Probability distribution characteristics of summer extreme precipitation in Xinjiang, China during 1970-2021

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Abstract

Based on the daily precipitation data of 96 stations in Xinjiang from 1970 to 2021, the Generalized Extreme Value (GEV) model was used to investigate the fitting effect of stationary and non-stationary GEV models on summer extreme precipitation series in Xinjiang. The time trend of extreme precipitation in summer and the difference of probability distribution of extreme precipitation in South and North Xinjiang were analyzed. The results show that: (1) In North and South Xinjiang, the averaged PRCPTOT (The summer total precipitation) at most stations were between 20–50 mm and exceeded 50 mm in the past 50 years, respectively. The RX1day (maximum 1-days precipitation) and RX5day (maximum 5-days precipitation) at most stations in Xinjiang showed a an increasing trend, while the summer CDD (consecutive dry day) at most stations in Xinjiang showed a decreasing trend. (2) The increase of return period, the confidence interval (uncertainty) of the return level of each extreme precipitation induces increases. The average intensity of RX1day and RX5day at stations in North Xinjiang are greater than at stations in South Xinjiang. The average intensity and inter-annual variability of CDD at stations in South Xinjiang are greater than at stations in North Xinjiang. (3) The RL20 (20-year return level) of RX1day and RX5day at most stations are 25 ~ 40 mm and 30 ~ 60 mm respectively except central region of Xinjiang. However, the RL20 of CDD at most stations in South Xinjiang exceeded 40 days, and experienced 30 ~ 50 days in North Xinjiang.

1 Introduction

Climate extremes, such as heavy precipitation and droughts, are one of the most influential natural disasters in the world, and the extreme precipitation events have significantly increased under global warming (IPCC 2021). Since the late 1970s, extreme precipitation events have occurred frequently in China (Zhai et al. 2005). Xinjiang, located in northwest China, has significantly less precipitation than eastern China due to factors such as uneven geographical distribution and distance from the sea. The precipitation in Xinjiang is mainly concentrated in summer, and the spatial distribution shows that the precipitation in North Xinjiang is more than that in South Xinjiang (Jiang et al. 2013; Xie et al. 2018; Hu et al. 2021).

It is notable that the global temperature continues to rise, precipitation and extreme precipitation events at regional scale changed significantly (Ailiyaer et al. 2021). Since the 1960s, the intensity and frequency of extreme precipitation events as rainstorm and flood has significantly increased while the drought events decreased, there are spatial and temporal differences in the trend of extreme precipitation over Xinjiang (Zhang el al. 2019; Chen et al. 2021). Jiang et al. (2013) and Wang et al. (2021) found that precipitation extremes and the annual precipitation of most stations in Xinjiang showed a significant increasing trend, but the increase of some stations was limited. Wang et al. (2014) studied extreme precipitation in the surrounding area of the Taklimakan Desert, the results show that the consecutive dry day (CDD) index showed a decreasing trend from 1961 to 2009, while the number of days with daily precipitation less than 25% quantile showed an increasing trend. Guan et al. (2021) investigated the historical and future changes of extreme climate indices over Xinjiang based on climate models. They suggested that the consecutive wet days (CWDs) lengthened and CDDs shortened during historical period. Besides, the impact of global warming on extreme climate indices was approximately linear. In terms of the mechanism of extreme precipitation, Zhou et al. (2021a) analyzed the changes and circulation characteristics of extreme precipitation in North Xinjiang based on summer precipitation and NCEP/NCAR reanalysis data during 1961–2017. The results show that the frequency of extreme precipitation of different grades increases in summer, and the abnormal water vapor transport in North Xinjiang provides favorable conditions for the occurrence of extreme precipitation events. Zhou et al. (2021b) found that the summer extreme precipitation in North Xinjiang was positively correlated with the spring sea surface temperatures (SST) over the tropical Indian Ocean and the equatorial eastern Pacific, and when the SST showed a warm anomaly, the extreme precipitation in North Xinjiang was more. Studies also indicated that the mechanisms of summer extreme precipitation in Xinjiang are characterized by a zonal wave pattern with the deepening of the western Siberian trough, central Asian high, and Mongolian high. Further, summer extreme precipitation are linked to the SSTs from the Indian Ocean, the Kuroshio, the central-eastern Pacific, and part of the Atlantic Ocean (Wang and Yang 2017; Ning et al. 2021).

In addition, extreme precipitation events have the characteristics of low frequency, relatively large or small intensity value and leading to serious social and economic losses. Extreme value model can describe the distribution characteristics of extreme precipitation in summer, and it has been widely used in the research and analysis of extreme climate problems. For example, Li et al. (2005) used the generalized Pareto distribution (GPD) to establish a statistical model of extreme precipitation in Western Australia, and tested the changes of annual and seasonal maximum daily precipitation. Villafuerte et al. (2015) studied the response of global warming and ENSO to extreme precipitation in Southeast Asia by using a non-stationary generalized Extreme Value (GEV) model. Domestic scholars have also carried out a number of studies on regional extreme climate events in China using extremum theoretical models. Li et al. (2018) used a non-stationary GEV model to detect the impact of human activities on extreme precipitation at a regional scale in China. The study points out that the effects of human activities on precipitation extremes in historical periods are not detected by observations or simulations (not significant). Lu et al. (2019) used the non-stationary GEV model to study the influence of urbanization on annual maximum daily precipitation (Maximum 1-day precipitation, Rx1day) and annual maximum 5-day consecutive precipitation (maximum 5-day precipitation, Rx5day and Rx5day increased by 25.9% and 59.1% in highly urbanized stations, 34.2% and 36.9% in low urbanized stations, and 30.7% and 61.5% in rural stations, respectively.

There are many studies on the spatial-temporal variation characteristics of summer extreme precipitation in Xinjiang. However, there are few studies on the characterization of the probability distribution characteristics of summer extreme precipitation index and the difference of the probability distribution of summer extreme precipitation index in South and North Xinjiang. Hence, this study evaluate the fitting effect of GEV model on summer extreme precipitation index in Xinjiang based on stationary and non-stationary GEV models, and explore the intensity and variability of summer extreme precipitation index and the difference of summer extreme precipitation in South and North Xinjiang. Section 2 introduce the data and the modeling process of GEV model. Section 3 gives the fitting effect of GEV model, the probability distribution characteristics of summer extreme precipitation index and the difference of extreme precipitation index in South and North Xinjiang. Section 4 gives the discussion and conclusion.

