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An analysis of precipitation variations in the west-central Tianshan Mountains over the last 300 years

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A B S T R A C T

Tree-ring based precipitation/PDSI series from six sites were applied to reconstruct the regional precipitation (dry/wet) index for the west-central Tianshan Mountains for the last 300 years. The analysis of the reconstructed index series indicates that the dry and wet years in the whole time period were almost equal in frequencies. The results show that the 300-year period is characterized by a series of dry/wet stages, including six dry stages (1707–1719, 1768–1782, 1822–1832, 1880–1886, 1913–1924 and 1973–1989) and five wet stages (1723–1741, 1843–1857, 1893–1907, 1933–1940 and after-1990 period). The reconstructed regional precipitation (dry/wet) series also exhibits quasi-periodicities of 2–5 y, 7–8 y, 11 y, 30 y, 50 y and 80 y, with the 11 y, 30 y and 50 y quasi-periodicities being more significant. Shifts from dry to wet climate occurred in 1720, 1779 and 1886, and the shifts from wet to dry climate occurred in 1741, 1854 and 1904. In addition, the analysis also indicates that solar activities might have significantly affected the regional precipitation (dry/wet) variability on ~10 y scale during 1770s–2000s. The effects of solar activities on annual precipitation in the Tianshan Mountains are more complicated than expected, and the complexity might be associated with a number of unknown processes.

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1. Introduction

The Tianshan Mountains of northwestern China extend for over 1700 km from west to east and 250–300 km from south to north, with an average elevation of approximately 4000 m above sea level (Hu, 2004). The mountains divide Xinjiang Uyghur Autonomous Region into two regions (southern and northern) with different climatic and environmental characteristics, and they are also the sources of several important inland rivers in northwestern China and central Asia. Thus, the climatic conditions and climatic variability in the Tianshan Mountains are very important for the protection of ecosystems and environment as well as the sustainable development in the region (Wang et al., 2004a; Jin et al., 2005; Zhang et al., 2009).

The regional climate and recent climatic variations in northwestern China, including the Tianshan Mountains, have been extensively investigated. The previous studies revealed an evident climatic shift from dry-cold to wet-warm conditions around the end of 1970s and showed that the surface air temperature and precipitation significantly increased over the past more than 50 years (Ren et al., 2000, 2005, 2007; Shi et al., 2000, 2003; Hu et al., 2002; Li et al., 2003). However, the short meteorological records (generally less than 60 years) available for the region do not permit to adequately depict the features of long-term climatic variability, particularly the features of precipitation in the region. To better understand the climatic regimes of the mountainous regions, it is necessary to obtain proxy data of the past climatic variations.

Tree-ring records have advantages of high temporal resolution and climatic sensitivity, and can thus provide useful information on long-term climatic fluctuations. In the last decade, dendroclimatic research has expanded rapidly in investigating large-scale climate variations with temporal ranges extending from hundreds to thousands of years in China, especially on the Tibetan Plateau and Northwest China (Shao et al., 2005; Chen et al., 2010; Fang et al., 2010; He et al., 2014; Wang et al., 2014; Yang et al., 2014). The proxy climatic records from northwestern China were compared with those from other regions of China and also from other regions of the Asian continent, and the comparisons revealed the regional difference of the long-term precipitation variations and also made it possible to place the recent climatic trends in a longer-term

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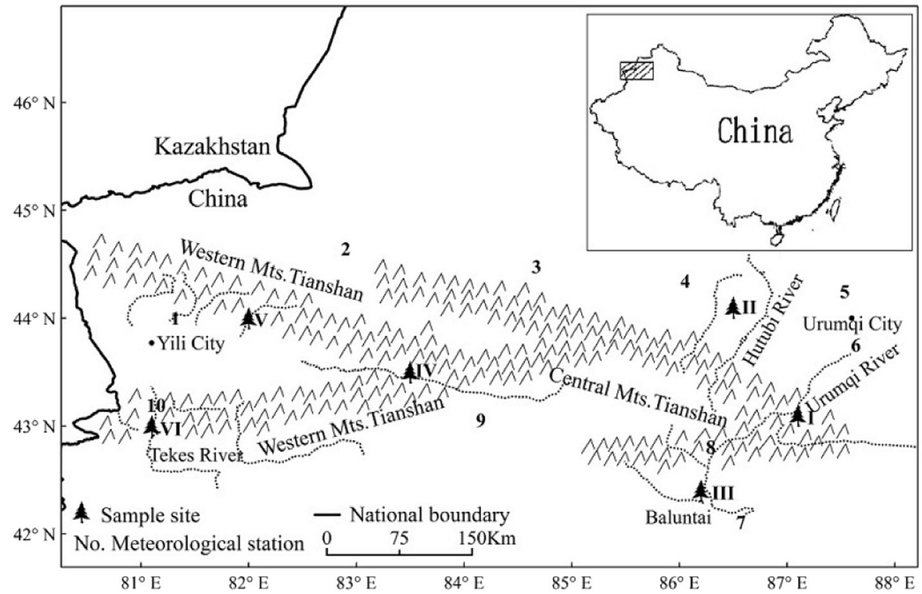

