Spatiotemporal variations in extreme precipitation and their potential driving factors in non-monsoon regions of China during 1961–2017

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Abstract

Extreme precipitation events affect the ecological environment and are also important for the sustainable development of regional socioeconomics. Although there are some local studies on extreme precipitation events in which the temporal and spatial variation characteristics of extreme precipitation events in non-monsoon regions (NMRs) are systematically assessed, detailed study on the driving mechanisms of variation are becoming increasingly important. In this study, nine extreme precipitation indices were used to analyze the characteristics of extreme precipitation event spatiotemporal variations in NMRs in China during 1961–2017. The results show that except for the consecutive dry days, which shows a significant decreasing trend ($P < 0.01$) of $-2.33$ days/decade, all other indices showed obvious increasing trends, especially the indices of wet day precipitation (PRCPOT), highest 5 day precipitation (RX5day) and light rain days (R5 mm), with significantly increasing trends ($P < 0.01$) of 6.80 mm/decade, 0.73 mm/decade and 0.45 days/decade, respectively. In addition, a correlation analysis between altitude, longitude, latitude and extreme precipitation shows that stations at an altitude of more than 3500 m have significantly correlations with both extreme precipitation and longitude in NMRs ($P < 0.05$). In addition, results also indicated that there are significant relationships between extreme precipitation events in NMRs and large-scale ocean-atmosphere circulation patterns ($P < 0.05$). The rapid increase in extreme precipitation indices over the past 20 years is closely related to the Atlantic Multidecadal Oscillation shift to a warm phase, while the Pacific Decadal Oscillation, El Niño–Southern Oscillation and Summer Monsoon Index show significant correlation with the extreme indices only in certain seasons ($P < 0.05$).

1. Introduction

Global warming affects global average temperature changes and has a large impact on regional precipitation by affecting the discrepancy in thermodynamic properties of both sea and land (IPCC 2013, Wang et al 2017a, Guo et al 2018, Lee et al 2018). Extreme precipitation is more sensitive to climate change than average precipitation (IPCC 2013). In the context of climate warming, extreme precipitation events have been increasing, which seriously damages regional ecological environments, affects industrial and agricultural production and human lives, and even results in great losses in social economy. Extreme precipitation has gradually become a hot issue in the field of climate change and its impact (Aguilar et al 2009, Agilan and Umamahesh 2018, Cammarano and Tian 2018, Dahal et al 2018).
As the extreme precipitation events continue to increase, an increasing number of researchers are conducting extensive studies on extreme precipitation from the climate change context. Alexander et al (2006) indicated that precipitation changes are widespread and show significant increases around the world and that extreme precipitation events also increased significantly. However, Alexander et al (2006) further pointed out that increasing trends in extreme precipitation are much less spatially coherent than temperature change, which indicates that there are some dissimilarities in extreme precipitation trends in different regions. In addition, research in the United States, Canada, Europe, Indo-Pacific region, Asia-Pacific network region, Japan, Caribbean, and southwestern Africa confirm that in the context of global warming, extreme precipitation shows an increasing trend in most areas (Bartholy and Pongracz 2007, Goubanova and Li 2007, Choi et al 2009, Chu et al 2010, Caesar et al 2011, Lovino et al 2014, Croitoru et al 2016a, Tan et al 2017, Forestieri et al 2018). However, study results from these different regions also show that extreme precipitation events do not have the same global consistency as extreme temperatures. You et al (2010) and Zhou et al (2016) also reached similar conclusions in their studies on changes in extreme precipitation at different time scales in China. Simultaneously, You et al (2010) also pointed out that although the trend in extreme precipitation in China is basically consistent with the global trend, due to the complex terrain in China, the regional atmospheric circulation background is quite different and shows obvious regional characteristics. The regional difference has its own unique distribution pattern and evolutionary trend. Extreme precipitation studies in the monsoon region of China, northwest arid zone, southwestern region, Yangtze River basin, Loess Plateau and Qinghai-Tibet Plateau (QTP) further clarified the new pattern and features of China’s extreme precipitation spatial and temporal distribution under climate change, and the understanding of extreme precipitation spatiotemporal characteristics at different regional scales in China has improved (You et al 2008b, Zhang et al 2012, Li et al 2012, Wang et al 2013b, Zhang et al 2014, 2015, 2017b, 2018, Gao et al 2017, Zhao et al 2017).

In past decades, extreme precipitation studies in China’s non-monsoon regions (NMRs) (including Xinjiang and most of the QTP, Gansu, and Inner Mongolia) have also received increasing focus from researchers. Zhang et al (2012) and Wang et al (2013a) pointed out that after 1980, the Xinjiang region exhibited a wetting tendency, and heavy precipitation extremes tended to be more severe and frequent. You et al (2008a) conducted research in the eastern and central QTP, which showed that most of the extreme precipitation indices in the region over the past 50 years had significant humidification trends, and the difference from Xinjiang was small. In addition, studies in northwest China also indicated that extreme precipitation has shown a significant increasing trend over the past half century (Deng et al 2014, Wang et al 2017b). These studies have shown that although the terrain and topography of NMRs are complex, these areas have similar temporal and spatial variation characteristics in extreme precipitation. Therefore, it is necessary to systematically analyze the climatic factors that affect extreme precipitation changes in the region.

It is well known that the factors affecting regional climate change mainly include natural and human activities (Ren and Zhou 2014, Angelil et al 2017, Mukherjee et al 2018). Although the area is large, the population is relatively small, the impact of human activities on the climate is limited, and regional climate change is increased due to changes within the climate system. Therefore, the previous discussion on the factors affecting climate change in the region were mainly focused on the background of atmospheric circulation patterns (Chen et al 2014, Tao et al 2017), while few researchers have focused on the influence of regional geographic factors such as longitude, latitude and altitude on extreme precipitation (Jiang et al 2012). Studying temporal and spatial variation characteristics of NMR extreme precipitation and its potential geographic and atmospheric factors at a larger regional scale is helpful for deeper understanding and prediction of future NMR extreme climate change trends. Additionally, prediction and early warning research on regional agricultural and livestock meteorological disasters are more easily conducted to mitigate the impact of extreme climate change on production, life and social activities.

In this study, we focus on the following: (1) analysis of the temporal trends and spatial distribution characteristics of extreme precipitation changes at annual and interannual scales under climate warming in the NMR during 1961–2017, (2) present the changes in regional precipitation in the past 57 years in terms of our various extreme precipitation indices, and (3) explore correlations between longitude, latitude, altitude, atmospheric circulation patterns and extreme precipitation using the Pearson analysis.