2 Data And Method

2.1 Data used

The daily precipitation data used in this study are from 105 national observation stations across Xinjiang during 1960–2021 and are provided by the National Meteorological Information Center, China Meteorological Administration (http://www.nmic.cn/). After eliminating the missing values and temporal inhomogeneity, 96 stations with relatively complete data from 1970 to 2021 are selected subsequent analysis, and three extreme precipitation indices (i.e., PRCPTOT, RX1day, RX5day and CDD) are calculated. The definitions of the four extreme precipitation indices are shown in Table 1.

Table 1
Definitions of the four extreme precipitation indices.

Index	Name	Definition Maximum	Unit
PRCPTOT	Summer total precipitation	Summer total precipitation with R ≥ 0.1 mm days	mm
RX1day	Summer maximum 1-days precipitation	Summer maximum 1-day Precipitation	mm
RX5day	Summer maximum 5-days precipitation	Summer maximum consecutive 5-day precipitation	mm
CDD	Summer consecutive dry days	Maximum number of consecutive days with RR < 1 mm	days

2.2 Method

The GEV distribution can well model the characteristics of block maximum sequence (Coles 2001; Li et al. 2018; Kurniadi et al. 2021). Hence, the summer extreme precipitation indices of RX1day, RX5day and CDD are fitted to GEV distribution to describe the probability distribution characteristics. The cumulative distribution function of GEV model is given by:

$$G(X;\mu,\sigma,\xi)=\begin{cases}\exp\left\{-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right\}, 1+\frac{\xi(x-\mu)}{\sigma}>0, \xi\neq 0, \\ \exp\left[-\exp\left(-\frac{x-\mu}{\sigma}\right)\right], \xi=0.\end{cases} \quad (1)$$

where the μ,$\sigma$and$\xi$are location, scale and shape parameters, respectively, and $\mu,\xi \in \mathrm{R}$,σ>0.

There are many parameter estimation methods for extreme model, but for complex model, maximum likelihood estimation has better adaptability. Suppose extreme precipitation series $x_1, x_2, \ldots, x_n$is independent and identically distributed and obeys GEV distribution. Then the logarithmic likelihood function of GEV distribution is given by:

$$
l(\mu, \sigma, \xi) = \begin{cases} -n\log\sigma - \left(1 + \frac{1}{\xi}\right)\sum_{i=1}^{n}\log\left[1 + \xi\left(\frac{x_i - \mu}{\sigma}\right)\right] - \sum_{i=1}^{n}\left[1 + \xi\left(\frac{x_i - \mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}, \\ 1 + \xi\left(\frac{x_i - \mu}{\sigma}\right) > 0, i = 1,2,\ldots,n, \xi \neq 0 \\ -n\log\sigma - \sum_{i=1}^{n}\left(\frac{x_i - \mu}{\sigma}\right) - \sum_{i=1}^{n}\exp\left[-\left(\frac{x_i - \mu}{\sigma}\right)\right], \xi = 0. \end{cases} \quad (2)
$$

Further, the index of time series (t=1,2... ,50) is introduced as covariate into the location parameter of GEV model (i.e., $G(X; \mu(t), \sigma, \xi)$) to explore the temporal trend of summer extreme precipitation in Xinjiang. For extreme precipitation indices of each station, two parameter assumptions are given in Table 2.

Table 2
Two parameter assumptions

Model	**Parameter assumption**
M_0	μ, σ, ξ
M_{Time}	$\mu(t) = \mu_0 + \mu_1 Time(t), \sigma, \xi$

At the same time, the likelihood ratio test (LRT) is used to select the best statistical model for each station, and LRT of M_{Time} is also used to test the significance of the time trend of summer extreme precipitation indices. The test statistics of LRT is given by the deviation function:

$$
D = 2(l_{Time} - l_0) \quad (3)
$$

Where l_{Time} and l_0 are the maximum logarithmic likelihood estimators of non-stationary model M_{Time} and stationary model M_0 respectively. In addition, Kolmogorov-Smirnov (K-S) test is used to test the fitting effect of stationary model M_0 on summer extreme precipitation, and Mann-Kendall (MK) test is used to test the trend of total summer precipitation during 1970–2021.

Based of the fitting results of GEV model, the return periods and return levels of extreme precipitation indices can be calculated as follows:

$$
RL(1 - p) = \mu + \frac{\sigma}{\xi}\{[-\ln(1 - p)]^{-\xi} - 1\} \quad (4)
$$

It is noted out that, for the stations with non-stationary model (i.e., the M_{Time} is slected the best statistical model), the return period and return level of extreme precipitation indices given in this study are multi-year average.

3 Results

3.1 Trend of summer extreme precipitation

To analyze and compare the difference between summer total precipitation and extreme precipitation, the spatial distribution of averaged PRCPTOT during 1970–2021, PRCPTOT anomaly (difference of PRCPTOT between 2001–2021 and 1970–2020) and PRCPTOT trend are showed in Fig. 1. In the past 50 years, the averaged PRCPTOT of most stations in Xinjiang was more than 20 mm. In South Xinjiang (south of the red dotted line in Fig. 1a), the averaged PRCPTOT of most stations was between 20–50 mm, and some stations reached 60–70 mm. In North Xinjiang (north of the red dotted line in Fig. 1a), the PRCPTOT of most stations exceeded 50 mm, and some stations reached more than 90 mm. Compared with 1970–2000, the average PRCPTOT of most stations was increased from 2001 to 2021, while that of some stations in central Xinjiang was decreased. Among them, the PRCPTOT anomaly of most stations in western Xinjiang exceeded 15 mm, and some stations exceeded 25 mm (Fig. 1a). Meanwhile, it can be seen from Fig. 1 (c) that the PRCPTOT of most stations in Xinjiang showed an increasing trend, while some stations showed a decreasing trend. And the PRCPTOT at most stations in South Xinjiang showed a statistically significant increasing trend (significant at 0.05 level based on the MK test).

Over the past 50 years, the PRCPTOT of most stations in Xinjiang showed an increasing trend, and the precipitation in North Xinjiang was more than that in South Xinjiang. In order to further analyze the variation characteristics of summer extreme precipitation in Xinjiang during historical period, Fig. 2 shows the trend of RX1day, RX5day and CDD. It can be seen that the summer RX1day and RX5day of most stations in Xinjiang showed an increasing trend, while the summer RX1day and RX5day of some stations in central Xinjiang showed a decreasing trend. The stations with significant increases in summer RX1day and RX5day (significant at 0.1 level) are mainly located in the southern South Xinjiang, and the stations with significant increases in summer RX5day were more than the stations with significant increases in summer RX1day (Fig. 2a, b).