Fig. 1. Locations of the sampling sites and of nearby meteorological stations: Site I: Urumqi River Basin; Site II: Hutubi River Basin; Site III: Baluntai Area; Site IV: Nilka County; Site V: Yili Region; Site VI: Tekes River Basin. Meteorological stations: No.1: Yining; 2: Jinghe; 3: Wusu; 4: Shihezi; 5: Caijiahu; 6: Urumqi; 7: Yanqi; 8: Baluntai; 9: Bayinbuluke; 10: Zhaosu.

context of climatic variability. These long-term records have also been used for investigating the relationships of the past climatic variability with external factors (Huang and Shao, 2005) and also with internal ocean-atmospheric modes such as the Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO) (Wang et al., 2014).

Dendroclimatological studies have also been carried out in different areas of the Tianshan Mountains (Yuan et al., 2001a, 2003; Wang et al., 2005, 2007; Yu et al., 2005; Li et al., 2006; Cui et al., 2007; Pan et al., 2007; Xu et al., 2009; Shang et al., 2010). The changes in precipitation or dry-wet patterns over the past several centuries have been reconstructed and analyzed in those studies. However, most of the previous studies focused on only one site or a small area and very few of the studies were conducted on a larger spatial scale (Wei et al., 2008). It is apparent that integrated analyses for the larger regions using proxy data from more sites are needed to better understand the temporal characteristics of precipitation variability in the entire mountainous region.

In this paper, we report a 300-year precipitation (dry/wet) index series for the west-central Tianshan Mountains derived from six reconstructed climatic data series which represent different areas from west part to central part of the Tianshan Mountains. Characteristics of long-term dry-wet variations are examined based on the precipitation (dry/wet) series. Furthermore, the possible linkages of the regional precipitation variations with the solar activities are discussed.

2. Data and methods

2.1. Study region and climate

The west-central Tianshan Mountains, characterized by a complex topography, are located in northwestern China (Fig. 1). Precipitation in the study region is mainly affected by the prevailing westerlies and the elevations greatly enhanced the precipitation through orographic processes, with the western parts and higher elevations having more precipitation. Our tree-ring study target is *Picea schrenkiana*, the dominant forest species in the middle and upper zones of the Tianshan Mountains, accounting for about 61% of the timber stock and about 45% of forested land in the entire Xinjiang region. The tree-ring samples of the reconstructed series for all sites were collected from the *Picea schrenkiana* forests.

We used monthly total precipitation data from 10 meteorological stations around the study region (Fig. 1) for testing the sensitivity of tree-ring to precipitation. It is clear that the monthly precipitation conditions differ from the western part to the central part (Fig. 2). The largest monthly precipitation appears in summer at some stations (e.g., Baluntai and Zhaosu stations), but it occurs in spring at others stations. The annual precipitation and its variations with time for each of the stations were shown in Fig. 3. The annual values and the variances for the 10 stations are different, indicating a distinctive spatial heterogeneity of precipitation in the region. However, the annual precipitation for all the sites display evident upward trends in the recent 60 years, consistent with the results based on a dataset from more meteorological stations in the Tianshan Mountains (Zhang et al., 2013).

2.2. Series collection

Five high-resolution precipitation records and one Palmer Drought Severity Index (PDSI) record reconstructed using tree-ring data for the west-central Tianshan Mountains were collected. These datasets are independent, and each covers a distinct area with no overlap with others (Fig. 1 and Table 1). Two series for the Urumqi River Basin and the Baluntai Area were based on residual chronologies and the others on standard chronologies. For reconstructing the six series, two methods, leave-one-out and cross-validation, were employed to examine the stability and reliability of the transfer functions used in the calibration period. Other single-site proxy data series and regional reconstructions were used for validating the reconstructed series in the original studies. The explained variances for the original reconstructions range from 36% to 62%, indicating that they can fairly represent the observed precipitation or wetness at the sites.