2. Data and methods

2.1. Overview of study area

In this study, the range of NMRs in China is mainly based on the summer monsoon boundary proposed in 1962 by Gao et al (1962), which has been accepted by many researchers and is widely used in the climate research field (Chen et al 2016, Gao et al 2017, Li et al 2017) (figure 1). The NMR in China is mainly located in the western and northern parts of the country, with a range of 73°–121° E, 35°–53° N and an area of approximately 3.9 × 108 km². The terrain of this area is complex, and the landscape is diverse; for example, the area includes the Taklimakan Desert, which is the
largest desert in China, and the QTP, known as ‘the roof of the world’. The regional altitudes various from −156 to 8058 m. Because the area includes most of the arid climate zone in China, the annual average precipitation is less than 250 mm (Yang et al. 2017). Over the past 57 years (during 1961–2017), the annual average precipitation of wet days was 216 mm, among them, the precipitation in summer is 127 mm, followed by autumn 43 mm and spring 39 mm, the winter precipitation is only 7 mm. The NMR also includes China’s major alpine mountain climate zone, which has a fragile and complex ecological environment and is extremely sensitive to climate change (Cui et al. 2017). Moreover, the NMR is China’s most important water resource, and most of the QTP (known as the ‘Chinese Water Tower’) and Tienshan Mountains are located in the NMR. Therefore, the climate change characteristics of NMRs are of great significance to China’s water resources and ecological environmental security.

2.2. Data source
226 meteorological stations were selected in the study area. To ensure the consistency and completeness of precipitation data as much as possible, stations with missing data of more than 30 d were removed, and stations with missing data of less than 30 d were interpolated with the most relevant adjacent stations. Using these guidelines, we selected 154 stations with complete daily precipitation data for 1961–2017. All meteorological station data were downloaded from the National Meteorological Administration of China (http://data.cma.cn/).

Considering the global climate change and regional atmospheric circulation background (Chen et al. 2014, Tao et al. 2017), ten atmospheric circulation indices, which have a month scale resolution, were selected in this paper to study the influence of atmospheric circulation on extreme precipitation indices in the NMR. The indices include six large-scale oceanic and atmospheric circulation patterns of Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) (including the multivariate ENSO index (MEI) and Nino3.4 sea surface temperature), which are obtained from the Earth System Research Laboratory of the Physical Sciences Division of the United States National Oceanic and Atmospheric Administration (https://esrl.noaa.gov/psd/data/climateindices/list/). In addition, there are four summer monsoon indices, including the East Asian Summer Monsoon Index (EASMI), South Asian summer monsoon index (SASMI), South China Sea summer monsoon index (SCSMI), and Indian Summer Monsoon Index (ISMNI) (Li and Zeng 2002, 2003, Wang et al. 2008a). The seasons of extreme precipitation indices and atmospheric circulation patterns are defined as winter from December to February of the following year, spring from March to May, summer from June to August, and autumn from September to November.

2.3. Definition of extreme indices
In this study, a total of nine extreme precipitation indices are employed to study the characteristics of extreme precipitation in the NMR (table 1), which are defined and recommended by the Expert Team on Climate Change Detection and Indices (Alexander et al. 2006, Stephenson et al. 2014, Ding et al. 2018, Xi et al. 2018). Detailed information about these indices can be found in table 1. All extreme precipitation indices are calculated using R language-based
RClimDex software after strict quality control (Zhang and Yang 2004).

2.4. Study methods

2.4.1. Line tendency test

Trends were computed using the ordinary least square (OLS) (Croitoru et al. 2016b) and Mann-Kendall non-parametric test (M-K test) (Mann 1945, Kendall 1975) methods to obtain significant trends. OLS uses a linear model to estimate the slope magnitude, which was calculated using SPSS 24.0 software, while the M-K trend significance test was represented by statistical parameter Z (Liu et al. 2016, Piticar et al. 2018). When the slope is less than 0, a decreasing trend is seen in the extreme indices, an increasing trend is seen when the slope is greater than 0, and the magnitude of its absolute value reflects the rate at which the extreme indices rise or fall. The statistical significance of the trends was assessed at the 95% confidence level \((P < 0.05)\) if \(|Z| > 1.96\) and at the 99% confidence level \((P < 0.01)\) if \(|Z| > 2.58\) (Sharma et al. 2016).

2.4.2. Principal component analysis (PCA)

PCA is a multivariate statistical analysis method that selects multiple variables (or factors) through linear transformation to obtain less important variables. This method solves the issue of excessive or too few variable selections, which affects the accuracy of the research process, the method reflects the original information as much as possible and maintains the variables as independent of each other (Li et al. 2012, Wang et al. 2013b). The calculation formula can be found in the Gao (2005).

2.4.3. Correlation analysis

The Pearson correlation analysis method describes the degree of compactness by analyzing the linear relationship magnitude between two variables (Sharma et al. 2016, Iqbal and Athar 2017, Ding et al. 2018). When the correlation coefficient value is greater than 0, the two variables are positively correlated and are negatively correlated when the coefficient is less than 0. An absolute value of the correlation coefficient that is nearer to 1 indicates a stronger correlation between the two variables, whereas a correlation coefficient value nearer to zero shows a weak correlation. A correlation coefficient equal to zero indicates that no linear relationship exists.

3. Results

3.1. Regional annual tendency and spatial patterns in extreme precipitation indices

The regional average of the annual series trends in selected extreme precipitation indices were analyzed using the linear regressive method, and the statistical significance of trends was evaluated using M-K tests. Figures 2(a)–(h) and table 2 presents the results of linear tendencies and statistical analyses at selected extreme precipitation for the period from 1961 to 2017 in the NMR.

Table 2 shows the linear tendencies of consecutive dry days (CDDs) in the NMR range from −12.0 to 10.98 days/decade, with a regional average of −3.23 days/decade \((P < 0.01)\) (figure 2(a)). The five-year moving average line in figure 2(a) indicates a slight oscillation and decrease before the mid-1980s, and thereafter, a significant decreasing trend with a greater fluctuation is seen. Decreasing trends are observed at 88.3% of stations, while the other 11.7% of stations exhibit increasing trends (table 2). Furthermore, MK significance testing for CDD trends show that 22.7% of stations have significant decreasing trends \((P < 0.05)\) and only 0.6% of stations show significant increasing trends \((P < 0.05)\). Because most of the stations show significant downward trends in the CDD, this means that drought is decreasing, and restraining desertification in the NMR may be beneficial.