Meanwhile, the summer CDD of most stations in Xinjiang showed a decreasing trend, while that of some stations showed a decreasing trend, and the stations with a significant decrease in summer CDD (significant at 0.1 level) were mainly located in the southern South Xinjiang (Fig. 2c). Further, the stations with increasing trend of summer RX1day and RX5day and decreasing trend of summer CDD basically overlapped. Combined with the variation characteristics of PRCPTOT, RX1day, RX5day and CDD, it can be seen that the summer precipitation in the southern South Xinjiang increased from 1970 to 2021, while the continuous dry days decreased.

Further, Fig. 3 shows averaged summer extreme precipitation anomalies over North and South Xinjiang. As shown in Fig. 3, negative anomalies of the PRCPTOT, RX1day and RX5day in North Xinjiang were mainly occur during 1970s - mid 1990s, and positive anomalies were occur after mid 1990s. Meanwhile, positive anomalies of CDD was occur during 1970s - late 1980s, negative anomalies was occur after late-1980s. In South Xinjiang, the PRCPTOT, RX1day and RX5day showed negative anomalies during 1970s - mid 1990s and late 2000s - early 2010s, showed positive anomalies during mid 1990s - late 2000s and early 2010s – 2020s, and significantly increased after 2010s in South Xinjiang. The CDD showed positive anomalies during 1970s - late 1980s and showed negative anomalies late-1980s. It also can be seen from the Fig. 3 that compared with North Xinjiang, the increasing trend of the PRCPTOT, RX1day and RX5day are weaker while the decreasing trend of CDD is stronger.

3.2 Statistical modeling of extreme precipitation

In order to analyze the statistical characteristics of summer extreme precipitation indices in Xinjiang, the GEV distribution introduced in Section 2 was used to model the time series of summer RX1day, RX5day and CDD at each station. Table 3 shows the best statistical model and significance test results of summer extreme precipitation indices at X51482, X51827 and X51839 stations, and X51482 station is located in North Xinjiang, while X51827 and X51839 stations are located in South Xinjiang (black triangle in Fig. 2c). As can be seen from Table 3, the best statistical model of the summer extreme precipitation indices of X51482 and X51839 stations are stationary GEV model (significant at 0.05 level based on KS test). For the X51827 station, the best statistical model of summer RX1day and RX5day are non-stationary GEV model (significant at 0.1 level based on LRT test), while the best statistical model of summer CDD is stationary GEV model (significant at 0.05 level based on KS test). Further, the location parameter μ and scale parameter σ of summer RX1day and RX5day (CDD) of X51482 station are significantly larger than (smaller than) the other two example stations. Which means that the average intensity and variability of summer RX1day and RX5day (CDD) at X51482 station were greater than (less than) the other two stations. The shape parameters of summer RX1day and RX5day (CDD) of X51482 station are lower (higher) than those of X51827 and X51839.

Table 3 Parameter estimates of stationary and non-stationary GEV model of summer extreme precipitation indices at three example stations. For the stations with stationary GEV models, the p-value of KS test are shown, while the p-value of LRT are shown for the stations with non-stationary GEV models.

Station	Index	$\mu(\pm se)$	$\mu_1(\pm se)$	$\sigma(\pm se)$	$\xi(\pm se)$	p
X51482	RX1day	23.5 ($\pm$1.41)	-	9.20 ($\pm$1.102)	0.02 ($\pm$0.09)	0.99
	RX5day	31.46 ($\pm$1.72)	-	11.14 ($\pm$1.28)	0.12 ($\pm$0.09)	0.76
	CDD	15.48 ($\pm$0.54)	-	3.35 ($\pm$0.43)	0.20 ($\pm$0.13)	0.48
X51827	RX1day	5.19 ($\pm$1.26)	0.07 ($\pm$0.04)	4.64 ($\pm$0.55)	0.12 ($\pm$0.10)	0.09
	RX5day	6.15 ($\pm$1.60)	0.09 ($\pm$0.06)	6.14 ($\pm$0.78)	0.17 ($\pm$0.12)	0.10
	CDD	37.29 ($\pm$1.51)	-	9.90 ($\pm$1.05)	-0.05 ($\pm$0.08)	0.26
X51839	RX1day	6.99 ($\pm$0.78)	-	4.84 ($\pm$0.63)	0.23 ($\pm$0.13)	0.99
	RX5day	9.78 ($\pm$1.21)	-	7.22 ($\pm$0.97)	0.19 ($\pm$0.15)	0.60
	CDD	36.75 ($\pm$1.79)	-	11.26 ($\pm$1.33)	0.02 ($\pm$0.12)	0.94

In order to further evaluate the fitting effect of GEV model on summer extreme precipitation indices of three example stations, Fig. 4 shows the probability and quantile plots of summer extreme precipitation. For the extreme precipitations with stationary (non-stationary) GEV models, the (residual) probability and quantile plots are given. As can be seen from Fig. 4 (a, c and e) that the empirical and model-derived probabilities are basically on the diagonal. For quantile plots, except for a few unusually high values, model-derived and empirical quantiles are basically on the diagonal (the off-diagonal points in Figs. 4b, d and f). In general, GEV model can well describe the behavior of the RX1day, RX5day and CDD sequences example stations.

Figure 5 shows the variation curves of summer RX1day, RX5day and CDD return level with return periods at the three example stations. It can be seen that the observed values of the extreme precipitation index of example stations are basically within the confidence interval, that is, these extreme precipitation events conform to the GEV model. For extreme events with a return period of more than 20 years, the return level of summer RX1day and RX5day are more than 40 mm, and the return level of summer CDD is about 30 days at X51482 station (blue curves of Fig. 5a, d and g). However, when the return periods are more than 20 years, for X51827 and X51839 stations, the return level of summer RX1day and RX5day are 20–40 mm, and the return level of summer CDD are more than 60 days. At the same time, it can be seen that with the increase of return period, the confidence interval (uncertainty) of the return level of each extreme precipitation index increases. In other words, the extreme precipitation events corresponding to the longer return period have greater uncertainty.

