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RESEARCH ARTICLE

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Variability of the precipitation over the Tianshan Mountains, Central Asia. Part I: Linear and nonlinear trends of the annual and seasonal precipitation

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Abstract

The Tianshan Mountains, with their status as 'water tower', receive quantities of precipitation that are among the highest in Central Asia. There are considerable knowledge gaps regarding the understanding of spatial and temporal patterns of precipitation over this water-scarce region. Based on the Global Precipitation Climatology Centre (GPCC) data set, this study evaluated the precipitation variations over Tianshan Mountains on different time scales by using Mann-Kendall (M-K) test approaches and the ensemble empirical mode decomposition (EEMD) method. The results show that (a) most parts of Tianshan experienced increasing annual precipitation during 1950–2016 while Western Tianshan, which is the wettest region, faced a downtrend of precipitation during the same 67 years; (b) the annual precipitation in the Tianshan Mountains has exhibited high-frequency variations with 3- and 6-year quasi-periods and low-frequency variations with 12-, 27-year quasi-periods. On the decadal scale, Tianshan had two dry periods (1950–1962 and 1973–1984) and two wet periods (1962–1972 and 1985–2016) and has experienced a tendency of continuous humidification since 2004; (c) the precipitation over the Tianshan Mountains shows a strong seasonality. In total, 63.6% of all precipitation falls in spring and summer. Distinctive differences are found in seasonal precipitation variations among the sub-Tianshan regions. Obvious upward trends of precipitation over Eastern Tianshan were found in all seasons, with Eastern Tianshan entering a humid period as early as 1986. Northern and Central Tianshan experienced a decreasing trend in summer and spring. However, in the other seasons, those two sub-Tianshan regions have been in humid periods since the 1990s. The precipitation over Western Tianshan showed an upward trend in summer and autumn. The obvious downward trends in spring and winter have led to dry periods in these two seasons from 1997–2014 to 2008–2016, respectively.

KEYWORDS

Central Asia, ensemble empirical mode decomposition, multi-decadal variability, nonlinear characteristics, precipitation, Tianshan Mountains

1 | INTRODUCTION

With regard to drought and overall water scarcity, mountains play an important role for precipitation and thus water supply in arid and semi-arid regions (Sorg *et al.*, 2012; Unger-Shayesteh *et al.*, 2013; Ragettli *et al.*, 2016). For Central Asia, which is located in the hinterland of the Eurasian continent and far from oceans, the Tianshan Mountains contribute to the vital supply of freshwater and feed most of the region's rivers and lakes by a combination of glacier meltwater, mountains' precipitation, and fissure water. Therefore, the Tianshan Mountains are recognized as the 'water tower' of Central Asia (Immerzeel *et al.*, 2010; Duethmann *et al.*, 2015; Chen *et al.*, 2016). As one of the largest mountain systems in Central Asia, Tianshan Mountains receive much more rainfall than the surrounding lowlands, and a high frequency of strong precipitation (Zhang and Deng, 1987; Schiemann *et al.*, 2008). For example, the Tianshan Mountains account for more than 40% of the precipitation in the Xinjiang province of China but its area is only 16% of the region (Shi and Xu, 2008). Driven by global warming, the temperature in Central Asia including the Tianshan Mountains has been increasing remarkably in recent decades (Hu, 2004; Yuan-An *et al.*, 2013). The warming trend leads to reduced reserves of snow and degradation of glaciers (Aizen *et al.*, 2006; Farinotti *et al.*, 2015). Currently, additional meltwater from shrinking glaciers adds to precipitation and seasonal snowmelt. If there are no additional water sources, for example from increasing precipitation, to compensate for the diminishing supply of water from heavily reduced glacier area and volume, the result may be reduced runoff (Shahgedanova *et al.*, 2020; Chen *et al.*, 2020; Zhang *et al*, 2020; Sorg *et al.*, 2012). This may have dramatic ecological consequences such as further shrinkage of the Aral Sea (Waltham and Sholji, 2001), the drying out of parts of the lower Tarim River (Duethmann *et al.*, 2015), and severe socio-ecological water crises in various parts of Central Asia (Bernauer and Siegfried, 2012). Moreover, the discharge of rivers and its seasonal distribution from snow meltwater and precipitation in the Tianshan Mountains are sensitive to long-term temperature and precipitation changes, especially at the end of winter when the melting season begins (Barnett *et al.*, 2005). Global warming has accelerated the water cycle by increasing water in the atmosphere evaporated from the surface, also triggering more extreme precipitation events (Yang and He, 2003; Jiang *et al.*, 2017). This will cause more hydrological and environmental crises in Central Asia (Chen *et al.*, 2017). Therefore, an in-depth study of the variability and patterns of precipitation in the Tianshan Mountains are crucially important for water resources as well as ecosystems management due to the immense impact on societies in the massive inland region of Central Asia.

A review on studies of precipitation and water cycle changes in the Tianshan Mountains in past decades is presented in Unger-Shayesteh *et al.* (2013). Most studies (Chen *et al.*, 2016; Guan *et al.*, 2018; Sorg *et al.*, 2012; Wang *et al.*, 2013) agree on general wetting trends in the Tianshan Mountains during past decades. Precipitation, as well as the water vapour content, showed significantly increasing trends. However, there are diverse results regarding the amount, spatial pattern, and precipitation trends across the Tianshan Mountains. A number of investigations suggest that the annual precipitation increased in Western and Northern Tianshan during the past century (Aizen *et al.*, 1997; Chen *et al.*, 2016; Chen *et al.*, 2017; Gerlitz *et al.*, 2018; Hu *et al.*, 2017; Sorg *et al.*, 2012; Yang and He, 2003; Yuan *et al.*, 2004; Zhang *et al.*, 2009). Diverse results have been presented for Central and Eastern Tianshan due to different delineation of study regions and varying data sources. Some studies found indications for a decrease in annual precipitation in Central Tianshan (Romanovsky *et al.*, 2002; Kriegel *et al.*, 2013). Conversely, Chen *et al.* (2016, 2017) stated that although the rate is weak, precipitation in Central Tianshan still shows an increasing trend. Similarly, studies on changes in seasonal precipitation reveal diverse results for different parts of the Tianshan Mountains. Increasing trends are seen in the cold season in the whole Tianshan (Aizen *et al.*, 1997), in mid to high altitudes of the Northeastern Tianshan (Zhang *et al.*, 2009), and in the Issyk-Kul basin (Romanovsky *et al.*, 2002). Other studies report precipitation increases for individual stations in the warm season only during some periods (Romanovsky *et al.*, 2002; Mamatkanov *et al.*, 2006; Zhang *et al.*, 2009). Overall, the temporal and spatial patterns of precipitation in the Tianshan Mountains are complicated while an overall positive trend can still be determined. Change rates typically range from −30 to +50 $\text{mm}\cdot 10\text{a}^{-1}$ for annual precipitation (Unger-Shayesteh *et al.*, 2013). With the substantially increased precipitation in recent decades, there has also been an increasing trend of extreme precipitation in the Tianshan Mountains since 1990 (Zhao *et al*., 2010).

Most of the previous studies on Tianshan or Central Asia precipitation, as reported above, were more concerned with average trends and linear variation (Aizen *et al*., 1997; Sorg *et al*., 2012; Chen *et al*., 2016; Zhang and Zhang, 2006; Zhong *et al*., 2017). The most widely used conventional statistical methods such as linear regression were suitable for the data aim to extract the rate of linear climate change trends (Wu *et al*., 2007). The linear method requires stationary time series data. It can only calculate a constant change rate (Draper and Smith, 1998). However, most climate factors with long-term variability, such as temperature and precipitation, show complex nonlinear changes accompanied by periodic oscillations (Huang *et al*., 1998; Wu and Huang, 2009). Traditional decomposition methods, such as Fourier transform and wavelet analysis, all have some defects in processing non-stationary signals (Pislaru *et al*., 2003; Huang and Wu, 2008). The ensemble empirical mode decomposition (EEMD) method developed in recent years by Wu and Huang (2009) can be locally adaptive in time series. For example, it can adaptively modify parameter characteristics for a given time series to adapt to dynamic changes of data, which is especially suitable for analyzing nonlinear and non-stationary time series (Wu and Huang, 2009). Moreover, the EEMD method decomposes complex data into a limited number of oscillating components based on the data itself without introducing basis functions in advance (Wu and Huang, 2009). Therefore, EEMD can effectively separate hidden intrinsic mode function (IMF) components on different time scales and trend components from the original time series (Wu *et al*., 2007; Wu and Huang, 2009). The EEMD method has been used successfully to analyze the long-term trends of various climatic variables such as air temperature (Qian *et al*., 2011), sea level (Chen *et al*., 2014), and precipitation (Xue *et al*., 2013; Guo *et al*., 2016; Duan *et al*., 2018). Consequently, the use of the EEMD method to reveal the multi-timescale variations and non-linear trend of the precipitation in the Tianshan Mountains is expected to deepen and enhance the understanding of precipitation changes in Central Asia. We describe the details of the EEMD method in Section 2.3.1.

In order to describe the precipitation variability over the Tianshan Mountains in a more meticulous way, this study reveals the temporal variations, including the linear trends, multi-timescale variabilities, and nonlinear trends of the annual and seasonal precipitation over the Tianshan Mountains during 1950–2016. This manuscript, therefore, is arranged as follows: the precipitation characteristics, including the spatial patterns of annual precipitation, and its interannual variability and decadal fluctuation over the Tianshan Mountains are presented in Sections 3.1 and 3.2. In Section 3.3, the linear and nonlinear trends of seasonal precipitation variability over the Tianshan Mountains are investigated in detail. In a follow up-study (Part II), we will focus on the atmospheric circulation anomaly corresponding to the change of precipitation over the Tianshan Mountains.

2 | STUDY AREA, DATA, AND METHODS

2.1 | Study area

The Tianshan Mountains cover a large portion of Central Asia, spanning regions from Uzbekistan to Kyrgyzstan, and from Kazakhstan to Uyghur Autonomous Region of Xinjiang in northwest China (Figure 1). As Tianshan is a transboundary mountain range, the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Centre (https://whc.unesco.org/en/list/1490/) defines the part of the Tianshan Mountains within Kazakhstan, Uzbekistan, and Kyrgyzstan as Western Tianshan and the part within China as Eastern Tianshan. However, the climate of the Tianshan Mountains presents distinct local characteristics depending on the distribution of the ranges and the different altitudes. In this study, we refer to the findings of Aizen *et al*. (1995), Sorg *et al*. (2012), Ning (2013), and Chen *et al*. (2016) to divide the Tianshan Mountains into four parts based on the atmospheric circulation prevailing in different parts of the mountains and the location of larger mountain ranges (Figure 1). Boundary 1 is bounded by Lake Issyk, Eastern edges of Kirgizskiy Alatau, and the Fergana range. The area west of Lake Issyk is Western Tianshan (Region I) including the Hissor Range, the Pakem Range, the Chatkal Range, and the Fergana valley. This region has a relatively moist climate, especially in winter and spring when it is affected by the interaction between the southwestern branch of the Siberian anticyclonic circulation and cyclonic activity from the west. In addition, the southwest cyclonic circulation brings warm, humid air masses into the region (Aizen *et al*., 1997). The dividing line 2 is bounded by Lake Issyk and the Ili Valley. Located to the north of the Lake Issyk and the south bank of the Ili Valley is Northern Tianshan (Region II). Northern Tianshan includes Zailiyskiy Alatau and Borohoro, Dzungarian Alatau, and the Yilianhabierga mountain ranges. The precipitation in Northern Tianshan is mainly caused by frontal cyclones formed when cold air masses entering from the north and northwest are blocked by mountain ranges (Aizen *et al*., 1997).