Table 1
Tree-ring based data sources and the reconstructed timespan (i.e., months) of precipitation/PDSI index.

No.	Site	Latitude	Longitude	Reconstruction index	Time span	Chronology type	Explained variance	References
I	Urumqi River Basin	43.1°N	87.1°E	Precipitation July–February	1646–1993	RES	62%	Yuan et al., 2001b
II	Hutubi River Basin	44.1°N	86.5°E	Precipitation August–July	1691–2003	STD	41%	Chen et al., 2009
III	Baluntai Area	42.4°N	86.2°E	Precipitation July–June	1360–2004	RES	53%	Zhang et al., 2011
IV	Nilka County	43.5°N	83.5°E	Precipitation July–August	1671–2006	STD	36%	Zhang et al., 2010a
V	Yili Area	44.0°N	82.0°E	PDSI January–August	1652–2005	STD	49%	Chen et al., 2011
VI:	Tekes River Basin	43.0°N	81.1°E	Precipitation July–June	1770–2006	STD	54%	Chen et al., 2010

RES: residual chronology; STD: standard chronology.

The five precipitation series in Table 1 were reconstructed for different timespans (months) of a year according to the highest correlations between tree-ring data and the instrumental records. An issue is whether or not the precipitation in these reconstructed timespan (i.e., months) can well represent that for the whole year. Correlation analysis was thus conducted to examine the relationship between the accumulative precipitation of different months and the annual total precipitation over the instrumental period for the individual sites (Table 2). The analysis demonstrated generally high correlations, implying that the precipitation in the months could be regarded as a proportional representative of the annual total precipitation to a large extent. This can be explained by the fact that the months originally chosen for reconstructions are mostly within the rainy seasons of the sites.

2.3. Reconstruction and analysis methods

We performed the following steps to reconstruct the regional mean annual precipitation (dry/wet) index for the west-central Tianshan Mountains over the past 300 years:

(1) Determination of length of the data series: the beginning year was set at 1700, and the end year at 2003, with the entire length of 304 years. It should be noted that one series (Tekes River Basin) has a later beginning year (1770) and one series (Urumqi River Basin) has an earlier end year (1993);
(2) Standardization of the data: all of the reconstructed precipitation (dry/wet) data series for the 6 sites were standardized for the sake of comparability;

Table 2
Correlation coefficients between the precipitation values of varied months and the annual values from nearby meteorological stations.

Site	Urumqi River Basin	Hutubi River Basin	Baluntai Region	Nilka Country	Tekes River Basin
Meteorological station	Urumqi	Shihezi	Baluntai	Jinghe, Yining, Zhaosu	Zhaosu
Varied months	July–February	August–July	July–June	July–August	July–June
Period	1951–1993	1954–2003	1958–2004	1956–2006	1956–2006
Corr. coefficient	0.852[a]	0.754[a]	0.639[a]	0.641[a]	0.520[a]

[a] The correlation is significant at the 0.01 level (two-tailed).

The PDSI is a measure of dryness (or wetness) based on recent precipitation and temperature data (Palmer, 1965). Many studies (Cook et al., 2004; Esper et al., 2007; Liang et al., 2007; Wang et al., 2008) have shown that the index is acceptable in identifying long-term meteorological drought. Zhang et al. (2010b) suggested that precipitation plays a greater role in the formation and development of drought than temperature in northwestern China. In the west-central Tianshan Mountains, therefore, the reconstructed PDSI series is more or less suitable for representing past precipitation (dry/wet) variation.

The correlations between each of the six reconstructed precipitation/PDSI series were shown in Table 3. Most of the correlations are statistically significant, with those of the Hutubi River Basin with all other sites being significant at the 0.01 confidence level. The results also indicate that the precipitation (dry/wet) changes in different regions in the west-central Tianshan Mountains were affected not only by local climatic characteristics but also by regional climatic variability, as indicated by the upward trends of annual total precipitation of the 10 meteorological stations in the region.

Table 3
Correlation coefficients between each of the reconstructed precipitation/PDSI series.