In addition, rare extreme precipitation events occurred in some areas of South Xinjiang in the summer of 2021. Figure 5 also shows the return periods and return levels of extreme precipitation indexes in the summer of 2021 for three example stations (black square dots). The summer RX1day and RX5day of X51827 station in 2021 reached 51.83 mm and 68.63 mm, respectively, a once-in-53-year event, while the summer CDD was a once-in-2.04 year event (i.e., the return level was 40 days). And the RX1day and RX5day of X51839 station were 1.33 years and 1.56 years (return level was 4.87 mm and 10.68 mm, respectively), and the CDD reached 74 days (17.67 years). Meanwhile, the RX1day, RX5day and the CDD of X51482 station were 1.83 years, 4.42 years and 55 years, respectively(return level are 25.45 mm, 45.34 mm and 34 days, respectively).

3.3 Probability distribution of extreme precipitation in summer

In order to further analyze the spatial characteristics of probability distribution of summer extreme precipitation indices, stationary and non-stationary GEV models are used to model time series of summer RX1day, RX5day and CDD of all stations. The non-stationary GEV model is used for stations with significant time trends (hollow stations in Fig. 2). The best statistical model of all stations are significant at 0.05 and 0.1 level based on K-S test (stationary model) and LRT (non-stationary model) respectively, indicating that the extreme value model can well simulate the characteristics of summer extreme precipitation in Xinjiang. Figure 6 shows the spatial distribution of average intensity (GEV model location parameters) and inter-annual variability (GEV model scale parameters) of the three extreme precipitation indices in Xinjiang during 1970–2021.

As can be seen from Fig. 6 (a), the spatial distribution of the average intensity of RX1day is basically consistent with the mean PRCPTOT (Fig. 1a). The average intensity of RX1day of most stations in North Xinjiang are more than 10 mm. Among them, some stations in the southern North Xinjiang reached 15 mm, and some stations are more than 25 mm. At most stations in South Xinjiang, the average intensity of RX1day are between 5 ~ 10 mm. Meanwhile, the interannual variability of RX1day at most stations in Xinjiang are between 4 ~ 8 mm, and only a few stations had a RX1day interannual variability of more than 8 mm (Fig. 6b). The average intensity of RX5day at most stations in North Xinjiang are between 10 ~ 20 mm, and some stations in southern North Xinjiang are between 30 ~ 40 mm. The average intensity of RX5day of most stations in South Xinjiang is less than 20 mm, and that of the southern stations is less than 10 mm. The interannual variability of RX5day of most stations in Xinjiang region is between 4 ~ 12 mm (Fig. 6c, d). In addition, the average intensity of CDD are 10 ~ 20 days at western stations, 20 ~ 30 days at central stations and eastern stations in North Xinjiang. The interannual variability of CDD at most stations in North Xinjiang are 4 ~ 8 days. The average intensity of CDD at the stations in South Xinjiang are more than 20 days, and the interannual variability are more than 8 days. The average intensity of CDD at the stations in South Xinjiang are 30 ~ 40 days (Fig. 6e, f).

As shown in Fig. 1 ~ 6, although the PRCPTOT, RX1day and RX5day showed an increasing trend in South Xinjiang, the mean intensity and interannual variability of summer RX1day and RX5day are weaker than those in North Xinjiang, and the mean intensity and interannual variability of summer CDD are stronger than those in North Xinjiang. Therefore, in order to further compare the differences of low-probability extreme precipitation events in North and South Xinjiang in historical periods, the spatial distribution of the 20-year return level (RL20) of summer RX1day, RX5day and CDD are presented in Fig. 7. It can be seen that the RL20 of RX1day and RX5day at stations in the central region of Xinjiang exceeded 40 mm and 60 mm, respectively, while the RL20 of RX1day and RX5day at other stations are 25 ~ 40 mm and 30 ~ 60 mm respectively. The RL20 of RX1day and RX5day at some stations are less than 30 mm (Fig. 7a, b). In addition, there are no significant spatial difference between RX1day and RX5day at stations in South Xinjiang and North Xinjiang stations. However, the RL20 of CDD at most stations in South Xinjiang exceeded 40 days, and the RL20 of CDD exceeded 60 days at most stations in southern South Xinjiang. However, the RL20 of CDD at most stations in North Xinjiang experienced 30 ~ 50 days, and some stations experienced more than (less than) 60 days (30 days).

According to the analysis in Fig. 7, there is no significant difference in the magnitude of extreme heavy precipitation events (except for stations in the central region) in North and South Xinjiang. However, record-breaking extreme precipitation events occurred at some stations in South Xinjiang in the summer 2021 (Fig. 5). In order to investigate the regional characteristics of this extreme precipitation event, Fig. 8 shows the spatial distribution of the return period of the extreme precipitation index in Xinjiang in summer 2021. For most stations, the return period of Rx1day, Rx5day and CDD in summer 2021 is less than 10 years. The return periods of Rx1day and Rx5day at stations in southern South Xinjiang exceeded 10 years, and the return periods of the two extreme precipitation indces at some stations exceeded 40 years. In addition, the return period of Rx5day at some stations in North Xinjiang was more than 10 years, and the return period of CDD at stations in eastern South Xinjiang was more than 30 years. Combined with Fig. 8 (a-c), it can be seen that the extreme precipitation events in 2021 are more precipitation in the southern South Xinjiang, and more drought in the eastern South Xinjiang. In other words, the southern South Xinjiang desert is wet, while the eastern South Xinjiang desert is dry.

4 Discussion

This study investigated and analyzed the regional differences and probability distribution characteristics of summer extreme precipitation indces in South and North Xinjiang in recent 50 years. In general, the extreme heavy precipitation at most stations in Xinjiang increased, while the drought events decreased. The extreme heavy precipitation events in South Xinjiang are weaker than those in North Xinjiang, while the drought events are stronger than those in North Xinjiang. The stations with statistically significant increasing trend of PRCPTOT and RX5day are more than RX1day. In addition, the summer extreme precipitation events in 2021 are obviously regional and local. The southern South Xinjiang desert is wet, while the eastern South Xinjiang desert is dry.

Studies in recent years has shown that since 1960s, the extreme precipitation increases at most stations in Xinjiang, drought extremes decreased in Northwest China. And the increasing trends were statistically significance only at some stations in Xinjiang due to the time and spatial variability of extreme precipitation (Zhang et al. 2015; Liu et al. 2019). Further, Xiao et al. (2016) pointed that the Northwest China has become more humid and the precipitation intensity increased slightly. It is notable that our study analyzed the time trend and variability of extreme precipitation indces over Xinjiang based on extreme value theory, and our results are similar the findings of these studies.