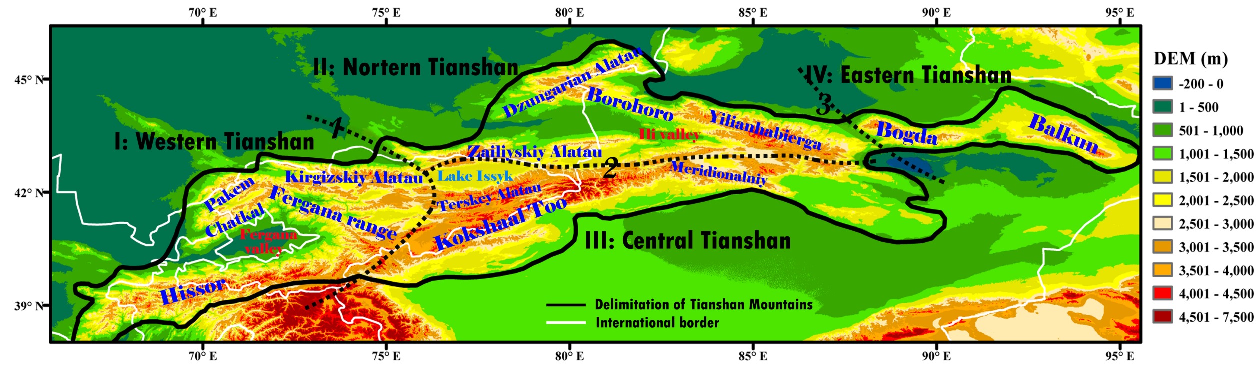

FIGURE 1 Study area and the sub-regions of the Tianshan Mountains. The dotted lines numbered 1 to 3 refer to the borders between the four sub-regions of the Tianshan Mountains detailed in the text [Colour figure can be viewed at wileyonlinelibrary.com]

South of the Ili Valley lies Central Tianshan (Region III) and includes the Kokshaal Too and Meridionalniy mountain ranges. Located to the lee of the surrounding mountain ranges, Central Tianshan receives much less precipitation than Northern Tianshan (Liu and Han, 1992). Boundary 3 is bounded by the cities of Urumqi and Dabancheng in China. The east part is called Eastern Tianshan (Region IV) and includes the Bogda and Balkan mountain ranges (Figure 1). The high mountain ranges around Central and Eastern Tianshan block the entry of water vapour, resulting in low winter precipitation (Liu and Han, 1992). However, Eastern Tianshan and Central Tianshan are not only affected by the westerly circulation but may also be affected by the East Asia monsoon and cyclone circulation from the south, leading occasionally to extreme precipitation events (Yao *et al.*, 2020).

2.2 | Data

Monthly precipitation is derived from Global Precipitation Climatology Centre (GPCC) (Schneider *et al.*, 2018). The Full Data Monthly Product V.2018 (V.8) is of higher accuracy and higher resolution (0.25°) compared with previous GPCC products. Compared with previous products, the number of stations used in GPCC V.8 increased from 75,100 to 79,200 with climatological normals (Schneider *et al.*, 2018). The data are available at https://www.dwd.de/EN/ourservices/gpcc/gpcc.html. Due to its high-quality control, GPCC data have been widely used in numerous hydro-meteorological studies in Central Asia and the arid northwest of China. Ahmed *et al.* (2019) found that GPCC performs much better in the arid regions of Pakistan compared with data sets of CRU (Climate Research Unit, Univ. East Anglia) (Harris *et al.*, 2014) and UDel (Center for Climatic Research-University of Delaware) (Matsuura and Willmott, 2012). Hu *et al.* (2017) also conclude that GPCC data over Central Asia has a higher accuracy than CRU data sets. They report that the correlation coefficient of the annual precipitation between GPCC and stations in Central Asia is larger than 0.88, and the absolute error is only 5 mm. Therefore, the GPCC V.8 data set has great credibility to describe precipitation over Central Asia. The temporal coverage of GPCC ranges from 1891 to 2016. Previous research on the evaluation of the GPCC and CRU data sets in China shows that there is a significant difference in the trends calculated from the two data sets before the year 1950, especially in the Xinjiang province of China, where part of the Tianshan Mountains are located (Sun *et al.*, 2014). Since there were only a few meteorological stations in Xinjiang and the meteorological and hydrological data recording was not continuous before 1950 (Zhang and Zhang, 2006), we assume that the precipitation data sets assimilated based on weather stations in Xinjiang are not sufficiently reliable and correct before 1950. Accordingly, we used GPCC data for the period from 1950 to 2016 in this study. In addition, The CRU monthly precipitation data (Harris *et al.*, 2014), which is available at http://doi.org/10.5285/gcmdf7, is used in the discussion section to compare the difference when using GPCC precipitation data in the Tianshan Mountains.

2.3 | Method

2.3.1 | EEMD

Empirical Mode Decomposition (EMD) is a time-frequency analysis method for decomposing complex nonlinear and non-stationary data (Huang *et al.*, 1998). According to the different frequency-amplitude characteristics of each period's signal, data can be decomposed into a series of sequences with different feature-specific timescales (Wu and Huang, 2009). Ensemble EMD

(EEMD) is an improved version based on the EMD method. The decomposition process of EMD is introduced first before that of EEMD. Through a sifting process that uses only local extrema, EMD decomposes time series data $X(t)$ into a finite number of inherent mode functions (IMFs) and a residual (Wu and Huang, 2009),

$$X(t)=\sum_{i=1}^{n} C_i(t)+\mathrm{R}(t) \quad (1)$$

where $C_i(t)$ represents the ith component IMF, n is the total number of the IMFs, and $\mathrm{R}(t)$ is the residual.

However, during the sifting process of EMD decomposition, there exists a modal aliasing phenomenon meaning that an IMF will contain characteristic components with different time scales, which occur due to the signal itself as well as the defection of the EMD algorithm itself (Wu and Huang, 2009). Therefore, the EEMD method was improved by adding white noise to the original data series which assists in attenuating the effects of mode mixing in order to improve the decomposition. More details about EMD and EEMD can be consulted in Wu and Huang (2009) and Duan *et al.* (2018). The supplementary information (Figure S1) also presents a demonstration by using annual precipitation data from one grid point (42.125°N, 70.375°E) in the Tianshan Mountains to exhibit the sifting process of EMD and EEMD.

2.3.2 | Definition of the decadal signals

The decadal climate variability is between the long-term climate trend and the interannual climate variation and provides the background for interannual climate change. Studies show that decadal climate variability enhances or mitigates the vulnerabilities of water systems (Wan *et al.*, 2015). With climate change, the evaluation of the impacts of decadal climate variability on the vulnerability of regional water resources, particularly in arid regions, has become increasingly important (Xia *et al.*, 2017). One of the leading factors in the formation of decadal drought is the decadal change in precipitation (Bichet *et al.*, 2011). Therefore, studying the characteristics of decadal changes in precipitation is a key issue in the study of decadal-scale drought. In this paper, decadal drought is defined as a negative anomaly of precipitation during a period of at least 10 years. Decadal humidification is likewise defined as a positive anomaly of precipitation with a duration of more than 10 years (Xu *et al.*, 2017). Consequently, based on the time scale studied, the decadal signals with periods of more than 20 years are treated as multi-decadal variability (MDV). In addition to MDV, the nonlinear trend cannot be ignored. Together they constitute the multi-decadal change in precipitation (Wu *et al.*, 2007). It is worth noting that 'dry period' and 'drying tendency period' are different concepts. While a 'dry period' simply denotes a period with below average precipitation, 'drying tendency period' refers to the tendency of climate and ecological environment to develop into a more arid climate, which has as one characteristic the continuous decrease in precipitation (Xu *et al.*, 2017). Therefore, the drying tendency period presents a continuous reduction in precipitation on a multi-decadal scale.

2.3.3 | Mann-Kendall and student's *t* test

In addition, in this study the linear trend is used to quantify the tendency of the annual precipitation, which is obtained by the Mann-Kendall (M-K) test (Mann, 1945; Kendall, 1975). The coefficient of variation (CV) is used to measure the variabilities of annual precipitation in the Tianshan Mountains. CV defined as the ratio of the *SD* to the mean can assess the variability of the time series and permits the comparison of variates free from scale effects (Brown, 1998). A detailed description of the M-K test can be found in (Mann, 1945; Kendall, 1975).

3 | RESULTS

3.1 | Inter-annual variations and linear trends of precipitation

Inter-annual variation of precipitation over Tianshan was analyzed during the period of 1950–2016. The average annual precipitation in the entire Tianshan Mountains is 253 mm (Figure 2). This finding is consistent with the results of Chen *et al.* (2016), although the exact values are different due to the use of different periods and the selection of data sources. The average annual precipitation in Chen *et al.* (2016) is about 290 mm, with 97 mm annual precipitation falling in Eastern Tianshan and 455 mm in Western Tianshan. The overall annual precipitation of Tianshan shows a statistically insignificant, weakly increasing trend at a rate of 0.90 mm per decade (Figure 2). The maximum annual precipitation occurred in 1969 (305 mm), which is far higher than that in other years, while the driest year is 2001 with 231 mm of annual precipitation. It can be seen from Figure 2 that, apart from the anomalous high precipitation in 1969, the annual precipitation in most years before 1986 was basically below 265 mm, but after 1986 the precipitation in many years was above this value. By calculating the accumulative anomaly, Tianshan entered a period of excessive

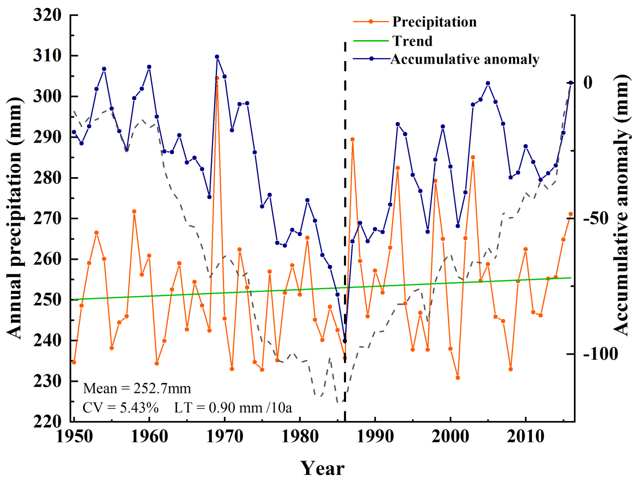

FIGURE 2 Annual precipitation, linear trend, and accumulative annual precipitation anomaly over all of Tianshan during 1950–2016; CV: Coefficient of variation (%); LT: Linear trend (mm·10a^{-1}) [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation after 1986 when the accumulative anomaly reached its minimum in the overall time series (Figure 2). Moreover, the annual precipitation variation amplitude during 1986 to 2016 is higher than that during 1950 to 1986. The mean value (256 mm) and the coefficient of variation (CV) of the annual precipitation during 19,862,016 of 5.6% are both larger than in the previous period (250 mm and 5.4%, respectively), implying that the annual precipitation after 1986 has indeed increased with a slightly larger volatility than that in during 1950–1986.