Series no.	I	II	III	IV	V	VI
I	1					
II	0.167[a]	1				
III	0.072	0.418[a]	1			
IV	0.055	0.263[a]	0.330[a]	1		
V	0.148[a]	0.231[a]	0.176[a]	0.114	1	
VI	0.077	0.427[a]	0.430[a]	0.250[a]	0.393[a]	1

Site names and periods of the series are shown in Table 1.
[a] The correlation is significant at the 0.01 level (two-tailed).

(3) Calculation of regional average precipitation (dry/wet) series: the standardized precipitation (dry/wet) of the 6 sites was averaged arithmetically to obtain a regional average annual precipitation (dry/wet) series.

Eleven-year running average was calculated for indicating the low-frequency variations and power spectrum analysis was applied for examining possible periodicities of the regional reconstruction. Wavelet analysis was also conducted using a Morlet wavelet to investigate periodicities of the reconstructed. The cross wavelet transform was used to explore the linkage between the reconstructed series and solar activity. The details of the calculation methods can be found in von Storch and Zwiers (2003).

3. Results

3.1. Verification of reconstruction

To determine whether the reconstruction was reliable or not, comparisons of the reconstructed regional precipitation (dry/wet) series with observational data and the previous reconstruction by Wei et al. (2008) were made. The annual precipitation records from the 10 stations shown in Fig. 1 were also standardized and averaged to represent the regional climate condition. The reconstructed precipitation (dry/wet) index series in the present study is well consistent with the observational data for the time period from 1960 to 2003 (Fig. 4) and also with the previous reconstruction for time period from 1770 to 2003 (Fig. 5). For the calibration period (1960–2003), the explained variance of the reconstruction is 34% between the reconstruction and observation. The positive correlations between the reconstruction and observation for period of 1960–2003 and between the two reconstructions for the period of 1770–2003 are all statistically significant (Table 4), although some differences exist in inter-annual variability for the two periods. The differences from the previous reconstruction may result from the differences in spatial extents and in the lengths of chronologies.

Table 4
Correlation coefficients of the present reconstruction with observational records and the reconstruction by Wei et al. (2008).

	Observation	Wei's reconstruction
Corr. coefficient	0.599[a]	0.690[a]
Period	1960–2003	1770–2003

[a] The correlation is significant at the 0.01 confidence level (two-tailed).

The reconstructed precipitation (dry/wet) series also captured the climatic signal of the significant increase of annual total precipitation since 1980s for the study region and also for northwestern China as a whole (Ren et al., 2000, 2005; Shi et al., 2000, 2003). The decadal variations in the reconstruction after 1950s are generally consistent with the results reported by Zhang et al. (2013). Furthermore, the decadal dry periods identified in this study are also well consistent with those reported by Wang et al. (2004b) using such proxy records as ice cores and lake sediments. Overall, the reconstructed precipitation (dry/wet) series presented in this paper is quite reasonable and thus acceptable, and it can represent the regional average annual total precipitation (dry/wet) variations in the west-central Tianshan Mountains.

3.2. Annual to multi-decadal variability

Fig. 6 shows the annual precipitation (dry/wet) index series reconstructed for the west-central Tianshan Mountains for the past 300 years. The standard deviation (δ) of the index series was 0.596. Adopting the criterion developed by the Chinese Academy of Meteorological Science (1981), we classified the regional annual precipitation (dry/wet) into five grades: the values of -0.33δ to 0.33δ representing normal precipitation condition; the values of 0.33δ to 1.17δ wet condition; -1.17δ to -0.33δ dry condition; the values of $>1.17\delta$ very wet condition; and $<-1.17\delta$ very dry condition (Fig. 6 and Table 5). There were 113 wet (including very wet) years, 111 dry (including very dry) years, and 80 normal years in the whole time period, accounting for 36.9%, 36.3% and 26.3% of the entire timespan (i.e., 304 years) (Table 5).

Table 5
Numbers of years and the percentages of different grades of precipitation in the west-central Tianshan Mountains during 1700–2003.

	Very dry	Dry	Normal	Wet	Very wet
Criterion	$<-1.17\delta$	-1.17δ to -0.33δ	-0.33δ to 0.33δ	0.33δ to 1.17δ	$>1.17\delta$
No. of years	34	77	80	79	34
Percentage (%)	11.2	25.3	26.3	26	11.2

Three significant extreme events were identified before the instrumental-recording period (Fig. 6), including extreme drought years of 1917–1918 and 1943–1945, and the extremely wet year of 1941–1942. These abnormal events have been described from the historical documents. For example, in 1917 and 1918, the entire Xinjiang region was affected by the severe drought and the crops were almost completely failed in most of the counties, as recorded in the official documents of Republic of China. In 1941 and 1942, at least 20 counties in northern Xinjiang including Yining, Hutubi and Urumqi in the Tianshan Mountains were flooded according to the description of the official documents (Liu, 1999).