Besides, studies also indicated that the regional averaged summer extreme precipitation over Northwest China increased significantly, and the annual extreme precipitation increases and annual CDD shows a decreasing trend at most area of Xinjiang while the annual CDD shows a increasing trend northeast of Xinjiang. (Long et al. 2016; Wang and Yang 2017). The finding of CDD trends is different from our conclusion, this might be our analysis are based on the station dataset.

5 Conclusion

Based on the daily precipitation data in Xinjiang during 1970–2021, the trend of observed PRCPTOT and extreme precipitation over North and South Xinjiang are compared, and return level and return period of extreme precipitation are analyzed. The results show that:

(1) In North and South Xinjiang, the averaged PRCPTOT at most stations were between 20–50 mm and exceeded 50 mm in the past 50 years, respectively. The PRCPTOT at most stations in South Xinjiang showed a statistically significant increasing trend. The summer RX1day and RX5day of most stations in Xinjiang showed an increasing trend, while that of some stations in central Xinjiang showed a decreasing trend. Meanwhile, the summer CDD at most stations in Xinjiang showed a decreasing trend, while that of some stations showed a decreasing trend.

(2) The increase of return period, the confidence interval (uncertainty) of the return level of each extreme precipitation indices increases. In other words, the extreme precipitation events corresponding to the longer return period have greater uncertainty. In addition, rare extreme precipitation events occurred in some areas of South Xinjiang in the summer of 2021. The summer RX1day and RX5day of X51827 station in 2021 reached 51.83 mm and 68.63 mm, respectively, a once-in-53-year event, while the summer CDD was a once-in-2.04 year event (i.e., the return level was 40 days). And the RX1day and RX5day of X51839 station were 1.33 years

and 1.56 years (return level was 4.87 mm and 10.68 mm, respectively), and the CDD reached 74 days (17.67 years). Meanwhile, the RX1day, RX5day and the CDD of X51482 station were 1.83 years, 4.42 years and 55 years, respectively (return level are 25.45 mm, 45.34 mm and 34 days, respectively).

(3) The average intensity of RX1day at most stations in North and South Xinjiang are more than 10 mm and between 5 ~ 10 mm, respectively. Meanwhile, the interannual variability of RX1day at most stations in Xinjiang are between 4 ~ 8 mm. The average intensity of RX5day at most stations in North and South Xinjiang are between 10 ~ 20 mm and less than 10 mm. The interannual variability of RX5day at most stations in Xinjiang region is between 4 ~ 12 mm. In addition, the average intensity of CDD is 10 ~ 30 days and more than 20 days at most stations in North and South Xinjiang, respectively. The interannual variability of CDD at most stations in North Xinjiang are 4 ~ 8 days, while that are more than 8 days in South Xinjiang. The RL20 of RX1day and RX5day at most stations are 25 ~ 40 mm and 30 ~ 60 mm respectively except central region of Xinjiang. However, the RL20 of CDD at most stations in South Xinjiang exceeded 40 days, and experienced 30 ~ 50 days in North Xinjiang.

Extreme precipitation in Xinjiang had significant relationship with North Atlantic Oscillation, Atlantic Multidecadal Oscillation, Multivariate ENSO Index and Indian Ocean Dipole Index (Guo et al. 2014; Xiao et al. 2017; Xie et al. 2019; Hu et al. 2021). The further work will study and quantization the impact of different climate indices on extreme precipitation in Xinjiang and investigate possible mechanism, and try to build predictive models.

Declarations

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Author Contributions. All authors contributed to the study conception and design. Material preparation, data collection and data curation were performed by Zhang Hailiang, Gao Jiacheng, Wen Cong and Song Meiqi. The methodology and software were performed by Zhu Lianhua and Liu Junjian. The investigation, visualization, writing - original draft preparation and analysis were performed by Ailiyaer Aihaiti, Wang Yu and Ali Mamtimin. And all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability Statement. The datasets used in this study can be provide by Ali Mamtimin (ali@idm.cn) upon request.

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Figures

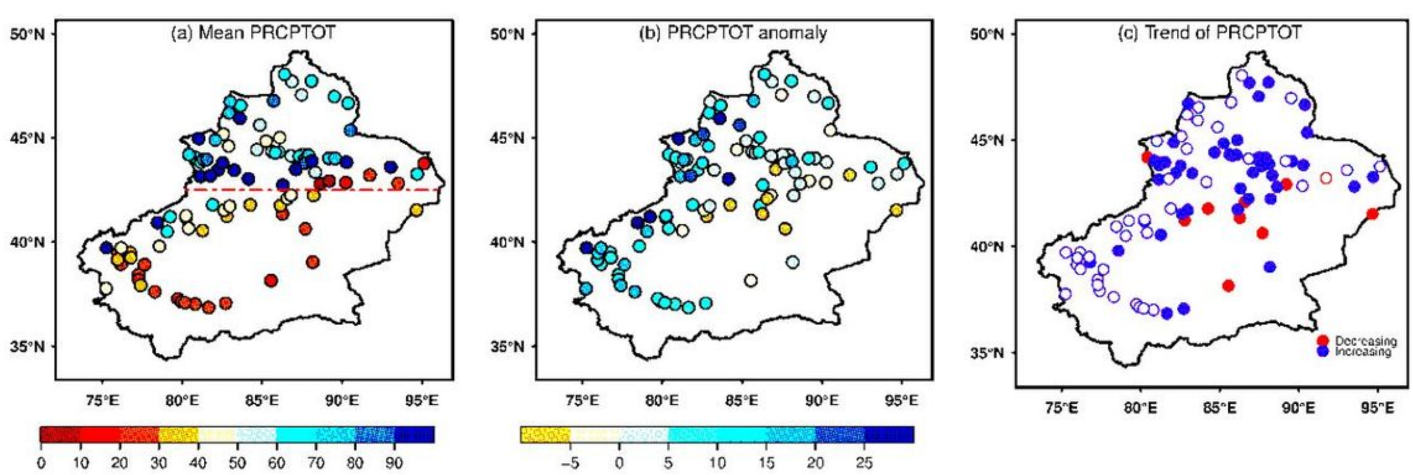

Figure 1

The spatial distribution of (a) averaged PRCPTOT (unit: mm) during 1970-2021, (b) PRCPTOT difference between 2001-2021 and 1970-2000 (unit: mm) and (c) trend of PRCPTOT during 1970-2021. The dotted line in figure (a) (lat = 42.5 °N) represents the dividing line between North and South Xinjiang, and the hollow circle in figure (c) represents trend of PRCPTOT significant at 0.05 level based on MK test.