The regions of Western Tianshan and Northern Tianshan receive most precipitation, with annual average precipitation of 403 and 312 mm, respectively (Figure 3). Eastern Tianshan and Central Tianshan have relatively little precipitation, with annual average precipitation of 140 and 156 mm, respectively. Similar to the entire Tianshan, Eastern, Northern, and Central Tianshan all show increasing trends at rates of ~1.47, 1.93, and 1.14 mm per decade, respectively. Moreover, the increasing

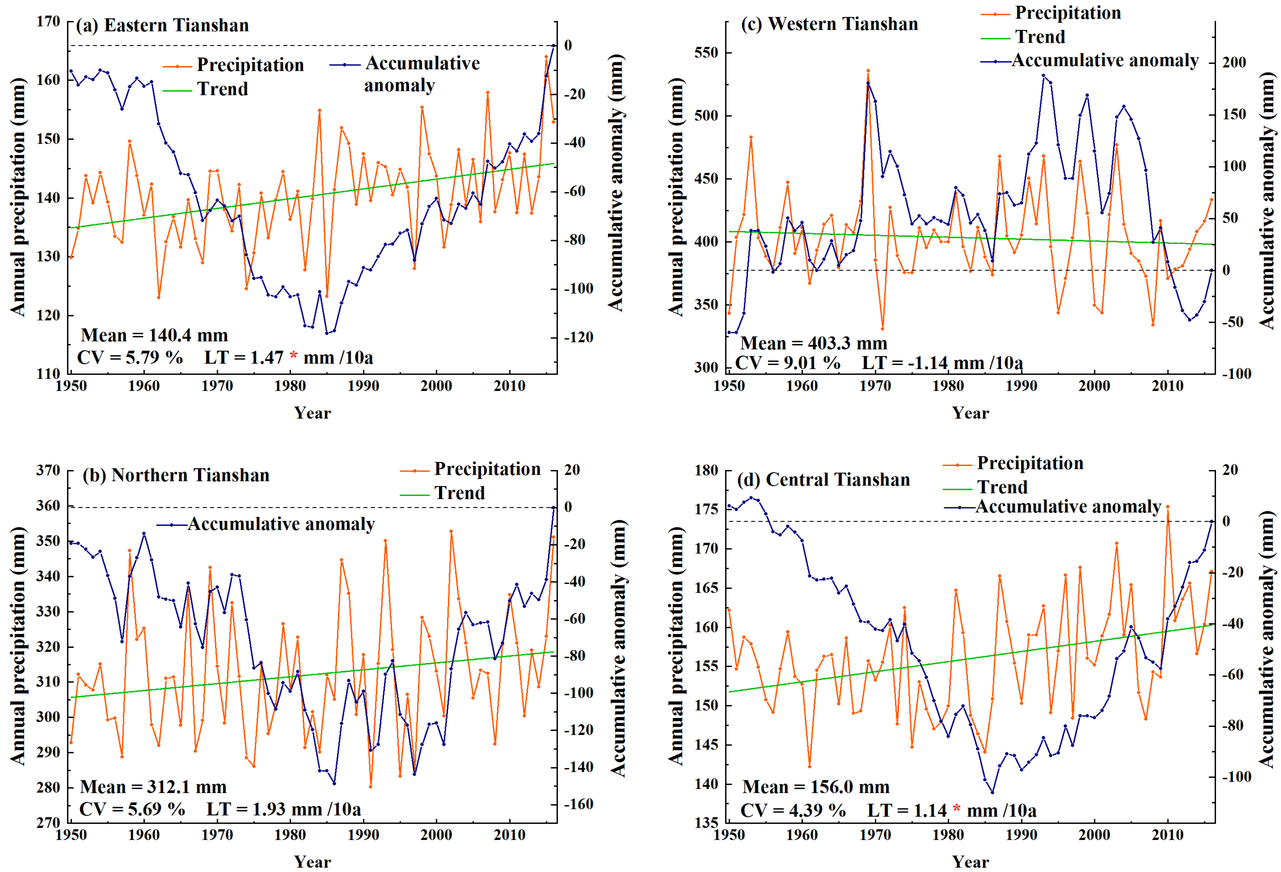

FIGURE 3 Annual precipitation, linear trends, and annual precipitation accumulative anomalies over sub-regions of Tianshan during 1950–2016, CV: Coefficient of variation (%); LT: Linear trend (mm·10a^{-1}). *denotes that the linear trends is significant at the 95% confidence level [Colour figure can be viewed at wileyonlinelibrary.com]

trend of annual precipitation in both Eastern Tianshan and Central Tianshan passed the significance test ($p \le .05$) for the Mann-Kendall trend method. Additionally, we found from analyzing the accumulative anomalies that the annual precipitation in Eastern Tianshan, Northern Tianshan, and Central Tianshan increased significantly after 1986. In contrast, we observed a weak downward trend over Western Tianshan during the 67 years, at a rate of −1.14 mm per decade. Furthermore, within this overall downward trend there are four periods of increasing/decreasing trends in Western Tianshan: 1950–1969 and 1986–2000 were periods with upward trends while precipitation mainly showed downward trends during 1970–1985 and 2001–2014. The specifically large CV (9.01%) over Western Tianshan indicates that precipitation variability is larger and precipitation shows a more complex character than that in other parts of the Tianshan Mountains.

Figure 4 illustrates the spatial distribution of annual mean precipitation and its linear trend over the Tianshan Mountains during 1950–2016. Consistent with the results reported above, there is more precipitation in Western Tianshan and Northern Tianshan Mountains. In Western Tianshan some regions can even have more than 900 mm of annual precipitation. In accordance with the results of the overall trend analysis presented above, according to the linear trend most parts of the Tianshan experienced increasing annual precipitation during the study period. In particular, increasing trends were mostly significant in Northern Tianshan and Central Tianshan. In these regions there are only a few grid points with decreasing trends in Northern Tianshan. Except for the precipitation decrease in the southwestern part of Eastern Tianshan, the annual precipitation in other areas of Eastern Tianshan showed a statistically significant increase. However, the region with the highest annual precipitation, Western Tianshan, faced a downtrend of precipitation during those 67 years: Areas of seriously reduced precipitation mainly occur in the high mountain areas of Western Tianshan (Figure 4).

3.2 | Multi-timescale variations of precipitation

In general, the precipitation variability results from a complex nonlinear system including various uncertainties. The regularity of non-linearity and non-stationary cannot be reflected simply by linear regression and correlation analysis. Therefore, the annual precipitation sequence over Tianshan during 1950–2016 was decomposed into five independent IMFs and one trend component by using the EEMD method to show its multi-timescale characteristics and non-linear trend. IMF1 to IMF5 reflect the fluctuation of precipitation from high to low frequency and each IMF presents an oscillation component with a definitive period, while the trend represents the general non-linear and non-stationary trend of annual precipitation.

EEMD results show that annual precipitation in Tianshan has oscillation periods of 3.3, 6.4, 12.2, and 26.8 years (Figure 5 and Table 1). IMF1 and IMF2 contain the highest frequencies, maximum amplitudes, and shortest wavelengths, reflecting components on an inter-annual timescale. To compare each IMF component and reveal the essential oscillation of the original sequence, the variance contribution rate of IMFs is calculated and presented in Table 1. IMF1 was found to be the dominant IMF in over half (55.2%) of all components, followed by IMF2 (22.4%). That is, the inter-annual signal is the dominant component of the annual precipitation variability over Tianshan. Besides, 12.2 years (IMF3) and 26.8 years (IMF4) periodic cycles were detected on the inter-decadal and multi-decadal scale respectively, which together contribute 15.8% to the total precipitation variability (Table 1). IMF 5 series has only one local maximum and therefore the mean period could not be determined (Wu and Huang, 2009; Molla *et al.*, 2011). The results are consistent with previous studies by Hu *et al.* (2017) and Guo *et al.* (2016) who had calculated annual precipitation with EEMD in Central Asia and Xinjiang province

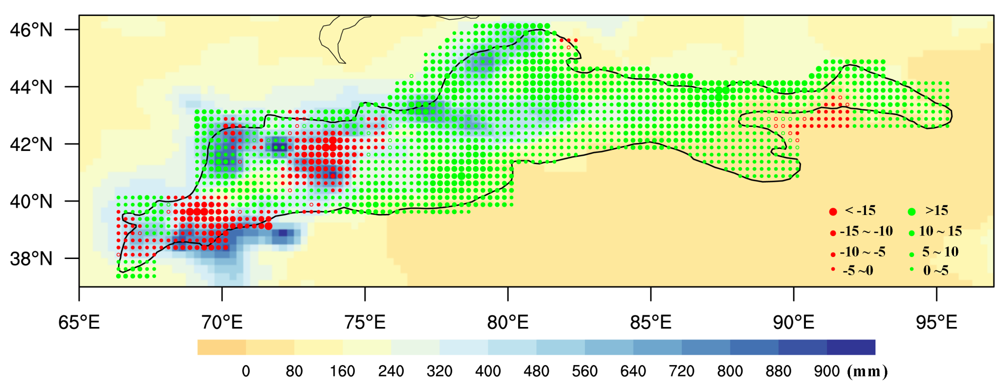

FIGURE 4 The climatology (shading) and trends (circles, units: mm·10a^{-1}) of annual precipitation in the Tianshan Mountains during 1950–2016. Filled circles indicate the confidence level at 95% and green (red) circles indicate increasing (decreasing) trends [Colour figure can be viewed at wileyonlinelibrary.com]