Decadal variability was highlighted by applying an 11-year running average to the reconstruction. Six dry periods and five wet periods were distinguished. The dry periods were 1707–1719, 1768–1782, 1822–1832, 1880–1886, 1913–1924 and 1973–1989 and the wet periods were 1723–1741, 1843–1857, 1893–1907, 1933–1940 and after 1990. It is noticeable that the last dry period (1973–1989) and the last wet period (after 1990) were among the driest and wettest ones during the 304-years period (Ding and Ren, 2008). The fertilization effect of the increasing atmospheric CO_2 concentration in the past decades might have played a role in the increased width of the tree-rings (Briffa et al., 1998, 2000).

3.3. Periodicities

A power spectrum analysis was conducted to examine the possible periodicities in the precipitation (dry/wet) index series (Fig. 7). The results revealed spectral peaks at 50.9 y, 29.1 y, 12 y, 11.2 y, 9.9 y, 8.2 y, 7.8 y, 7.1 y, 5.9 y, 4.9 y, 4.5 y, 4 y, 3.4 y and 2.1 y over the past 300 years. The peaks at 10–12 y are well consistent with the 11-y cycle of solar activity, and those at 2–8 y fall within the range of inter-annual variability of the Quasi-biennial Oscillation (QBO) and the El Niño-Southern Oscillation (ENSO) (Yang et al., 2005; Hao et al., 2007; Shi et al., 2007; Tian et al., 2012; Chen et al., 2013). These quasi-periodicities may suggest a strong modulation due to naturally external driver and a close teleconnection with ENSO variability. The quasi-30 y and quasi-50 y cycles were also found in previous studies in other regions of China (e.g., Qian et al., 2011; Ren et al., 2011).

The temporal characteristics of the various cycles were also revealed through wavelet analysis as illustrated in Fig. 8. It is noticeable that a quasi-100 y cycle was attenuated to a quasi-80 y cycle over the entire investigated period. Furthermore, a 60–70 y cycle was attenuated to a 40–50 y cycle from the 1700s–1870s and then increased to a 50–60 y cycle after the 1900s. A quasi-30 y cycle was detected from the 1700s–1770s and the 1830s–1900s, which subsequently increased to a 30–40 y cycle. The wavelet variance shows that the quasi-50 y cycle is the most robust, followed by the quasi-30 y and then quasi-10 y cycles. These findings, with the exception of the 80–100 y cycle, were also confirmed through power spectrum analysis.

In a study focusing on the correlations of the eastern China Flood/Drought index with North Atlantic Oscillation (NAO) index, quasi-50 y, quasi-30 y and quasi-10 y cycles, in addition to a quasi-80 y cycle, were also reported (Fu and Zeng, 2005). Regarding the quasi-30 y and quasi-80 y cycles of summer and annual precipitation, Pacific Decadal Oscillation (PDO) was found to coincide with the signals of these two cycles in the middle and lower Yellow River (Hao et al., 2007). These linkages may suggest that the precipitation or dry/wet variation in most regions of China including the Tianshan Mountains might have been affected in some extents by the low-frequent variability of atmospheric-ocean oscillations.

3.4. Abrupt changes

By using a moving mean *T*-test method, the possible abrupt changes or shifts in the reconstructed precipitation (dry/wet) index series were analyzed. Table 6 shows that there occurred six shifts of annual precipitation in the study region over the past 300 years. Years with shifts from dry to wet were 1720, 1779, and 1886, and those from wet to dry were 1741, 1854, and 1904.

Table 6
Years with abrupt changes in the reconstructed precipitation (dry/wet) index series.