Most stations in the northwest and northeast NMR are characterized by significant decreasing trends in the CDD (figure 3(a)), and the most substantial decreasing trend is observed at the Xin Barag Right Banner and Dabancheng stations. The greatest increasing trend occurred at the Qiiaojin station. Generally, the northwest and northeast NMR and
northeast QTP show higher decreasing rates of CDDs than other parts of the NMR (figure 3(a)).

Different from the CDD, the regional average of the CWD shows a slightly increasing trend at a rate of 0.03 days/decade ($P > 0.05$), and the linear tendencies range from $-0.33$ to 0.55 days/decade (table 2). The five-year moving average line in figure 2(b) shows a rapidly increasing trend and then a slight increase; after 1975, in addition to increasing trends, a greater fluctuation in the CWDs occurs. The results of the CWD linear tendencies show that 31.2% of stations have decreasing trends, and 68.8% of stations exhibit increasing trends (table 2). Meanwhile, 11.0% of stations exhibit significant increasing trends ($P < 0.05$), and only 1.3% of stations have significant decreasing trends ($P < 0.05$).

Based on the spatial pattern of linear tendencies in CWDs (figure 3(b)), most of the higher trend stations are mainly in the southeast NMR, and the linear tendencies in those regions show a greater variation than the other parts of the NMR. The highest decreasing and increasing trends both occur in this region at the Jiali and Zaduo stations, respectively. However, most of the stations showing significant increasing trends are

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**Figure 2.** Regional average of annual series for extreme precipitation over the period of 1961–2017.
located in Xinjiang, and only a few scattered stations are in the southeast NMR.

The results show that in the past 57 years, the linear tendencies of the PRCPTOT ranged from −10.46 to 48.17 mm/decade, with a regional average of 6.80 mm/decade (table 2 and figure 2(c)). Considering the five-year moving average line (figure 2(c)), there is a slight but persistent increasing trend in the PRCPTOT of the NMR from the early 1960s to the mid-1980s, and then, rapidly increasing trends with larger variations are shown. Increasing trends were observed at 87.7% of stations, while only 12.3% of stations exhibited downward trends (table 2). The MK significance tests showed 42.2% of stations had significant increasing trends ($P < 0.05$), but no stations with downward trends passed the MK significance tests at the 95% confidence interval.

As seen in figure 3(c), nearly all stations in the western and southeast NMR and northeast QTP were characterized by an increasing tendency, and most of the stations in these regions exhibit significant trends, while some stations in the northeast NMR show decreasing trends. Overall, most regions in Xinjiang (especially northern Xinjiang) and northeast QTP showed a larger increasing rate in the PRCPTOT, while east Inner Mongolia was dominated by lesser increases, which even exhibit decreasing trends. Those data indicated that there is no consistency in gradual increasing precipitation, and a regional difference in the NMR over the past 57 years is apparent.

The regional long-term trends of R5 mm and R10 mm show similar characteristics, which present as a persistent increasing trend during 1961–2017, and among the trends, upward trends after 2005 are more obvious (figures 2(d)–(e)). These two indices have a regional average range of −1.07–3.37 days/decade (at an average of 0.45 days/decade) and −0.35–2.23 days/decade (at an average of 0.22 days/decade), respectively. The results of the linear tendencies and MK significance testing show (table 2) that a total of 16.9% of stations show negative trends in R5 mm, while the other 83.1% indicate a positive trend, with 35.1% of stations being significant. For R10 mm, approximately 20.1% of stations show decreasing trends with no significant stations, 78.6% showed increasing trends with 26.6% being significant, and another 1.3% indicated no trend.

In the spatial distribution patterns of the linear trend aspect (figures 3(d)–(e)), R5 mm and R10 mm are similar, showing that most of the stations in Xinjiang and northeastern QTP showed an upward trend. Meanwhile, the spatial distribution patterns of significantly increasing trend stations for these two indices are consistent with PRCPTOT (both in western Xinjiang and northeastern QTP). In addition, the stations with unmarked upward trends are mainly in south and southeast Xinjiang, the Hexi Corridor and most regions of Inner Mongolia and southeastern QTP. However, the declining trends of R5 and R10 mm showed some discrepancies. Stations with declining trends in R5 mm were mainly distributed in the eastern Xinjiang and Inner Mongolia areas, while R10 mm showed a large declining trend in the southeast QTP and Inner Mongolia areas. There were no trends in R10 mm at Shanshan and Guoluo stations.

Different from R5 mm and R10 mm, the R20 mm showed fluctuating characteristics (figure 2(f)), with a downward trend from the 1960s to the mid-1980s and a significantly upward trend with a large fluctuation after 1985. In the past 57 years, the regional annual mean R20 mm increased significantly at a rate of 0.05 mm/decade, with a range from −0.24 to 0.59 mm/decade. As seen in table 2, 61.7% of stations exhibited increasing trends, and among them, significant trends were found in 11.7% of stations for R20 mm ($P < 0.05$). Notably, 31.8% of stations showed decreasing trends in all NMR regions, and no stations passed the significance test at the 95% level.

In regards to the spatial distributions (figure 3(f)), the annual mean values of R20 mm were obviously larger in northern Xinjiang than it in southern Xinjiang, and most of the stations that showed a significantly increasing trend were distributed in the former. Furthermore, most stations in the northeast

| Indices | Unit | Range of regional trends (mean) (decade$^{-1}$) | Decreasing trend (SS) | Increasing trend (SS) | No trend |
|---------|------|-----------------------------------------------|-----------------------|----------------------|----------|
| CDD     | d    | −12.0 ± 10.98 (−3.23)                         | 88.3 (22.7)           | 11.7 (0.6)           | 0        |
| CWD     | d    | −0.33 ± 0.53 (0.03)                           | 31.2 (1.3)            | 68.8 (11.0)          | 0        |
| RX1day  | mm   | −2.24 ± 3.43 (0.45)                           | 30.5 (0)              | 69.5 (15.6)          | 0        |
| RX5day  | mm   | −3.47 ± 4.57 (0.73)                           | 29.9 (0)              | 70.1 (17.5)          | 0        |
| R5      | d    | −1.07 ± 3.37 (0.45)                           | 16.9 (0)              | 83.1 (35.1)          | 0        |
| R10     | d    | −0.35 ± 2.23 (0.22)                           | 20.1 (0)              | 78.6 (26.6)          | 1.3      |
| R20     | d    | −0.24 ± 0.59 (0.05)                           | 31.0 (0)              | 61.7 (11.7)          | 6.5      |
| SDII    | mm d$^{-1}$ | −0.36 ± 0.46 (0.06)                        | 24.7 (0.6)           | 75.3 (19.5)          | 0        |
| PRCPTOT | mm   | −10.46 ± 48.17 (6.80)                         | 12.3 (0)              | 87.7 (44.2)          | 0        |

No trend: indicates that the station does not have these extreme indices.