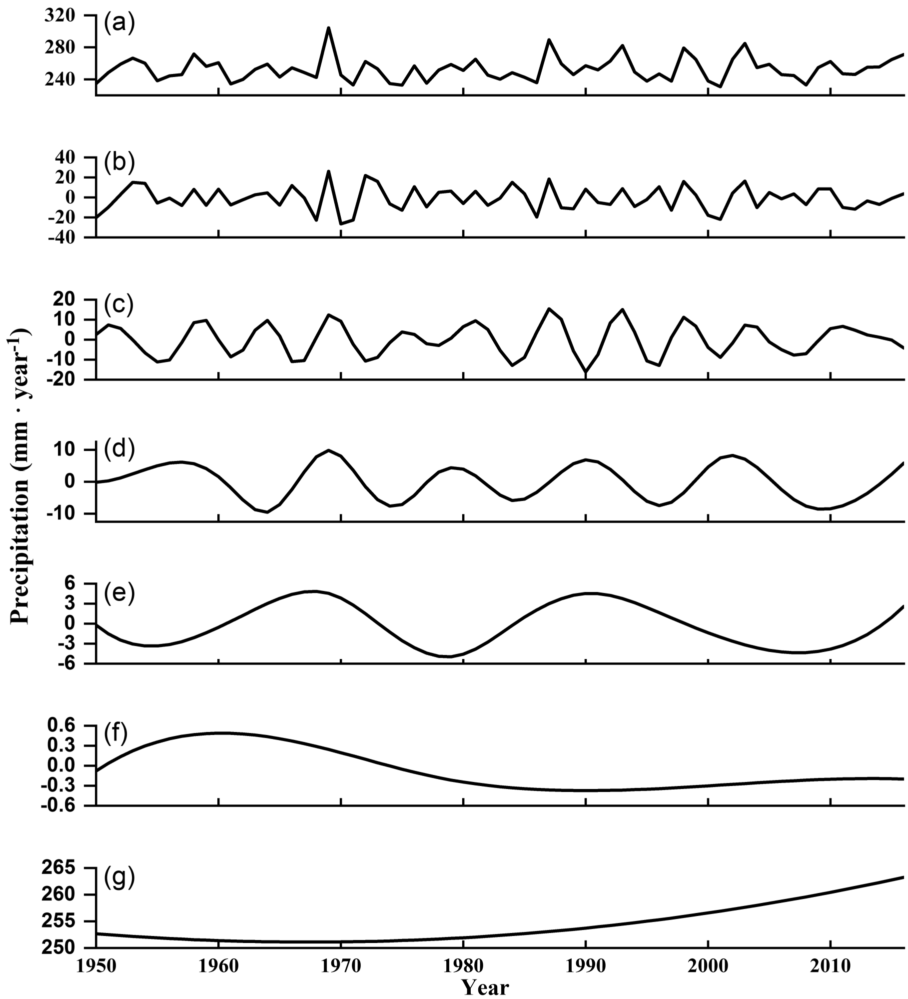

FIGURE 5 The original annual precipitation data (a), the EEMD-based intrinsic mode functions (IMFs) (b–f), and the extracted trend (g) for the entire Tianshan region

TABLE 1 Periods and their variance contributions to various time-scale components of annual precipitation

Study area		IMF1	IMF2	IMF3	IMF4	IMF5	Trend
Entire Tianshan	Period/year	3.3	6.4	12.2	26.8	/	
	Variance contribution /%	55.2	22.4	11.5	4.3	/	6.5
Eastern Tianshan	Period/year	2.9	7.0	10.8	28.0	33.2	
	Variance contribution /%	41.8	21.7	8.3	2.9	2.5	22.9
Northern Tianshan	Period/year	3.0	7.7	14.4	40.2	/	
	Variance contribution /%	50	11.7	10.5	1.2	/	26.6
Western Tianshan	Period/year	3.6	8.3	13.7	29.4	/	
	Variance contribution /%	68.7	14.9	11.9	4	/	0.4
Central Tianshan	Period/year	3.4	8.4	16.1	22.7	/	
	Variance contribution /%	39.7	23.4	6.4	1.9	/	28.2

located in the arid region of northwest China. For example, Hu *et al.* (2017) obtained quasi-periods of 3, 6, 13, 30 years for IMFs 1–4, respectively in the mountainous area in Central Asia. Guo *et al.* (2016) captured oscillations of annual precipitation in Xinjiang with periods of 2 years, 6 years, 12 years and 23 years.

Table 1 further lists the EEMD results in the different parts of Tianshan. Annual precipitations over all four regions of Tianshan show the inter-annual components with periods of quasi 3 years and quasi 6 years. The inter-annual variation is also the dominant component (IMF1 and IMF2) of the annual precipitation over all four regions with 64% (Eastern Tianshan), 62% (Northern Tianshan), 84% (Western Tianshan), and 63% (Central Tianshan) variance contribution, respectively (Table 1). Especially, the quasi 3 years oscillation explains over 68% of the variance contribution over Western Tianshan. In terms of multi-decadal timescales, each region exhibits different characteristics. Periodic cycles with values of 10.8, 28.0, and 33.2 years were found in Eastern Tianshan while Northern Tianshan shows 14.4 and 40.2 years variations on inter-decadal and multi-decadal scales, respectively. Similar to the results of the entire region, there are 13.7 and 16.1 years periodic variations of annual precipitation on inter-decadal scales in Western Tianshan and Central Tianshan, respectively. Furthermore, the 29.4 and 22.7 years multi-decadal periodicities were captured respectively in those two areas.

Figure 6 shows that, over a period of 26.8 years, there is a significant multi-decadal variability (MDV) in the annual precipitation on the Tianshan Mountains. According to the trend line, the precipitation anomaly changed to a positive phase after 1986. This result is consistent with the result of the interannual change analyzed in Section 3.1. The MDV is superimposed on the nonlinear trend, resulting in two dry periods with precipitation anomalies below zero and two wet periods with precipitation anomalies above zero during 1950–2016. The dry periods are from 1950 to 1962 and from 1973 to 1984. The wet periods are from 1962 to 1972 and from 1985 to 2016 as summarized in Table 2. Tianshan experienced a tendency of continuous humidification since 2004 owing to reinforcement of the trend to the MDV component (Figure 6). It can also be seen from Figure 6 that the drying tendency periods of the Tianshan Mountains are from 1968 to 1978 and 1991 to 2004. The wetting tendency periods are from 1955 to 1968, 1979 to 1991, and 2004 to 2016.

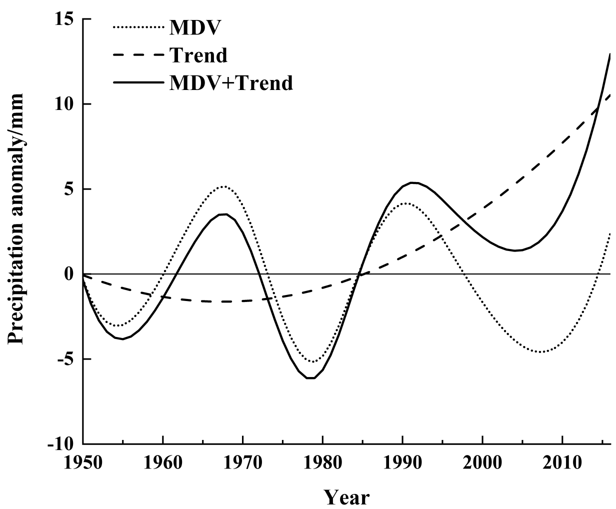

FIGURE 6 Characteristics of multi-decadal precipitation on the Tianshan based on EEMD method. MDV represent multi-decadal variability. MDV + trend indicate the multi-decadal change

Similarly, the above analysis is performed on the different parts of Tianshan. There are specific differences in the multi-decadal oscillation and the length of the periods in the four sub-regions (Figure 7). For Eastern Tianshan, the multi-decadal variability is more irregular with periods of 28.0 and 33.2 years (Figure 7a; Table 1). From the trend line, the precipitation in Eastern Tianshan turned into a positive anomaly after 1993, and continued to be strongly positive ever after (Figure 7a). The MDV with the trend added reveals that Eastern Tianshan was in a dry period before 1986, and then entered a humid period. Especially since 1999, Eastern Tianshan has been in the process of humidification (Figure 7a). With 40.2 years, the dry period is longer in Northern Tianshan than in other Tianshan regions. Further, its long-term trend shows a fast linear growth characteristic, which drives the time series towards a positive anomaly after 1981 (Figure 7b). MDV plus trend indicates that 1950–1959 and 1970–1988 are the dry periods in Northern Tianshan, respectively. 1960–1969 is a wet period and another continuous wet period started in 1989.

As is presented in the Figure 7c, there is an obvious 30-year multi-decadal oscillation in Western Tianshan, which is similar to the entire Tianshan precipitation. Even though the long-term trend of precipitation shows a downward trend over the entire study period of 67 years, the precipitation anomaly trend is still in a positive phase. The MDV superimposed with the trend depicts that Western Tianshan was in humid periods in 1951–1974 and 1983–2000, and a dry period from 2001 to 2014. A short drought occurred between 1975 and 1982. However, as it lasted only 8 years, it was not counted as a decadal dry period. According to multi-decadal oscillation, Western Tianshan has now been in a humid period since 2014 (Figure 7c). Annual precipitation in Central Tianshan shows different multi-decadal scale characteristics compared to all other sub-regions of Tianshan (Figure 7d). Although the multi-decadal periodic oscillation of the precipitation in Central Tianshan is also about 20 years, the long-term trend shows a non-linear characteristic of first decreasing and then increasing trend (Figure 7d). Precipitation entered a negative anomaly phase in 1955, followed by a positive anomaly in 1994 and after that has been showing a strongly positive trend. The superposition of multi-decadal oscillation and long-term trend in precipitation in Central Tianshan resulted in a dry period from 1955 to 1987 followed by a humid period since 1988 (Figure 7d).