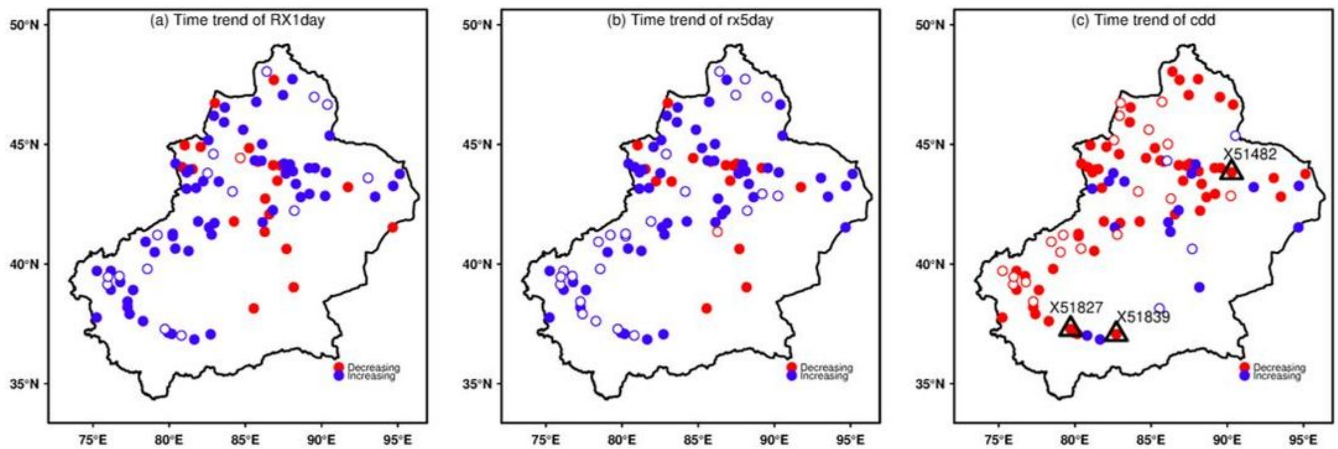

Figure 2

Trend of summer (a) RX1day, (b) RX5day and (c) CDD. The hollow dots indicate that the extreme precipitation indices significant at 0.05 level based on MK test. The black triangles represent the three example stations, respectively.

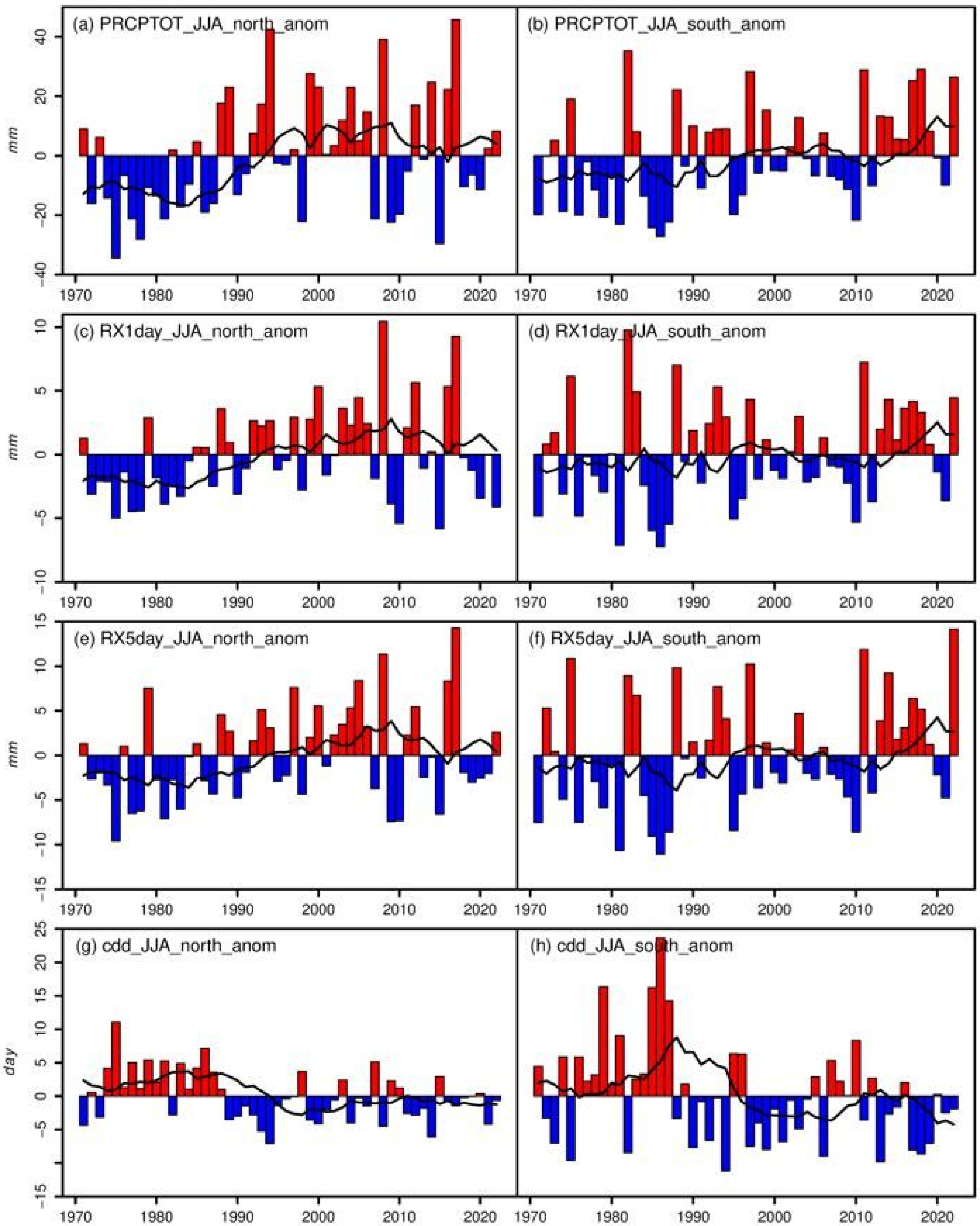

Figure 3

The time series of averaged summer (a, b) PRCPTOT (unit: mm), (c, d) RX1day (unit: mm), (e, f) RX5day (unit: mm) and (g, h) CDD (unit: day) anomalies over North and South Xinjiang. The bar diagram and the black solid line indicate the extreme precipitation indices anomalies and their 11-year running mean.