Table 2. Regional decadal changes in extreme precipitation and the numbers of stations with statistically significant (SS) (significant at the 0.05 level) extreme precipitation trends.
QTP and Hexi Corridor showed upward trends, and some show a significantly increasing trend. However, most stations in the southern QTP and Inner Mongolia showed decreasing trends. Rikaze and Dingqing had the largest declining trends in the southern QTP and showed decreasing trends of $-0.24$ mm/decade.

Although no stations have passed the significance test at the 95% confidence interval, a larger decreasing trend is exhibited, especially in eastern Inner Mongolia.

The linear tendencies of RX1day and RX5day varied between $-2.24$ to $3.43$ mm/decade and $-3.47$ to $4.57$ mm/decade, respectively. Although the changes in different regions are relatively large, they still show a significant ($P < 0.01$) upward trend, and with regional averages of $0.45$ mm/decade for RX1day and $0.73$ mm/decade for RX5day during 1961–2017 (table 2). From the perspective of regional average annual change trend, the changes in the two indices are similar (figures 2(g)–(h)). The five-year moving average line in figures 2(g)–(h) indicates a slightly long-term variation from the 1960s to the mid-1980s.

A large, fluctuating increasing trend in these two indices in the NMR began between the mid-1980s and

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**Figure 3.** Spatial patterns of trends in extreme precipitation over the period of 1961–2017.
later-1990s and showed a persistent upward trend. Then, the index trend rapidly declined, and finally, it showed a persistent upward trend after the early-2000s. Statistically significant increasing (positive) and decreasing (negative) trends as well as no trends are also represented in Table 2. For RX1day, a total of 30.5% of all stations showed negative trends and no stations were significant, while another 69.5% indicated positive trends and 15.6% of all stations were significant (P < 0.05) (Table 2). Similar to RX1day, 29.9% of RX5day stations showed negative trends, while another 70.1% exhibited positive trends and 17.5% of all stations were significant (P < 0.05) (Table 2).

The spatial distribution of linear tendencies of the RX1day and RX5day series is illustrated in Figures 3(g)–(h). Generally, northern Xinjiang, the piedmont of Tienshan Mountains and the northeastern parts of the QTP experienced a larger increasing rate of RX1day and RX5day than other parts of the NMR, and most of the stations with significant upward trends are located in these areas. Meanwhile, the stations showing the largest upward trends for the RX1day and RX5day were Yinchuan and Delingha, respectively. Considering the spatial distribution of the stations with downward trends, RX1day and RX5day also have similar spatial distribution characteristics. Except for a few stations with downward trends scattered in the Tianshan area, most of the stations with decreasing trends are located in the southern QTP, Helan Mountains area and Inner Mongolia region. Although there were no stations that exhibited significant declining trends in the two indices, there are still many stations showing an obviously downward trend in these regions, and the largest downward rates of RX1day and RX5day were sited in Zhongning and Xin Barag Right Banner, respectively.

Similar to most other precipitation intensity and persistence indices, the long-term variations in the SDII for the NMR also showed a significant increasing trend at the 99.9% confidence interval for the past 57 years (Figure 2(i)), which has a regional range from −0.36 to 0.46 mm/day/decade (average of 0.06 mm/day/decade). In terms of the five-year moving average, the regional trend is similar to RX1day and RX5day, but the fluctuation of SDII is larger, and since the 2000s, the SDII exhibited a significant increasing trend at a rate of 0.25 mm/day/decade. In terms of individual stations trends (Table 2), upward trends are detected at 75.3% of stations, while 19.5% of stations passed the significance test at the 0.05 level. The other 24.7% of stations exhibited downward trends, with statistically significant decreases observed at only 1 station.

The spatial distributions of the change trends of SDII and RX1day are very similar (Figure 3(i)). Stations characterized by increasing trends are mostly located in northern Xinjiang, the Hexi Corridor and Helan Mountains area, while stations with lower negative tendencies are observed in southern Xinjiang and southern QTP. Meanwhile, stations with significant upward trends are mainly located in the northern piedmont of the Tienshan Mountains, Altai Mountains and northeast QTP, and the station with the largest upward trend is Bayan Mod. However, only one station showed a significant downward trend in the NMR, which was Xin Barag Right Banner station, located in eastern Inner Mongolia.

3.2. Seasonal variations in RX1day and RX5day
We analyzed the spatial and temporal variations of extreme precipitation indices at an interannual scale in preceding parts of the manuscript, and the extreme precipitation presents different spatiotemporal change patterns. Thus, the trend differences within the annual changes need to be explored. To detect the potential trend change in seasonal extreme precipitation, we analyzed the regional average trends of spring, summer, autumn and winter for RX1day and RX5day during 1961–2017 (since the RClimDex1.0 software provides only monthly data for RX1day and RX5day in the calculation of extreme precipitation indices, we analyze only the seasonal changes in these two indices in this paper). The results indicate that (Figure 4) these two extreme precipitation indices showed significantly upward trends during all seasons (P < 0.05, but the
variation trends of different seasons were obviously different. Among the seasonal trends, RX1day showed the largest increase during summer with a rate of 0.27 mm/decade, which was followed by spring, with an increasing trend of 0.24 mm/decade. The winter showed the lowest upward tendency at rate of 0.17 mm/decade. The increasing trend of RX5day during each season was similar to that of RX1day, but the increased rate is obviously higher than that of RX1day. In the past 57 years, the summer showed the highest increasing trend at a rate of 0.49 mm/decade, followed by autumn at a rate of 0.39 mm/decade, and the increasing trend for spring and winter were both 0.26 mm/decade. Furthermore, a statistical significance test showed that except for autumn of RX5day not passing the significance test at 0.05, all other seasons in these two extreme precipitation indices exhibited significantly increased trends at confidence intervals of 99.9%.