Year	1720	1741	1779	1854	1886	1904
Change	dry → wet	wet → dry	dry → wet	wet → dry	dry → wet	wet → dry

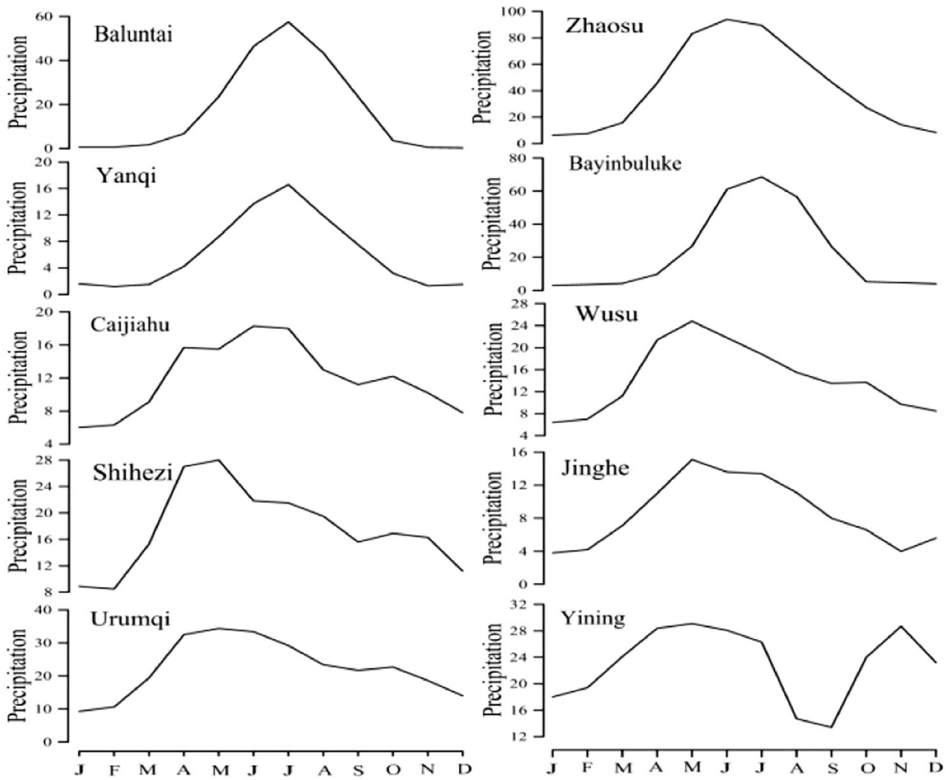

Fig. 2. Monthly precipitation of the 10 meteorological stations for the period 1951–2013 (Unit: mm).

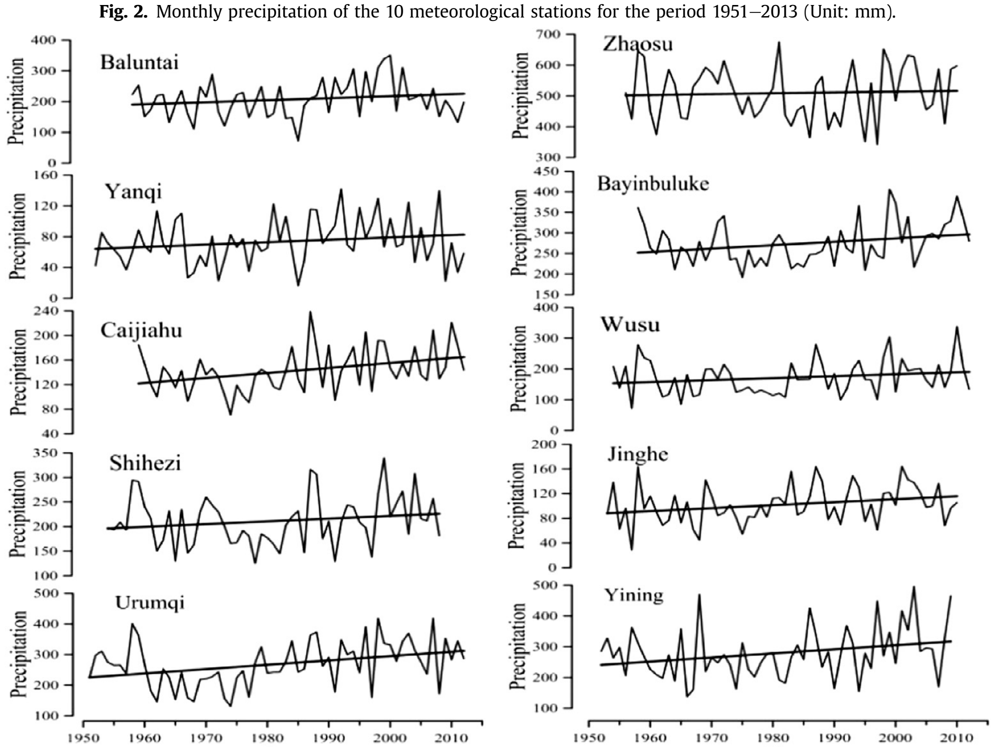

Fig. 3. Annual precipitation variations of the 10 meteorological stations and the linear trend lines for the period 1951–2013 (Unit: mm).