TABLE 2 Multi-decadal wet and dry periods of precipitation in the Tianshan Mountains

	Entire Tianshan	Eastern Tianshan	Northern Tianshan	Western Tianshan	Central Tianshan
Dry periods	1950–1962	1950–1985	1950–1959	2001–2014	1955–1987
	1973–1984		1970–1988		
Wet periods	1963–1972	1986–2016	1960–1969	1951–1974	1988–2016
	1985–2016		1989–2016	1983–2000	

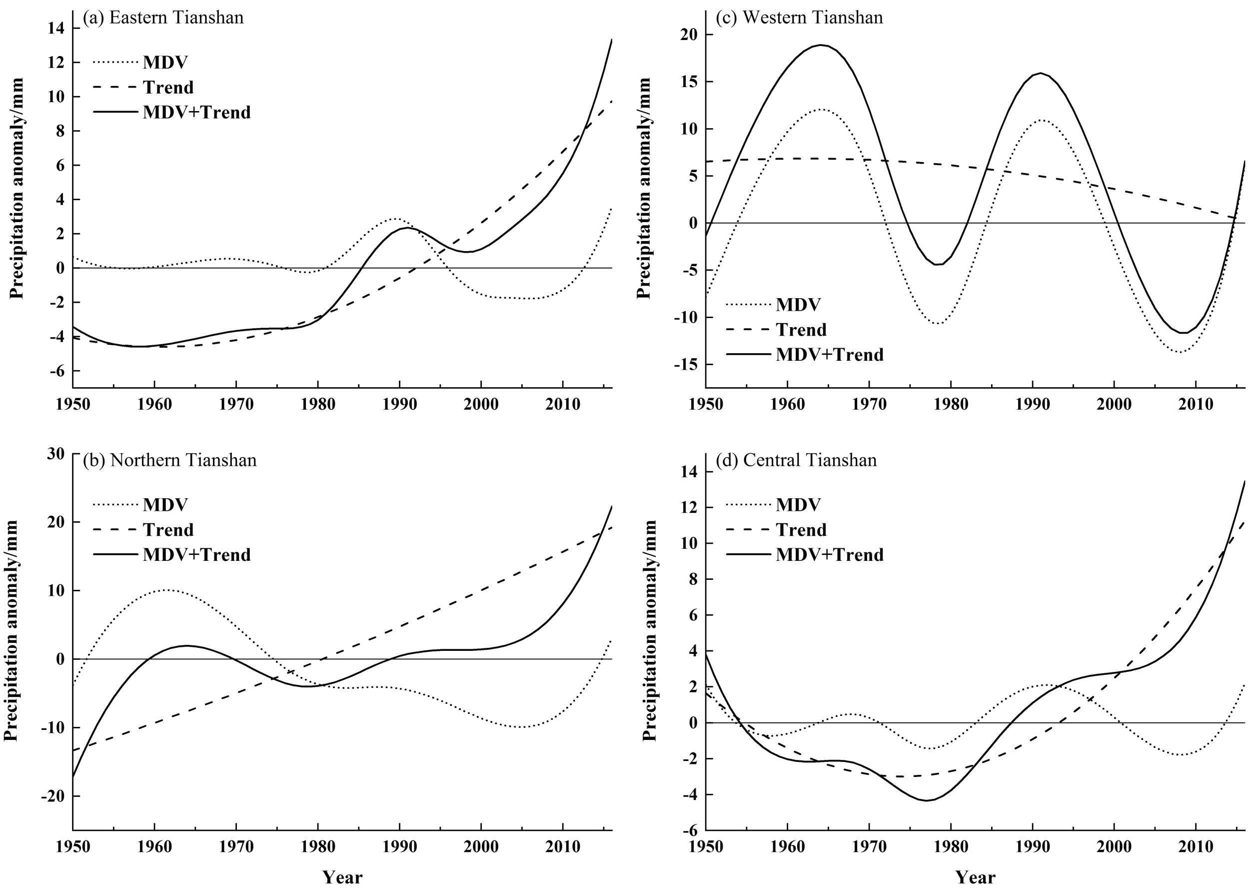

FIGURE 7 Characteristics of multi-decadal precipitation of the sub-Tianshan based on EEMD method. MDV represent the multi-decadal variability. MDV + trend indicates the multi-decadal change

In summary, Eastern Tianshan, Northern Tianshan, and Central Tianshan show positive long-term trends. Among them, Northern Tianshan first entered the period of positive precipitation anomaly in 1981. In Eastern Tianshan the change from a negative to a positive precipitation anomaly occurred in 1993. Central Tianshan was the last region that changed from drought to humid in 1994. An important result is that, due to the combined effects of multi-decadal variability and long-term trend, the entire Tianshan is currently not only in a humid period but also in a humid tendency period. Therefore, on a multi-decadal scale, Tianshan has entered an abnormally humid period. Many studies have shown that the arid area of Central Asia where Tianshan is located has been fairly humid during recent decades (Hu *et al*., 2017; Xu *et al*., 2017), which also echoes our findings. Nonetheless, there is a significant difference in precipitation variation between the Tianshan Mountains sub-regions. Especially Western Tianshan shows a distinctly different pattern compared with the rest of the study area.

3.3 | Variability of seasonal precipitation

The precipitation in the Tianshan Mountains is mainly concentrated in spring and summer (Table 3). The average spring and summer precipitation values are 87 and 74 mm, accounting for 34.4 and 29.2% of the annual

TABLE 3 Mean value (mm), linear trend (mm·10a^{-1}) of the seasonal precipitation, and the proportion of the seasonal precipitation in the annual precipitation (P: %) in the four seasons March–May (spring, MAM), June–August (summer, JJA), September–November (autumn, SON), and December–February (winter, DJF) over Tianshan and its sub-regions during 1950–2016)

Region	Season	Mean	P (%)	LT
Entire Tianshan	MAM	87	34.4	−0.60
	JJA	74	29.2	0.47
	SON	48	19	0.50
	DJF	44	17.4	0.45*
Eastern Tianshan	MAM	32	23	0.35*
	JJA	64	44.8	0.84**
	SON	31	22.8	0.43***
	DJF	13	9.4	0.11
Northern Tianshan	MAM	102	32.8	0.00
	JJA	87	28	0.32
	SON	70	22.6	1.10**
	DJF	52	16.6	0.30***
Western Tianshan	MAM	171	42.6	−2.67*
	JJA	71	17.6	0.25
	SON	64	15.5	0.25
	DJF	98	24.3	0.50
Central Tianshan	MAM	43	27.5	0.25
	JJA	73	46.2	0.54**
	SON	27	17.6	0.38***
	DJF	13	8.7	0.17**

*indicates significance at the 90% confidence level.
**indicates significance at the 95% confidence level.
***indicates significance at the 99% confidence level.

precipitation, respectively, followed by the average autumn precipitation (48 mm) and winter precipitation (44 mm), which account for 19.0 and 17.4% of the annual precipitation, respectively. However, there are distinctly different characteristics of seasonal precipitation in the four sub-regions of Tianshan. The amounts of spring precipitation in Western Tianshan and Northern Tianshan reach 171 and 102 mm, constituting 42.6 and 32.8% of the annual precipitation, respectively. Except for spring, Northern Tianshan has more precipitation in summer (88 mm, accounting for 22.6% of the annual precipitation) while Western Tianshan has more precipitation in winter (98 mm, accounting for 24.3% of the annual precipitation). For Eastern Tianshan and Central Tianshan, the precipitation mainly falls in summer, with average precipitation values of 33 and 73 mm, respectively. The average winter precipitation in both Eastern and Central Tianshan is 13 mm. Both these regions receive less precipitation throughout the year than the other two Tianshan areas (Table 3).

The precipitation in the Tianshan Mountains showed a downward trend in spring (LT = −0.60 mm·10a^{-1}) and upward trends in the remaining three seasons from 1950 to 2016 (Figure 8, Table 3). It can be seen from the spatial distribution that the declining trend of the precipitation in spring mainly occurs in parts of Western Tianshan and Northern Tianshan. It is especially strong in Western Tianshan where the overall linear trend of spring precipitation is −2.67 mm·10a^{-1} (Figure 8a, Table 3). The download trend of summer precipitation is concentrated in Central and western regions of the Tianshan Mountains, particularly in the Krigizskiy Alatau and the Fergana range. In contrast, the precipitation in Eastern Tianshan presents a significantly increasing trend (Figure 8b). In autumn and winter, significantly increasing trends of precipitation in Northern and Central Tianshan were observed (Figure 8c, Figure 8d, Table 3). Although the overall precipitation trend in winter is on the rise (Table 3), decreasing trends were found in parts of Eastern and Western Tianshan (Figure 8d).

EEMD results show that the seasonal precipitation in the Tianshan Mountains has also exhibited high-frequency variations with 3- and 6-year quasi-periods. The inter-annual variation is the dominant component (IMF1 and IMF2) of the precipitation over all four seasons with 86.3% (spring), 77.3% (summer), 88.6% (autumn), and 80.5% (winter) variance contribution, respectively (Table 4). Values of 12.2 and 26.8 years periodic cycles were found in spring while summer and autumn precipitation have 33.5 years variation at multi-decadal scales. Besides, 13.4 and 44.7 years periodic variations at inter-decadal and multi-decadal scales, respectively were identified in winter precipitation (Table 4).

Similarly, we analyzed the multi-decadal variabilities of precipitation in the sub-regions of Tianshan in each season. In the following we summarize the result for precipitation in spring:

- The precipitation turned into a positive anomaly after 1991 and maintained strongly positive ever after. Eastern Tianshan was in a long dry period from 1958 to 1993 and entered a humid period after 1994 (Figure 9a).
- The precipitation in Northern Tianshan entered a humid period from 1956 to around 1980. After 1981, Northern Tianshan entered a dry period and turned back to a humid period again after 1999 (Figure 9b).
- The turning point of the spring precipitation to a negative phase in Western Tianshan is in 1979. MDV plus

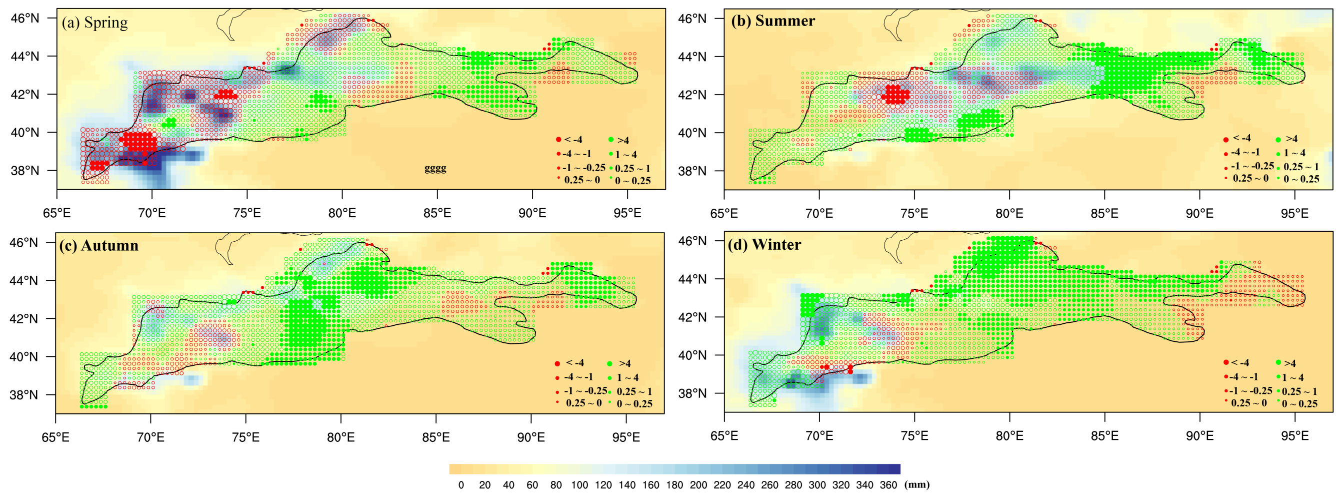

FIGURE 8 The climatology (shading) and trend (circles, units: mm·10a^{-1}) of seasonal precipitation in the Tianshan Mountains, during 1950–2016. Filled circles indicate the confidence level at 95% and green (red) circles indicate increasing (decreasing) trend [Colour figure can be viewed at wileyonlinelibrary.com]

trend shows that 1975–1985 and 1997–2014 are dry periods, while 1957–1974 and 1986–1996 are wet periods in Western Tianshan (Figure 9c).