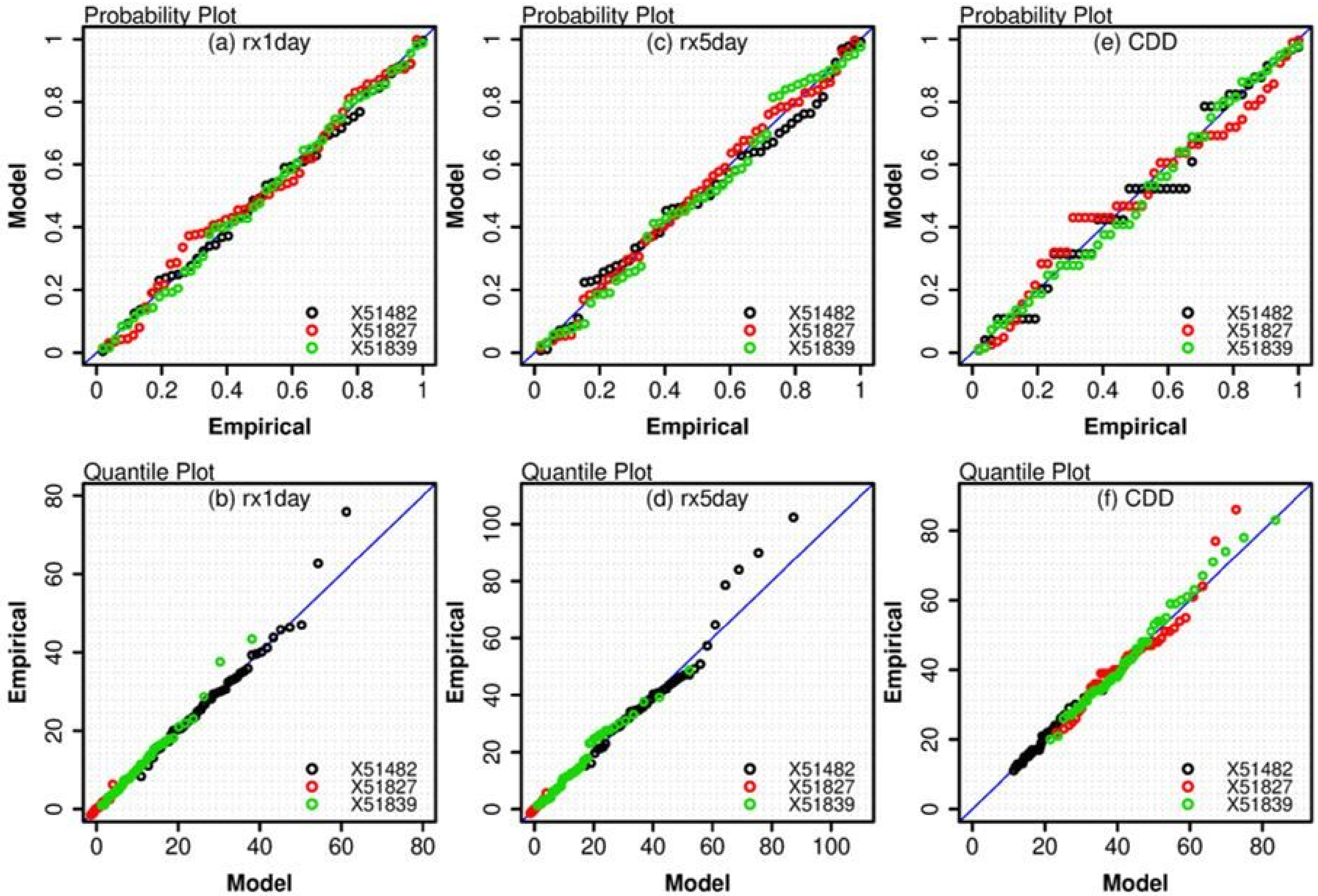

Figure 4

The (a, c, e) probability plot and the (b, d, f) quantile plot of the extreme precipitation indices at three example stations. The probability plot (Fig. a, c, e) shows the empirical and model-derived probabilities, the quantile graph (Fig. b, d, f) shows the model-derived and empirical quantiles, and the solid blue line represents the line 1-1.