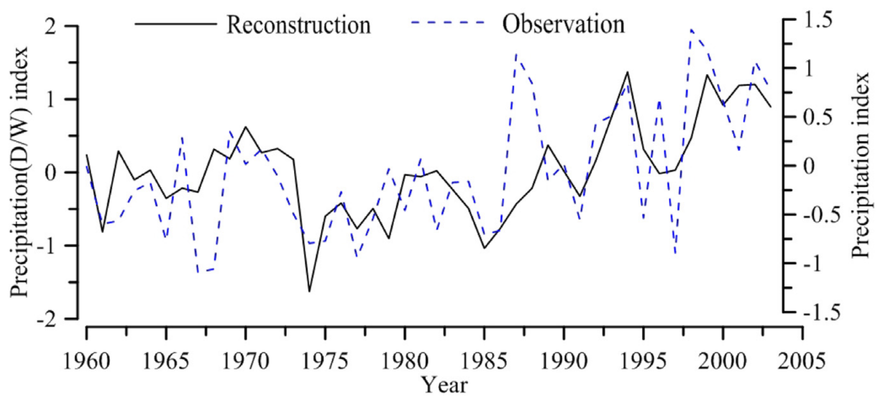

Fig. 4. Comparison of the annual precipitation (dry/wet) between the reconstruction and observation (1960–2003).

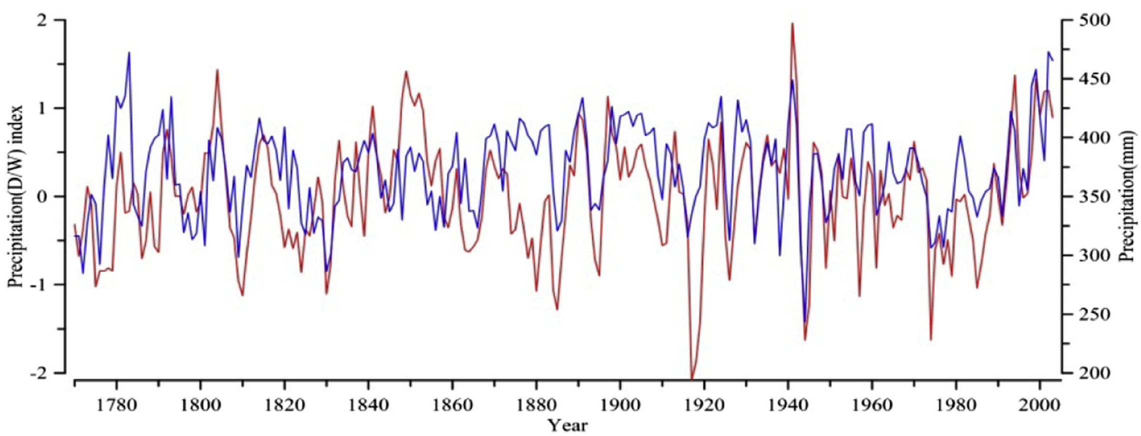

Fig. 5. Comparison between this reconstruction (red) and the reconstruction by Wei et al. (2008) (blue) (1770–2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Linkages to solar activity

A number of studies have demonstrated that periodic solar activities can affect climatic variations in direct and/or indirect ways (Feng et al., 1998; Han and Han, 2002; Krivova and Solanki, 2002; Le and Wang, 2004). The relationship between the reconstructed precipitation (dry/wet) index series and number of sunspots was examined, and the potential effects of solar activities on the precipitation variation in the west-central Tianshan Mountains were discussed. The sunspots relative number was used in this paper as a proxy to indicate the solar activities. Data of the annual sunspot relative number over the period 1700–2003 were obtained from the Solar Influences Data Analysis Center (SIDC) (http://www.sidc.be/silso/DATA/yearssn.dat).