3.3. Principal component analysis

To further explore the intrinsic meaning of the spatial and temporal variations in extreme precipitation indices in the NMR region for the last 57 years, we used the principal component analysis (PCA) method to analyze the characteristics of extreme precipitation indices. The PCA identified four factors with eigenvalues greater than 1, which explained the 95.9% variances. The results generally reflected the characteristics of precipitation intensity, frequency and its duration in the NMR regions during 1961–2017 (table 3). Factor 1 (F1) accounted for 72.5% of the total variance in the extreme precipitation and included almost all precipitation indices except for CDD and CWD, indicating a common increasing trend of extreme precipitation in the NMR during 1961–2017. Notably, RX1day, RX5day, R20 mm and SDII have higher factors scored in F1, which are all higher than 0.70 and possibly reflects the increase in precipitation strength. However, the score of PRCPTOT in F1 is only 0.46, while it was 0.81 in F2, and the scores of R5 mm and R10 mm in F2 are also above 0.80 (scores are 0.86 and 0.81, respectively). F2 accounted for 9.6% of the total variance, and these indices may have reflected the increase in effective precipitation days and precipitation frequency. CWD dominated F3 (score of 0.95), which accounted for 7.9% of the total variance. As seen by its spatial distribution, the areas with significant increasing trends in CWD are mainly located in the western and northern regions of Xinjiang, especially in the Altai Mountains region. The increase in CWD mainly reflected the extent of the precipitation duration in the NMR area in the last 57 years. The CDD is the only index that exhibited a decreasing trend and was the principal constituent of F4, which accounted for 5.5% of the total variance.

In general, the significant increase in total precipitation over the past 57 years in the NMR area was the result of the combined effects of intensity, frequency and duration of precipitation. However, further analysis of the extreme precipitation index scores in all 4 factors showed that the contribution of the indices to the total precipitation differs. Combining the Pearson correlation analysis results, we found (table 4) the correlation between PRCPTOT, R5 mm and R10 mm to be the highest, with correlation coefficients of 0.98 and 0.97, respectively (\(P < 0.01\)), which is obviously higher than other indices and indicates that the increase in total precipitation in the NMR region from 1961 to 2017 is closely related to the increasing trend seen in these two indices.

### 3.4. The effects of latitude, longitude and altitude on extreme precipitation indices

From the previous statement, we found that many stations with significant trends were distributed in the piedmont of the Tienshan Mountains, Qilian Mountains, northeast QTP and its surrounding areas, whereas many stations in the plains showed relatively smaller changes (figure 3). To further analyze the possible influence of other geographic factors (such as geographic location, topographic environment, etc) on the variation trend in extreme precipitation indices, the Pearson correlation analysis method was applied to analyze the correlation between latitude, longitude and altitude and the extreme precipitation indices (table 5).

Altitude affects the thickness of clouds and water vapor contents and then affects the amount of precipitation. Using the Pearson correlation analysis method, the correlation between the variation trends in extreme precipitation indices and elevation of different stations in the NMR over the last 57 years was analyzed. The results showed that all correlation coefficients between extreme precipitation indices and altitude did not pass the significance test at the 0.05 level, and the correlation coefficients are all less than 0.25, indicating that the regional average change trend in extreme precipitation in the NMR area showed no obvious correlation with altitude. Previous research (Wotling et al. 2000, Sokol and Blizňák 2009) indicated

| Indices  | Factors | 1   | 2   | 3   | 4   |
|----------|---------|-----|-----|-----|-----|
| CDD      | -0.28   | -0.31 | -0.06 | 0.90 |
| CWD      | 0.18    | 0.25 | 0.95 | 0.06 |
| RX1day   | 0.88    | 0.29 | 0.16 | 0.23 |
| RX5day   | 0.85    | 0.28 | 0.29 | 0.26 |
| R5 mm    | 0.34    | 0.86 | 0.28 | 0.22 |
| R10 mm   | 0.47    | 0.81 | 0.16 | 0.26 |
| R20 mm   | 0.79    | 0.49 | 0.07 | 0.14 |
| SDII     | 0.86    | 0.39 | 0.10 | 0.15 |
| PRCPTOT  | 0.46    | 0.81 | 0.24 | 0.26 |
| Variance (%) | 72.5 | 9.6 | 7.9 | 5.5 |
that due to the complexity of topography and geomorphology in mountainous areas, gradients of extreme precipitation trends were possibly not be strongly correlated to altitude. To further analyze the possible influence of altitude on extreme precipitation trends, based on the experience of previous research (You et al. 2008b), we conducted a correlation analysis between the extreme precipitation change trend of different altitude gradient stations and altitude (table 5). Only RX1day had a significant positive correlation with altitude at stations located at less than 500 m ($P < 0.05$), while none of the correlations between index change trends and altitude passed the 95% significance test from 500 to 3500 m, which indicated that the variation trend in the extreme indices in the NMR regions were weakly affected by the altitude at this range. However, the variation trends of RX1day, RX5day, R5 mm and PRCPPTOT at stations over 3500 m were significantly positively correlated with altitude ($P < 0.05$), and the correlation coefficients were 0.45, 0.49, 0.53, 0.57, respectively. This change feature indicates that from 1961 to 2017, the trend in extreme precipitation indices in high mountain areas of the NMR were more obvious than that in other areas. Meanwhile, Wotling et al. (2000) also indicated that extreme precipitation change trends at observation stations on high mountains has a strong correlation with altitude, while the observation stations in plain areas have a weak correlation.

In China, longitude influences water vapor contents and energy transport from the ocean to inland areas, thus affecting regional climate systems (O’Gorman and Schneider 2009). As shown in table 5, we found that except for the variation trend in SDII showing a non-significant correlation with longitude, all other indices showed significantly negative correlations with longitude ($P < 0.05$), and the correlation coefficient of most index change trends (other than CDD and SDII) reached the 99% confidence level. This result indicates that the longitude is closely related to the change trend in most extreme precipitation indices in the NMR area, and the farther east the longitude, the smaller the change trends in the indices. Generally, the higher the latitude, the lower the solar altitude, and the lower the solar radiation energy received on the surface of the Earth. In the NMR (table 5), except for the CDD showing a significant negative correlation with latitude ($P < 0.05$), the correlation with all other indices did not pass the significance test at the 0.05 level. Moreover, the correlation coefficient for all indices and latitude is less than 0.1, indicating that latitude has little effect on the trends of most extreme precipitation indices. The Qinghai-Tibetan Plateau has long been known as the ‘roof of the world’ and ‘the third pole’, due to its average altitude of over 4000 m, which greatly impacts the climate system in Asia. On the one hand, the QTP blocks the northward movement of the Indian monsoon. As a result, the warm and wet air flow in the Indian Ocean cannot penetrate Xinjiang, the Hexi Corridor and other areas of China. On the other hand, the westerly is forced to branch west of the Tienshan Mountains, leading to a decreased intensity and water vapor content. Since most of the stations are located in the QTP and its northern regions, determining whether the lower correlation between the extreme precipitation trend and latitude is caused by the QTP requires further analysis in combination with the main atmospheric circulation system of the NMR regions.