- The spring precipitation in Central Tianshan has a 33.5 years multi-decadal oscillation during the 67 years (Table 4) and presents a downward long-term trend (Figure 9d). The superposition of multi-decadal oscillation and the long-term trend of precipitation in Central Tianshan caused a dry period from 1966 to 1983 and a humid period from 1984 to 2005 followed by a dry period since 2006 (Figure 9d).

For the summer precipitation in sub-Tianshan regions, we obtained the results as listed below:

- The trend line of summer precipitation in Eastern Tianshan showed a strong increasing trend after 1970. Eastern Tianshan in summer was in a dry period before 2006, and then entered a humid period (Figure 10a).
- The summer precipitation in Northern Tianshan exhibits a negative anomaly after 1994 (Figure 10b). MDV plus trend reveals that 1965–1985 is a dry period in Northern Tianshan. From 1950 to 1964 and 1986 to 2011 we find wet periods.
- The non-linear trend of summer precipitation in Western Tianshan first declined and then rose after 1983, which with MDV caused Western Tianshan to be in humid periods from 1950 to 1963 and after 1985, and in a dry period from 1964 to 1984 (Figure 10c).
- The summer precipitation in Central Tianshan shows 22.3 years of multi-decadal variability (Table 4). The summer precipitation in Central Tianshan began to rise strongly in 1977 and finally entered a positive phase in 1995 (Figure 10d). Generally, the summer precipitation of Central Tianshan was in a dry period from 1954 to 1988 and in a humid period after 1989 (Figure 10d).

The autumn precipitation showed increasing non-linear trends in all sub-Tianshan regions (Figure 11). The turning points to the positive anomaly of autumn precipitation in Eastern, Northern, and Central Tianshan are 2001, 1986, and 1989, respectively. Additionally we note the following points regarding precipitation in autumn:

- Following the trend, Eastern Tianshan was in a dry period before 1986 and in a humid period since then (Figure 11a).
- Likewise, Northern Tianshan was in dry periods during 1952–1972 and 1991–2005, and in humid periods from 1973 to 1990 and from 2006 to present (Figure 11b).
- Although the autumn precipitation in Western Tianshan has maintained an increasing trend, it generally remained in a negative phase during 1950–2016 (Figure 11c). Western Tianshan has been in a dry period since 1989 and was in wet periods during 1960–1969 and 1979–1988.
- Central Tianshan has remained in a humid period since 1996 (Figure 11d).

TABLE 4 Periods and their variance contributions to various time-scale components of seasonal precipitation in the Tianshan mountains and its sub-regions

Study areas	Season		IMF1	IMF2	IMF3	IMF4	IMF5	Trend
Entire Tianshan	MAM	Periond/year	3.1	5.8	12.2	26.8	/	
		Variance contribution/%	67.6	18.7	8.0	4.3	/	1.0
	JJA	Periond/year	2.9	6.7	12.2	33.5	/	
		Variance contribution/%	59.7	17.6	9.3	8.9	/	4.1
	SON	Periond/year	3.3	7.4	13.4	22.3	33.5	
		Variance contribution/%	68.8	18.5	4.4	6.9	1.4	0.0
	DJF	Periond/year	3.6	6.7	13.4	44.7	/	
		Variance contribution/%	64.5	16.0	9.8	3.2	/	4.2
Eastern Tianshan	MAM	Periond/year	3.3	8.4	12.2	44.7	/	
		Variance contribution/%	62.7	21.2	7.2	1.2	/	7.0
	JJA	Periond/year	3.0	5.8	12.2	26.8	/	
		Variance contribution/%	54.3	15.8	9.3	4.0	/	16.5
	SON	Periond/year	2.7	6.4	12.2	33.5	/	
		Variance contribution/%	48.5	30.1	6.1	5.4	/	9.7
	DJF	Periond/year	2.9	5.8	16.8	44.7	/	
		Variance contribution/%	40.7	19.5	10.3	2.8	/	26.6
Northern Tianshan	MAM	Periond/year	2.8	6.2	10.5	22.7	/	
		Variance contribution/%	60.4	19.7	6.9	2.1	/	6.3
	JJA	Periond/year	2.9	6.7	13.4	44.7	/	
		Variance contribution/%	54.2	29.5	8.8	4.1	/	0.6
	SON	Periond/year	3.1	6.7	13.4	33.5	/	
		Variance contribution/%	65.8	15.1	9.7	6.1	/	3.4
	DJF	Periond/year	3.0	6.7	12.2	26.8	33.5	
		Variance contribution/%	39.0	25.2	9.0	1.9	0.1	24.9
Western Tianshan	MAM	Periond/year	3.1	6.4	12.2	26.8	/	
		Variance contribution/%	64.6	19.4	7.2	7.0	/	0.8
	JJA	Periond/year	3.0	6.1	13.4	44.7	/	
		Variance contribution/%	52.6	22.5	16.9	6.4	/	1.6
	SON	Periond/year	3.2	5.6	12.2	26.8	33.5	
		Variance contribution/%	70.4	20.6	5.8	2.0	1.0	0.2
	DJF	Periond/year	3.4	6.7	14.9	26.8	/	
		Variance contribution /%	60.3	18.0	12.0	1.9	/	4.5
Central Tianshan	MAM	Periond/year	3.2	7.4	13.4	33.5	/	
		Variance contribution/%	53.2	30.7	4.3	10.5	/	0.4
	JJA	Periond/year	3.1	5.8	13.4	22.3	/	
		Variance contribution/%	52.6	16.6	11.3	3.5	/	15.1
	SON	Periond/year	3.6	7.1	13.4	33.5	44.7	
		Variance contribution/%	43.8	28.7	8.3	0.9	0.0	18.3
	DJF	Periond/year	3.2	6.7	13.4	19.1	33.5	
		Variance contribution/%	59.0	13.6	19.8	3.0	0.5	4.1

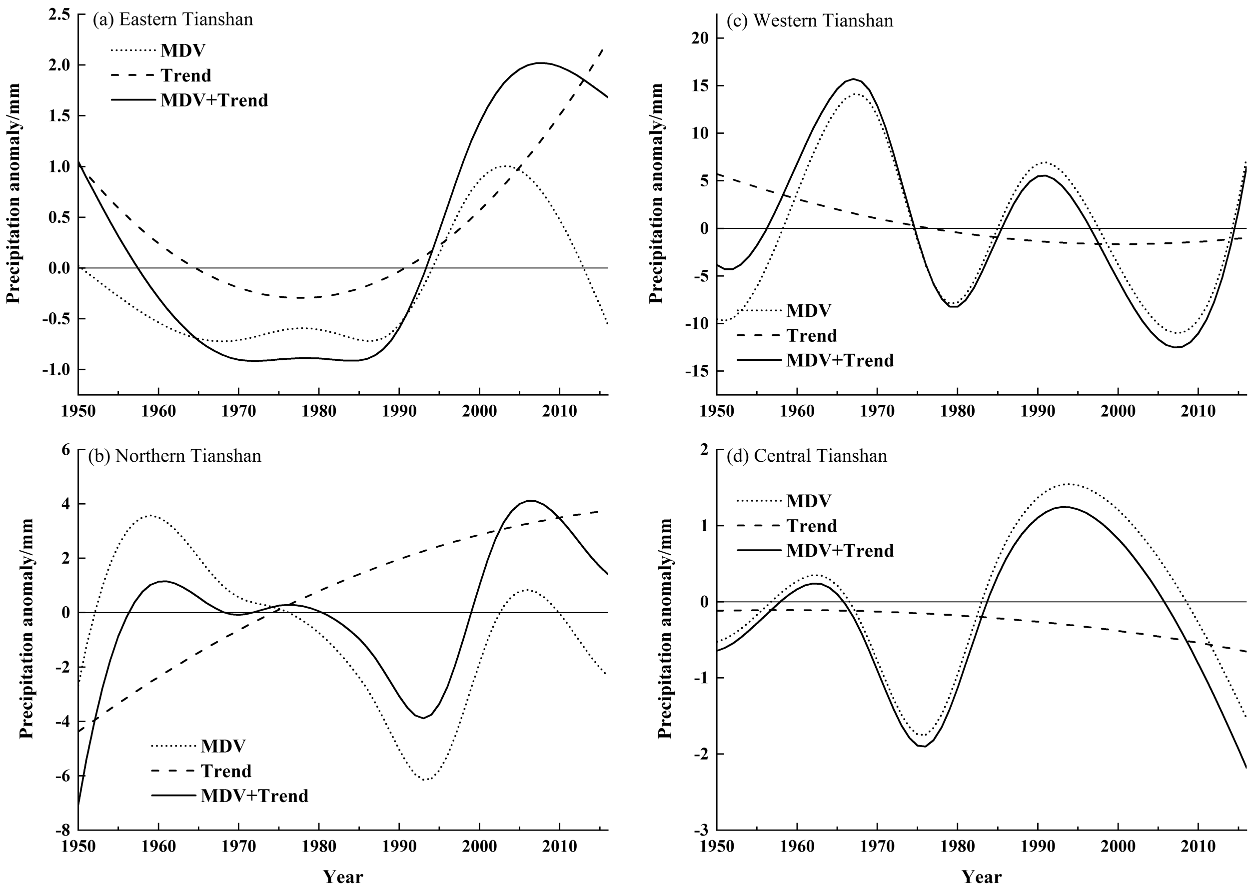

FIGURE 9 Characteristics of multi-decadal precipitation of the sub-regions of Tianshan in spring based on EEMD method. MDV represent the multi-decadal variability. MDV + trend indicates the multi-decadal change

In addition, the precipitation of Eastern, Northern, and Central Tianshan in winter all show significant non-linear increasing trends and entered a positive phase in 2004, 1983, and 1981, respectively (Figure 12a,b,d). By contrast, the winter precipitation in Western Tianshan decreased after 1971 and entered a negative phase in 1994 (Figure 12c). MDV plus trend shows that 1954–1968 was a dry period in Western Tianshan, and 1969–1979 and 1983–2007 were wet periods in winter.