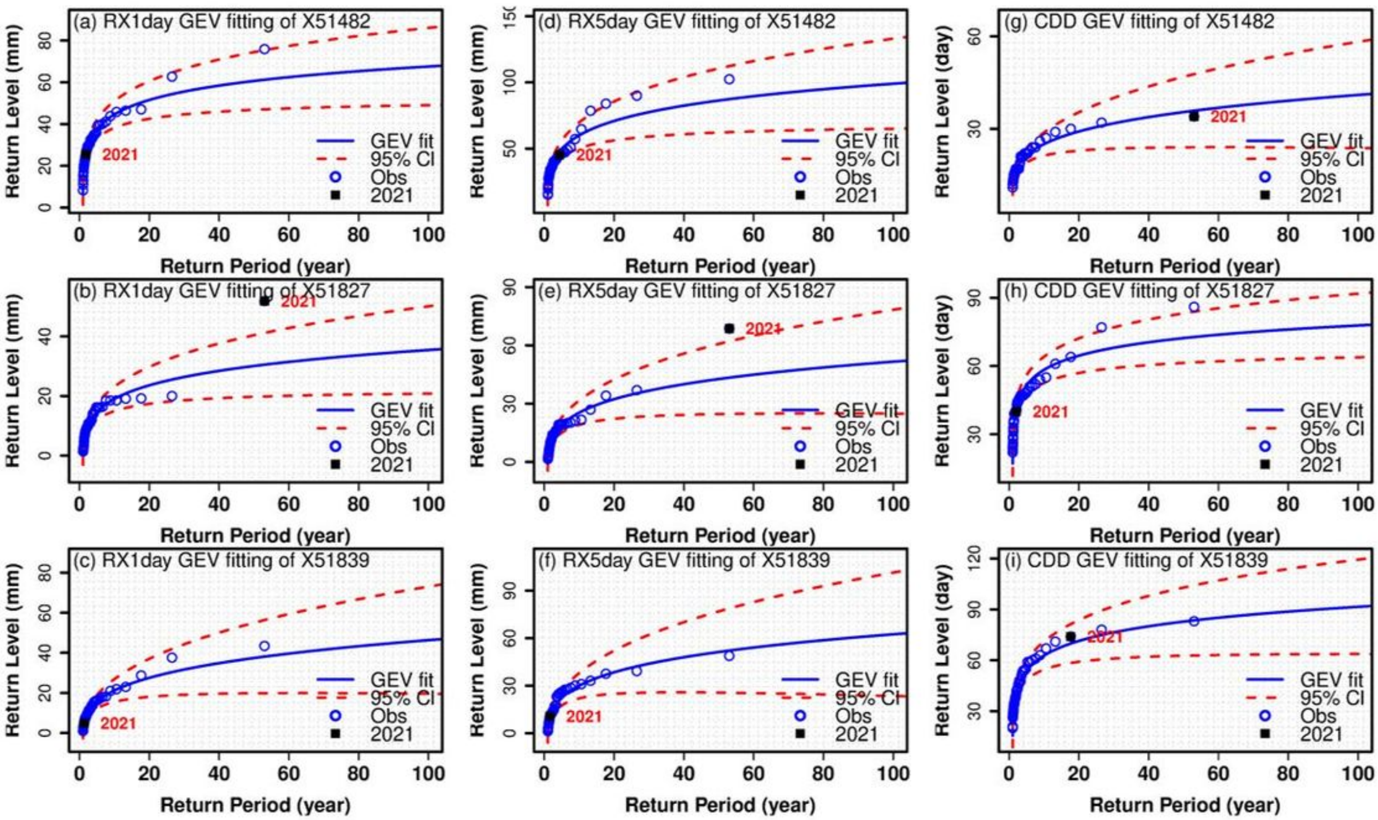

Figure 5

Changes of the return level of extreme precipitation indices with the return period at three example stations. The solid black line and the dotted red line represent the GEV fitting curve and 95% confidence interval respectively, while the blue origin and the black square point represent historical observations and extreme events in 2021, respectively.

Figure 6

(a, c, e) mean intensity (stationary GEV model location parameters) and (b, d, f) interannual variability (stationary GEV model scale parameters) of RX1day, RX5day and CDD in summer.

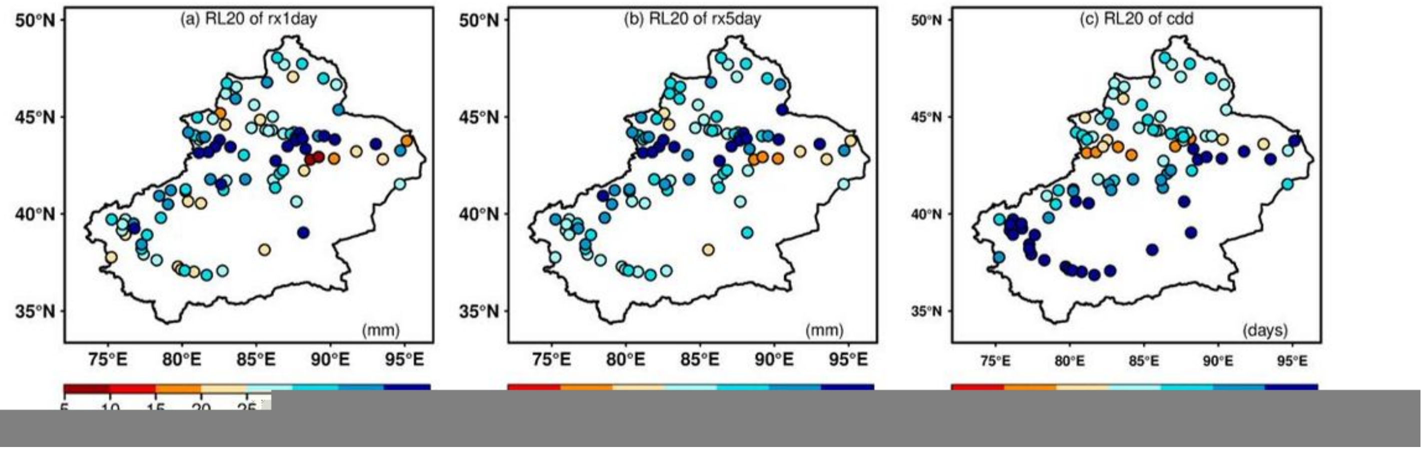

Figure 7

The spatial distribution of the RL20 of summer (a) RX1day (unit: mm), (b) RX5day (unit: mm) and (c) CDD (unit: day) in Xinjiang region.

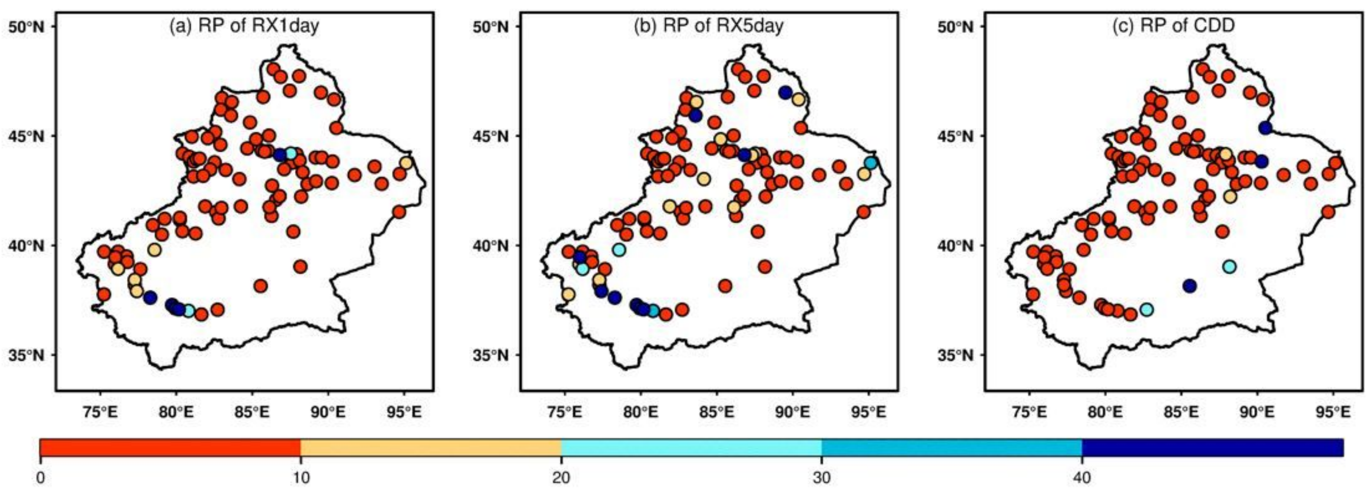

Figure 8

Spatial distribution of the return period of extreme precipitation indces in Xinjiang in 2021.