### Table 4. Correlations among extreme precipitation indices.

| Indices | CDD | CWD | RX1day | RX5day | R5 mm | R10 mm | R20 mm | SDII | PRCPPTOT |
|---------|-----|-----|--------|--------|-------|--------|--------|------|----------|
| CDD     | 1   |     |        |        |       |        |        |      |          |
| CWD     | −0.24 | 1  |        |        |       |        |        |      |          |
| RX1day  | −0.54$^b$ | 0.38$^b$ | 1     |        |       |        |        |      |          |
| RX5day  | −0.57$^b$ | 0.50$^b$ | 0.93$^b$ | 1     |       |        |        |      |          |
| R5 mm   | −0.58$^b$ | 0.54$^b$ | 0.66$^b$ | 0.68$^b$ | 1     |        |        |      |          |
| R10 mm  | −0.63$^b$ | 0.45$^b$ | 0.72$^b$ | 0.75$^b$ | 0.94$^b$ | 1     |        |      |          |
| R20 mm  | −0.52$^b$ | 0.36$^b$ | 0.84$^b$ | 0.82$^b$ | 0.70$^b$ | 0.80$^b$ | 1     |      |          |
| SDII    | −0.51$^b$ | 0.36$^b$ | 0.87$^b$ | 0.89$^b$ | 0.69$^b$ | 0.77$^b$ | 0.87$^b$ | 1   |          |
| PRCPPTOT| −0.63$^b$ | 0.52$^b$ | 0.75$^b$ | 0.76$^b$ | 0.98$^b$ | 0.97$^b$ | 0.80$^b$ | 0.76$^b$ | 1   |

*Note. a is the 0.05 confidence level, and b is the 0.01 confidence level.*

3.5. Association between atmospheric circulations and extreme precipitation

The variation in extreme precipitation reflects the overall situation of the regional precipitation change rate, as well as the background of the regional atmospheric circulation patterns and general characteristics of the climate system. To explore the relationships among the extreme precipitation indices and large-scale internal variability in the climate system, we calculated correlations between extreme precipitation index regional average annual change trends and AMO, AO, NAO, PDO, ENSO (MEI and Nino3.4) and four summer monsoon indices (including EASMI, SASMI, SCSMI, and ISMI) (figure 5).

Figure 5 shows significant positive correlations among most of the extreme precipitation indices (except CWD and CDD) and AMO ($P < 0.01$),
Table 5. Correlations between latitude, longitude, altitude and extreme precipitation.

| Indices | <500 (N = 10) | 500–1000 (N = 29) | 1000–1500 (N = 50) | 1500–2000 (N = 17) | 2000–2500 (N = 4) | 2500–3000 (N = 10) | 3000–3500 (N = 10) | >3500 (N = 24) | Longitude | Latitude |
|---------|---------------|------------------|------------------|------------------|------------------|------------------|------------------|-------------|-----------|----------|
| CDD     | 0.58          | 0.16             | –0.15            | –0.13            | –0.61            | –0.33            | 0.07             | 0.35        | 0.19 a    | –0.19 a  |
| CWD     | 0.60          | 0.01             | –0.13            | 0.20             | 0.39             | 0.09             | –0.52            | 0.39        | –0.37 b   | 0.08     |
| RX1day  | 0.69 a        | 0.09             | –0.02            | –0.14            | 0.68             | 0.29             | 0.06             | 0.45 a      | –0.25 b   | 0.06     |
| RX5day  | 0.42          | 0.08             | –0.07            | –0.07            | –0.46            | 0.15             | 0.17             | 0.49 a      | –0.27 b   | 0.07     |
| R5 mm   | 0.57          | –0.18            | 0.19             | 0.06             | –0.54            | –0.13            | –0.29            | 0.53 b      | –0.40 b   | –0.07    |
| R10 mm  | 0.47          | –0.03            | 0.06             | 0.34             | –0.44            | –0.19            | –0.16            | 0.33        | –0.26 b   | –0.09    |
| R20 mm  | –0.19         | 0.14             | –0.14            | 0.36             | 0.61             | –0.16            | 0.50             | –0.38       | –0.22 b   | –0.01    |
| SDII    | 0.42          | 0.19             | –0.18            | –0.05            | –0.74            | 0.05             | 0.05             | 0.32        | –0.15     | 0.01     |
| PRCPTOT | 0.55          | –0.14            | 0.11             | 0.47             | –0.24            | –0.14            | –0.17            | 0.57 b      | –0.42 b   | –0.06    |

Note: a is the 0.05 confidence level, and b is the 0.01 confidence level.
significant negative correlations between CDD and AMO ($P < 0.01$), and insignificant positive correlations between CWD and AMO in NMR These results indicate that the CDD would decrease with increasing AMO, while a reverse trend was observed for other indices. However, the AO, NAO, PDO and ENSO have weak significant correlations with all extreme indices, and all correlation coefficients are very low, indicating that these atmospheric circulation indices have a weak influence on the extreme precipitation indices in the NMR area on the annual change scale. Considering the relevance of the monsoon index and extreme precipitation indices (figure 5), three monsoon indices showed positive correlations with the CDD, and negative correlations with other extreme indices. Among them, the correlation between the SCSMI and extreme indices was the most significant, which shows significant positive correlations with CDD ($P < 0.05$), and significant negative correlations with other indices ($P < 0.01$). The EASMI has a significant negative correlation with other extreme precipitation indices ($P < 0.05$) except for CDD, and the correlation with most extreme indices reaches a confidence interval of 99%. Meanwhile, ISMI was significantly negatively correlated with only CWD ($P < 0.05$) and less correlated with other indices. Generally, although the NMR is located in northwest China, the range includes the first and second grades of 'China’s Three Terrain Grade', which has a complex terrain and is located far away from the sea, but the interannual variation of the extreme precipitation indices is still greatly influenced by the summer monsoon index (SMI).

According to the correlation analysis in table 4, the correlation coefficients of RX1day and RX5day and other extreme indices were all above 0.5 and passed the significance test at 0.01, indicating that the changes in these two indices basically reflects the overall extreme precipitation change characteristics in the NMR. To further explore the possible influencing mechanism of the atmospheric circulation index on the extreme precipitation indices, we also used the Pearson analysis method to analyze the correlation between the atmospheric circulation index and changes in seasons for RX1day and RX5day (table 6). The results showed that there was a significant positive correlation between the changes in AMO and the seasonal RX1day and RX5day values ($P < 0.05$), especially during spring, with correlation coefficients of 0.47 and 0.45, respectively. The correlation between AO, NAO and seasonal RX1day and RX5day values remained small, and none of them reached the significance level of 0.05, while the PDO showed a significant positive correlation with the winter RX1day ($P < 0.05$). These findings indicate that AO and NAO have a weak influence on the extreme precipitation indices in the NMR at annual and interannual scale, and the PDO has a slight influence on winter precipitation. Analogously, the ENSO and ISMI also have slight effects on winter precipitation (table 6). However, the relationship between the SMI and seasonal extreme precipitation is complex and presents strong seasonal characteristics. EASMI and SCSMI have less influence on the winter extreme precipitation, while SASMI is closely related to autumn and winter.