4 | DISCUSSION

From 1950 to 2016, Tianshan showed an increasing trend of precipitation, which is in accordance with the increase of precipitation in Central Asia (Chen *et al.*, 2016; Hu *et al.*, 2017). However, although the annual and seasonal precipitation in most parts of Tianshan showed a significant upward trend, the annual and spring precipitation in Western Tianshan experienced decreasing trends in these 67 years according to the GPCC precipitation data. As the place with the highest precipitation in the Tianshan Mountains, Western Tianshan is extremely important for water resources in Central Asia. Accordingly, precipitation decreasing in Western Tianshan is clearly adverse effects on water resources in that region. Against the backdrop of continued warming in Central Asia, the decrease in precipitation will intensify the melting of glaciers and snow in Western Tianshan, accelerating the melting and shrinking of the 'solid water reservoir', which is mainly composed of glaciers and snow (Bolch *et al.*, 2009; Jacob *et al.*, 2012). There will be an increase in runoff in Western Tianshan in the short term due to the increase in snow and ice meltwater (Hagg *et al.*, 2007). However, in the long term, due to the reduction of glaciers reserves, there will be a general trend of decreasing river runoff under the conditions of continued warming and possibly further decreasing precipitation in the future (Sorg *et al.*, 2012; Chen *et al.*, 2017). In addition, in the region around Western Tianshan, the demand for water in cities such as Almaty, Bishkek, and Tashkent is growing at a high rate. The populations of these arid and semi-arid foothills are heavily dependent on the runoff to buffer the capacity of water for irrigation, industry, and hydropower (Bekturganov *et al.*,

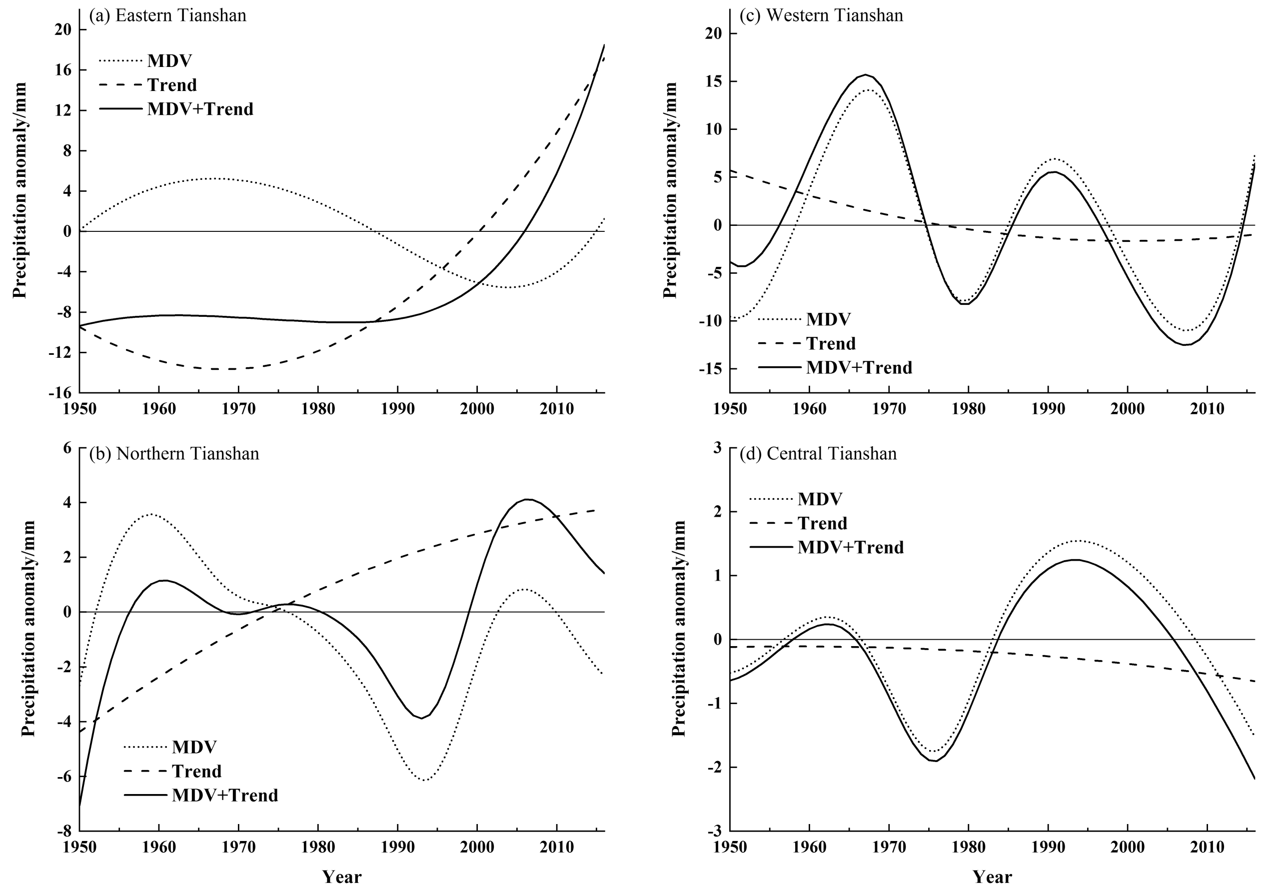

FIGURE 10 Characteristics of multi-decadal precipitation of the sub-regions of Tianshan in summer based on EEMD method. MDV represent the multi-decadal variability. MDV + trend indicates the multi-decadal change

2016; Xenarios *et al*., 2019). Reduced water availability will exacerbate water conflicts in the arid regions of Central Asia due to impacts of water shortage on the ecological, agricultural, social and economic levels, mitigation measures are required to compensate for changes in water availability (Sorg *et al*., 2012; Chen *et al*., 2020; Shahgedanova *et al*., 2020).

However, due to the poor availability of weather-station data and the different interpolation methods, different global reanalysis precipitation data show different results in Central Asia, especially in the driest deserts and the wettest alpine areas (Schiemann *et al*., 2008; Plessen *et al*., 2013). Many previous precipitation studies on Central Asia and Tianshan based on CRU precipitation data indicate that there is an increasing trend in Western Tianshan precipitation (Li *et al*., 2015; Chen *et al*., 2016; Chen *et al*., 2017; Dilinuer and Li, 2018), which contradicts our results. Hu *et al*. (2017), who also used GPCC precipitation data to study annual precipitation variations in Central Asia, exhibited that the precipitation in Western Tianshan has had a downward trend over the past few decades. Due to the differences between our results and previous research, we compared the linear trends of precipitation in the Central Asia area from 1950 to 2016 based on GPCC and CRU precipitation data, respectively. The linear trends of precipitation in Central Asia show relatively similar spatial distributions despite their differences in spatial resolution (Figure 13). However, the precipitation in the Western Tianshan calculated from CRU data displays a clear increasing trend (Figure 13a). Although the annual precipitation calculated from GPCC in the Fergana valley of Western Tianshan also shows an increasing trend, the precipitation in high-altitude mountainous areas of Kirgizsky Altoo and Hissor Range in Western Tianshan decreased (Figure 13b). Therefore, it is indispensable to further verify in future work whether decreasing trends in the high-altitude precipitation in Western Tianshan is due to the differences between reanalysis data sets.

The multi-scale oscillations of Tianshan precipitation obtained by EEMD are the result of the cyclical variations of the climate system under external forcing and its nonlinear feedback (Franzke, 2014). The high-frequency of 3- and 6- year signals are the dominant component of the Tianshan precipitation variability. Earlier studies suggested that precipitation in many regions includes a

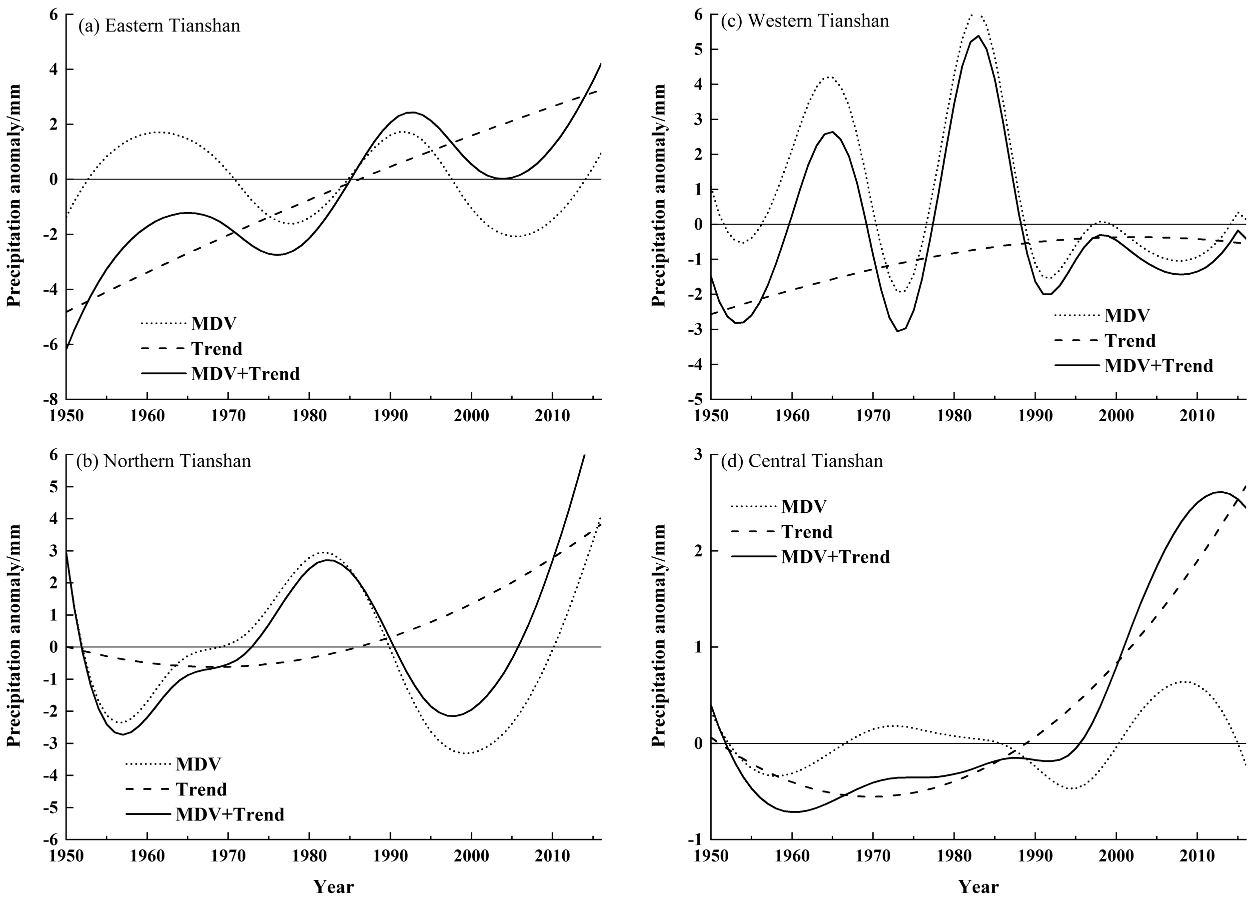

FIGURE 11 Characteristics of multi-decadal precipitation of the sub-regions of Tianshan in autumn based on EEMD method. MDV represent the multi-decadal variability. MDV + trend indicates the multi-decadal change

