribution characteristics of rainstorm events and providing the government with an accurate rainstorm disaster warning threshold. It is a problem that needs to be addressed in future research.

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