4. Discussion

In general, an appropriate increase in precipitation is conducive to alleviating regional drought and plays a
vital role in the restoration of ecological systems, industrial and agricultural production and the lives of residents. Especially in the NMR, for a typical arid and semi-arid area, grassland resources play an important role in the regional ecosystem balance, increased rainfall affecting the expansion of grass and oases in arid areas, and the maintenance of rivers and lakes has a pivotal position. However, the increase in extreme arid areas, and the maintenance of rivers and lakes has rainfall affecting the expansion of grass and oases in semi-arid area, grassland resources play an important role in the restoration of ecological systems, residents. Especially in the NMR, for a typical arid and industrial and agricultural production and the lives of residents. Meanwhile, for a typical arid area, the increasing trend of the world average precipitation intensity may have a significant positive correlation with the NDVI (Alexander et al. 2006, O’Gorman and Schneider 2009, IPCC 2013). Simultaneously, with the increase in total precipitation, the increasing trend of extreme precipitation in various regions is also obvious (Bartholy and Pongracz 2007, Aguilar et al. 2009, Faulk et al. 2017). The aforementioned analysis indicates that in addition to the significant decrease in CDD, the other indices in the NMR show an increasing trend of different degrees, although the PRCPOT was significantly smaller than the increasing trend of the world average, which was significantly higher than the increasing trend in China’s extreme indices over the same period (You et al. 2010). Furthermore, the increasing trends of the SDII and RX5day in the NMR are obviously higher than the world average (Alexander et al. 2006), while the decreasing trend of the CDD is higher than in China (You et al. 2010). The variation characteristics in these extreme precipitation indices indicate that in the context of global warming, the NMR has gradually become wetter. In addition, the change in extreme indices in this region has significant regional characteristics and is very sensitive to the response of global climate change.

Simultaneously, both RX1day and RX5day showed the largest increasing trends during summer in terms of annual scale changes (figure 4), and these two indices are important representations of precipitation intensity change, indicating that the summer precipitation intensity in the study area increased most significantly over the last 57 years. Accordingly, PCA analysis and correlation analysis showed that these two indices and PRCPOT have a significant positive correlation ($P < 0.01$), which illustrates that the increase in precipitation intensity has an important contribution to the change in extreme precipitation indices in the NMR. However, both the PCA analysis and Pearson correlation analysis also showed that the PRCPOT was more closely related to R5 mm and R10 mm, indicating that the increase in total precipitation in the NMR over the past 57 years mainly comes from the significant increases in R5 mm and R10 mm. In contrast, previous research (Li et al. 2012) in southwestern China showed that R10 mm and others contribute less to the increase in regional rainfall than RX1day, RX5day, and R20 mm. Our results show that extreme precipitation indices in the NMR have different responses to other areas of China.

The spatial distribution of extreme precipitation indices indicated that the regions with significant increasing trends are mainly distributed in the piedmont areas of the Tienshan Mountains, northeast QTP and its surrounding areas, especially in the northern piedmont of the Tienshan Mountains (figure 3). Coincidentally, in recent decades, the NDVI index in northwest China has also increased most significantly in the piedmont areas of Tienshan Mountains and Qilian Mountains and its surrounding areas (Li et al. 2003, Piao et al. 2005). This increase in precipitation has a significant positive correlation with the NDVI index change, and we believe that the increase in extreme precipitation in the study area is of some meaning to regional vegetation restoration and ecological environment improvement in recent decades. However, the specific effects of extreme precipitation indices on the NDVI needs further study in the future.

Due to the heterogeneity of the geographic location and topography and the different backgrounds of atmospheric circulations in different regions, the change trend in extreme precipitation may have

| Atmospheric circulations | RX1day | RX5day |
|--------------------------|--------|--------|
| AMO                      | 0.47$^b$ | 0.30$^a$ | 0.42$^b$ | 0.36$^b$ |
| AO                       | 0.06    | 0.07   | −0.04  | 0.09   |
| NAO                      | −0.05   | 0.11   | −0.22  | 0.08   |
| PDO                      | 0.21    | 0.21   | 0.03   | 0.31$^a$ |
| MEI                      | 0.22    | 0.08   | −0.03  | 0.37$^b$ |
| Nino3.4                  | 0.19    | −0.03  | −0.04  | 0.41$^b$ |
| EASMII                   | −0.25   | −0.19  | −0.37$^b$ | −0.16  |
| SASMII                   | −0.16   | −0.15  | −0.37$^b$ | −0.44$^b$ |
| SCSMII                   | −0.33$^a$ | −0.29$^a$ | −0.49$^b$ | −0.24  |
| ISMI                     | −0.09   | −0.01  | −0.14  | −0.29$^a$ |

Note: $a$ is the 0.05 confidence level, and $b$ is the 0.01 confidence level.
regional heterogeneity (Dai and Wigley 2000, Pepin and Seidel 2005, You et al 2008b, Ding et al 2018). Our study shows that the variation trend in extreme precipitation indices in the NMR are obviously influenced by longitude, and this may be due to climate warming, enhancing the discrepancy in the thermal properties of land and sea, enhancing the unstable regional climate system and increasing extreme precipitation events (IPCC 2013). We also found that the correlation between extreme precipitation indices and altitude are not obvious in the NMR. However, the correlation analysis of indices and altitude at different altitude ranges shows that stations with an altitude higher than 3500 m have a significant positive correlation with most indices. Moreover, stations at altitudes higher than 3500 m are mainly located in the QTP and its surrounding areas. Considering precipitation at this altitude is mainly in the form of snowfall, we conclude that extreme precipitation events in high mountain areas are more sensitive to climate change. Deng et al (2017) suggested that the average annual snowfall in the QTP increased at a rate of 0.7 mm/decade, while the greatest increasing trend was observed during winter (December to March) at a rate of 0.8 mm/decade (P < 0.01), and some stations reached a rate of 0.9 mm/decade. Similarly, RX1day showed a significant positive correlation with stations at altitudes of less than 500 m, indicating that the increasing trend of extreme precipitation in the plains should not be ignored.