tropospheric biennial oscillation (TBO) signal with a quasi 2–3 year cycle (Mukherjee *et al.*, 1985). In the East Asian monsoon region, the TBO of precipitation is closely related to the Southern Oscillation which also shows a quasi 2–3 year cycle (Zhang *et al.*, 2000). Huang *et al.* (2013) stated that the westerly strength TBO in the upper troposphere may be an important factor in the precipitation in Central Asia. After analyzing the relationship between precipitation and El Niño Southern Oscillation (ENSO) in Central Asia, Hu *et al.* (2017) concluded that ENSO, which also has a quasi 6-years cycle characteristic, can explain 17% of the interannual variance of precipitation in Central Asia. The low-frequency variations with 12-year, 27-year quasi-periods of Tianshan annual precipitation may be closely related to sunspot numbers which have a well-known quasi 11-years period and the quasi 22-years magnetic period (Hancock and Yarger, 1979; Wang and Zhao, 2012). On the multi-decadal scale, the positive trend of precipitation in the entire Tianshan is more obvious after the 1980s. Eastern, Northern, and Central Tianshan all entered a humid period in the 1980s and 1990s. This phenomenon of 'humidification' is not isolated and is closely related to the accelerated water cycle driven by significant global warming in the 1980s and 1990s (Solomon *et al.*, 2010). The raised temperature in Central Asia accelerated evaporation and evapotranspiration, resulting in an increase in the water vapour content (Yang *et al.*, 2011; Guan *et al.*, 2019), which give rise to the formation of local precipitation (Lioubimtseva and Henebry, 2009). Additionally, the gradually stronger southerly winds caused by rising temperatures accelerated the northward moisture transport from the Bay of Bengal, the South China Sea, and the Arabian Sea (Shi and Xu, 2008; Lehmann *et al.*, 2015). Meanwhile, the thermal difference between the Tibet Plateau and the Iranian Plateau also triggers the meridional moisture transport which has an impact on the precipitation in the Tianshan Mountains (Qian *et al.*, 2002; Liu *et al.*, 2012). Our analysis is based on trying to understand the nonlinear changes and the multi-decadal oscillations of the precipitation in Tianshan. In this study, the EEMD method was used to decompose not only the non-linear trends of the Tianshan precipitation changes but also to extract the oscillations of its interannual and interdecadal

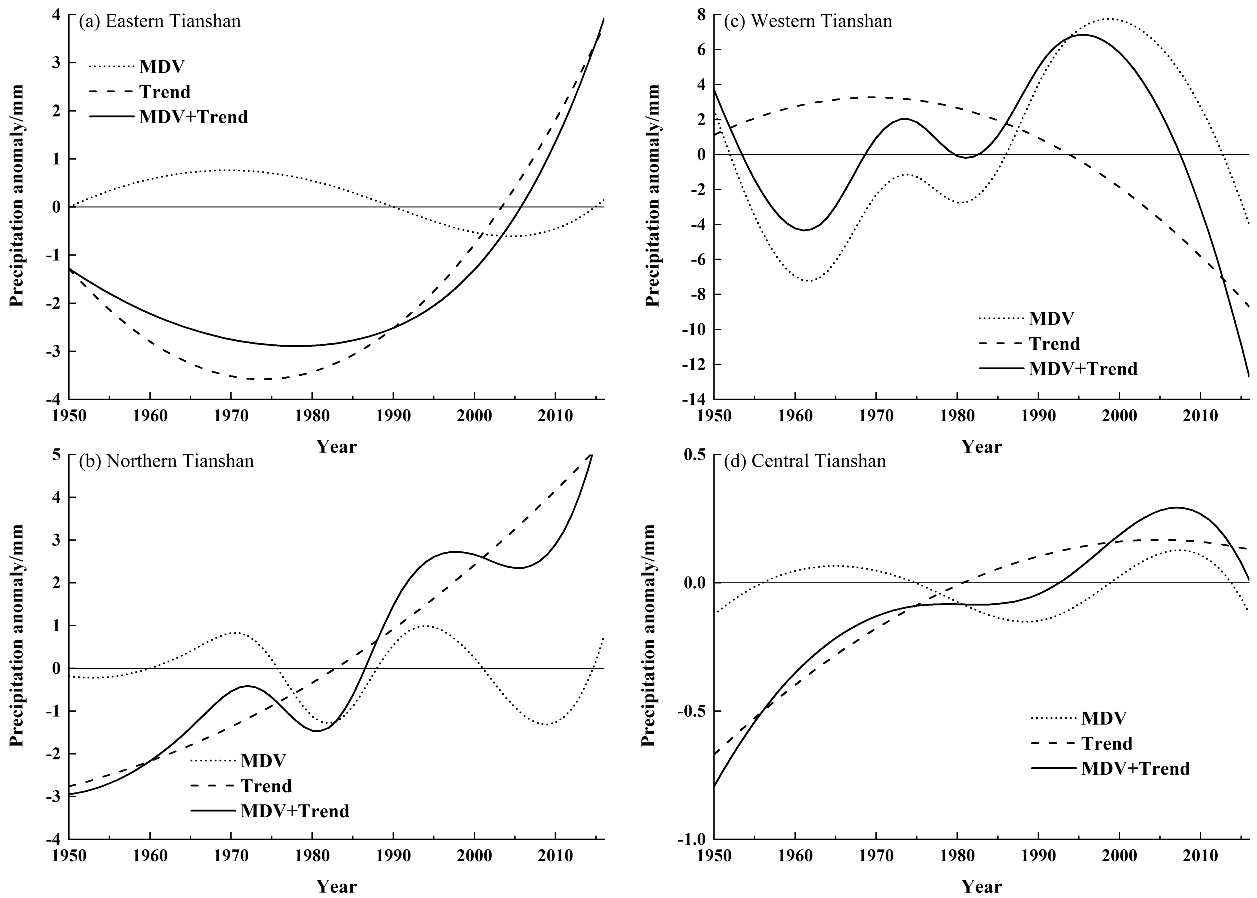

FIGURE 12 Characteristics of multi-decadal precipitation of the sub-regions of Tianshan in winter based on EEMD method. MDV represent the multi-decadal variability. MDV + trend indicates the multi-decadal change

variability—a feature which cannot be fully reflected by methods dealing with linear trends only. The EEMD method in contrast can effectively identify the periodicity and non-linear trends of climate sequences. This study focuses on the multi-scale characteristics and trends of precipitation over the Tianshan Mountains. The relationship between the variability of precipitation in the Tianshan Mountains and the atmospheric circulations will be further analyzed in a second publication (Part II).

5 | CONCLUSION

In this study, the temporal variations of the annual and seasonal precipitation over Tianshan Mountains on different time scales during 1950–2016 are analyzed in a meticulous way based on the EEMD method by using the GPCC precipitation data set. The annual precipitation of the entire Tianshan had a weakly increasing trend with a rate of 0.90 mm per decade. Tianshan entered a period of excessive precipitation after 1986 but no abrupt change occurred. The annual precipitation in Northern Tianshan, Central Tianshan, and Eastern Tianshan showed a significant upward trend while Western Tianshan experienced decreasing annual precipitation and greater volatility. The annual precipitation in Tianshan clearly had high-frequency variations (3- and 6-year quasi-periodic fluctuations) and low-frequency variations (12-, 27- quasi-periodic fluctuations) during 1950–2016. The inter-annual components with the periods of quasi 3-year and quasi 6-year can be extracted as the dominant components of the annual precipitation in all four regions of Tianshan. On the multi-decadal time scale, dry periods in the Tianshan Mountains were from 1950 to 1962 and from 1973 to 1984, respectively and wet periods were from 1962 to 1972 and from 1985 to 2016, respectively. Besides, Tianshan has experienced a tendency of continuous humidification since 2004. Eastern Tianshan, Northern Tianshan, and Central Tianshan presented non-linear growth trends, which all entered the period of positive precipitation anomaly around the 1980s and 1990s. Although precipitation in West Tianshan has been showing a downward trend, there has not yet been a transition into the negative phase of

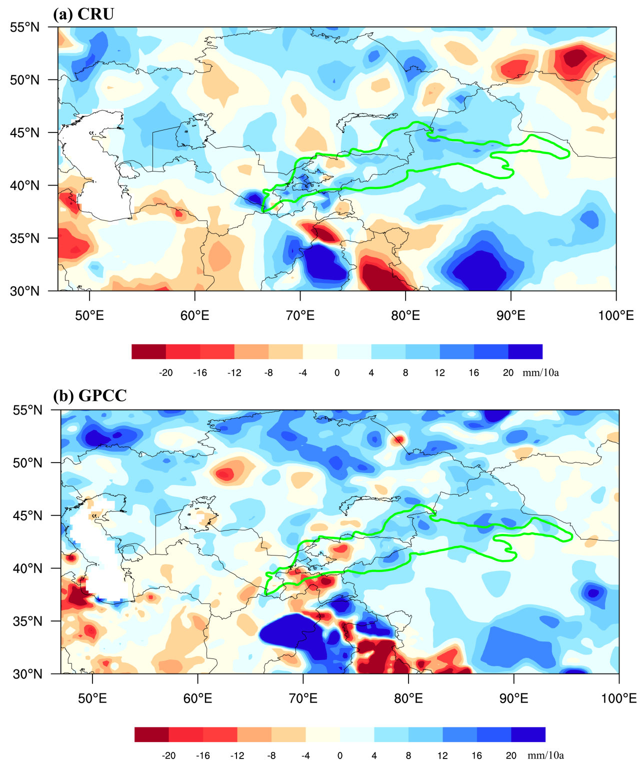

FIGURE 13 Linear trend (units: mm·10a^{-1}) of annual precipitation in Central Asia area during 1950–2016 based on (a) GPCC precipitation data, (b) CRU precipitation data. The area of the Tianshan Mountains in (a) and (b) is delineated with a green polygon [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation according to the long-term trend as revealed with the EEMD method.

Precipitation over the Tianshan Mountains has a strong seasonality and is generally concentrated in spring and summer. The seasonal precipitation in the Tianshan Mountains also displayed fluctuations on an inter-annual scale (3- and 6-year quasi-periodic) and a multi-decadal scale (12-, 27-, 34-, and 48-quasi-periodic) during the 67 years of the study period. There is a significant difference in seasonal precipitation variabilities among the four sub-regions of the Tianshan Mountains. As the precipitation showed a significant upward trend in all seasons, Eastern Tianshan entered humid periods in 1994 (spring), 2006 (summer and winter), and 1986 (autumn). Similarly, due to the upward trends of precipitation, the spring, autumn, and winter of Northern Tianshan have been in humid periods since 1999, 2006, and 1987, respectively. The slight declining trend of summer precipitation together with the multi-decade variability of precipitation caused Northern Tianshan to enter a period of drought in summer after 2011. The precipitation over Central Tianshan presented increasing trends in all seasons except in spring. Around the 1990s, Central Tianshan was in humid periods in summer, autumn, and winter. The precipitation over Western Tianshan showed an upward trend in summer and autumn but a downward trend in spring and winter. With humid period in summer since 1985, Western Tianshan was in dry periods for the other seasons during 1997–2014 (spring), 1989–2016 (autumn), and 2008–2016 (winter).

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AUTHOR CONTRIBUTIONS

Xuefeng Guan: Conceptualization; formal analysis; investigation; methodology; resources; visualization; writing-original draft. **Junqiang Yao:** Data curation; software. **Christoph Schneider:** Supervision; validation; writing-review & editing.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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