Previous research has indicated that the ENSO is one of the strongest signals yet observed for the air-sea interaction on an interannual timescale, its occurrence results in large-scale atmospheric circulation anomalies and leads to a significant impact on the climate of many places around the world (Dai and Wigley 2000, Larkin 2005, Jia and Ge 2017, Agilan and Umamahesh 2018). Especially in China, many studies have pointed out that extreme precipitation events in most areas of China are significantly affected by ENSO (Gao et al 2006, Wang et al 2008b, Ma et al 2018a). In the warm phase years (El Niño years), there was less precipitation in southeast China, while the opposite occurred during the cold phase years (La Niña) (Jin et al 2016). However, this study shows that there is no significant correlation between the ENSO index (MEI, Nino3.4) and extreme precipitation indices in the NMR on an annual scale (figure 5), while a significant positive correlation was observed during winter and a non-significant correlation was apparent during summer on an interannual scale. Gao et al (2006) also suggested that the relationship between ENSO and summer precipitation in China has weakened since the 1980s. These analyses indicate that the ENSO has a more obvious influence on the winter extreme precipitation than other seasons in the NMR.

The strong influence of the SMI (including EASMI, SASMI, SCSMI, and ISMI) on extreme precipitation in China has been confirmed by many researchers (Gu et al 2017, Agilan and Umamahesh 2018), and the most significant regions were observed in the summer in the south Yangtze River area. However, in this study, correlations between these SMIs and the autumn extreme precipitation in the NMR was more obvious, but only the SCSMI showed significantly negative correlations with the summer RX1day and RX5day. We conclude that the reason for this may be that most regions of the NMR are located in northwest China and are far away from the ocean, and thus, there may exist a lag in the response to these SMIs.

The AMO is a quasi-periodic warm and cold anomaly occurring in the sea surface temperature of the North Atlantic region, at the sea basin scale in space and multidecade scale in time (Enfield et al 2001, Teegavarapu et al 2013, Veres and Hu 2013). Numerous studies have shown that AMO plays an important role in climate change in Europe, North America and other regions of the world (Veres and Hu 2013, Goly and Teegavarapu 2014). As seen in figure 5 and table 6, the AMO has a significantly higher influence than ENSO (MEI, Nino3.4) and the Asian Summer Monsoon Index (including EASMI, SASMI, SCSMI and ISMI) on the NMR extreme precipitation, and this conclusion has been confirmed by other studies (Qian et al 2014). Furthermore, it is well known that the AMO entered a warm phase in approximately 1995 (figure 6), and Gao et al (2017) suggested that the AMO shift in the warm and cold phases in the 1990s possibly had a significant impact on the changes in extreme precipitation in China’s monsoon regions. As seen from table 7, the increasing trend in extreme precipitation in the NMR in the past two decades is remarkable, and the change trend of all extreme precipitation indices are significantly greater than those during 1961–1995 and 1961–2017. Therefore, we believe that the AMO not only affects extreme precipitation changes around the Atlantic Ocean but also has a profound impact on China, especially in the NMR. At the same time, we have further confirmed that the extreme precipitation indices in China’s NMR have increased significantly since the 1990s when the AMO shifted to a warm phase. These results will be more helpful for us to accurately predict the future trend of extreme precipitation in this region.

Generally speaking, there are numerous factors affecting regional precipitation variability, including the climate system variability characteristics (the periodic fluctuation of climate), the global atmospheric circulation patterns (AMO, PDO, etc), the natural geographical environment characteristics (longitude, latitude and altitude), human activities (anthropogenic aerosol) and solar radiation changes, etc (Qian et al 2009, Lu et al 2014, Ma et al 2018b). Therefore, the driving mechanism of extreme precipitation change is also very complicated, and the related researches are also controversial. The researches on the physical mechanism of regional atmospheric precipitation
mainly focuses on the changes of solar radiation intensity caused by atmospheric aerosol changes, and the controversy between the different atmospheric circulation patterns which bring water vapor to the study region. For example, previous studies have suggested that anthropogenic aerosols tend to increase the occurrence of extreme precipitation, especially in heavy precipitation events (Qian et al 2009) and extremes drought events (Zhang et al 2017a), while the recent study showing a strong suppression effects for extremes precipitation events (Lin et al 2016, Lin et al 2018a, 2018b). Furthermore, because NMR is located in the central region of Eurasia, there has been considerable controversy over the dominant atmospheric circulation pattern in this region. For example, some scholars believe that the change of precipitation in Northwest China is significantly affected by ENSO (Wen et al 2017), while others believe that the region is mainly affected by the circulation modes such as NAO, AMO, etc (Wang et al 2009), and the influence of ENSO varies greatly in different time scales (Gao et al 2006, Li et al 2011, Yang et al 2017), which is similar to our conclusion. Numerous studies have shown that the stability of the atmosphere will weaken as the global warming intensifies, and brings more extreme precipitation events (IPCC 2013, Sillmann et al 2013, Donat et al 2016). Our study also suggests that extreme precipitation in our study area (possibly even in a larger spatial scale) is affected by a combination of multiple factors, especially the atmospheric circulation patterns that provide water vapor source for regional precipitation. Therefore, in future study, a comprehensive synoptic analysis over a larger-spatial scale dominant mode and its physical mechanisms have great significance to better understand and predict the future extreme precipitation in NMR region.

5. Conclusions

Based on the daily precipitation data of 154 meteorological stations during 1961–2017, we analyzed the spatial and temporal distribution characteristics of the extreme precipitation indices and their potential controlling factors of change in detail. We have verified that most regions in the NMR showed a relatively consistent trend of wetting; however, the extreme precipitation indices still show large spatial variations, especially in the CDD, which has approximately 88.3% of stations showing a decrease and
11.7% of stations showing an increase. Among the stations, most (22.7%) with a significant decrease ($P < 0.05$) are located in the northwest and northeast NMR and northeast QTP. In addition, other stations with significant increasing trends are also located in the mountain regions, such as the northwest and north-east NMR and northeast QTP. Both RX1day and RX5day have the most significant increasing trends in summer and the smallest in winter. Although most extreme precipitation indices show a significant increasing trend, R5 mm and R10 mm possibly contribute more to the increase in total precipitation in the NMR Compared with latitude, the effects of longitude on the extreme precipitation trends may be more significant. Moreover, at altitudes above 3500 m, most extreme indices increase more as the altitude rise. The AMO has a strong influence on the NMR extreme precipitation indices at both interannual and annual scales, and the significant increase in most extreme indices in the NMR region is likely to be related to the AMO entering the warm phase in 1995. The influence of the SMI on the extreme precipitation in the NMR region is mainly reflected in the autumn, while the ENSO has a slight effect on the winter extreme indices.

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