Comparison between the precipitation (dry/wet) index series and the sunspot relative number series shows that the years with higher precipitation can appear at any years of (e.g., peaks, valleys and peak-to-valley transitions) the sunspot relative numbers. It is therefore difficult to find a clear relationship between the precipitation (dry/wet) and the sunspots or solar activities in the west-central Tianshan Mountains on annual to inter-annual scales (Fig. 9), although previous studies (Xu et al., 1998; Dong et al., 1999) claimed that droughts were more common when solar activities are weak in northwestern China. However, the two time series are indeed in conformity in some extents on decadal to multi-decadal

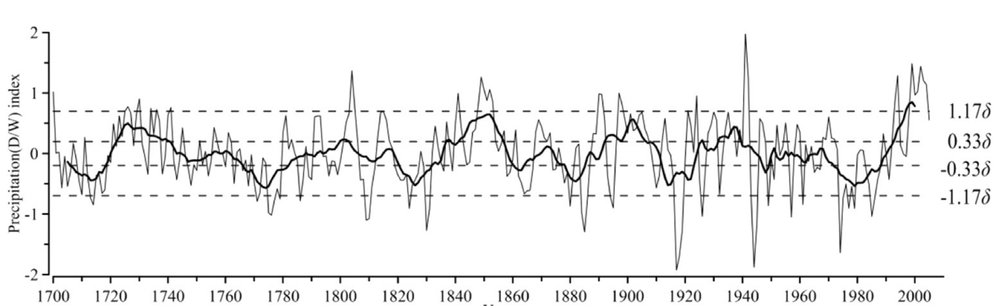

Fig. 6. Reconstructed annual precipitation (dry/wet) index (thin solid line) and 11-year running averages (thick solid line) in the west-central Tianshan Mountains during 1700–2003.

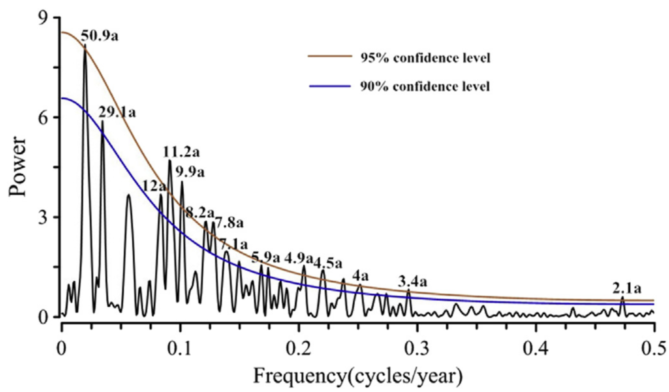

Fig. 7. Power spectrum of the reconstructed precipitation (dry/wet) index (1700–2003).

scales with the more precipitation generally occurring in the more active periods of the sun. Good examples are the relatively wet periods of 1720–1750, 1835–1860 and 1935–1960 when the sunspot relative numbers are in their higher levels.

Similar to the precipitation (dry/wet) index, the sunspot relative number series was decomposed using the wavelet analysis. This analysis revealed remarkable periodic variations and quasi-100 y, quasi-50 y, 30–40 y and 11 y cycles. The cross wavelet transform of the reconstructed precipitation (dry/wet) index and the sunspot relative number is shown in Fig. 10. There exists a significant relationship in the ~10 year band from the 1770s–2000s. The arrows show an in-phase relationship from the 1800s–1860s and after 1940s and an anti-phase relationship from the 1890s–1930s on time scale of quasi-10 y, an in-phase relationship from the 1700s–1950s and an anti-phase relationship after 1960s on time scales of 50–60 y, and an in-phase relationship in the 18th century and an anti-phase relationship since 19th century on time scale of quasi-100 y.

During the period 1700–2003, there is no significant correlation between the annual precipitation (dry/wet) index and the sunspot relative number. As pointed out above, however, the two time series share ~10 y and ~50 y quasi-periods, implying possible impacts of the solar activities on precipitation variations on decadal to multi-decadal time scales.

Fig. 11 shows the temporal changes in the real-part coefficients of the precipitation (dry/wet) index and the sunspot relative number on different time scales. On the two scales of 10 years and 50 years, the relationships between the two time series are relatively fair, with the correlation coefficient is 0.133 (significant at the 0.05 confidence level) on the 10 y scale, and as high as 0.368 (significant at the 0.01 confidence level) on the 50 y scale. Furthermore, there are different correlations within different time phases. For example, on the 10 y scale, there is a negative correlation in 1700–1819 (−0.038) and 1895–1935 (−0.795), but a positive correlation in 1820–1890 (0.383) and 1935–2003 (0.558), showing that the impacts of solar activities on annual precipitation in the

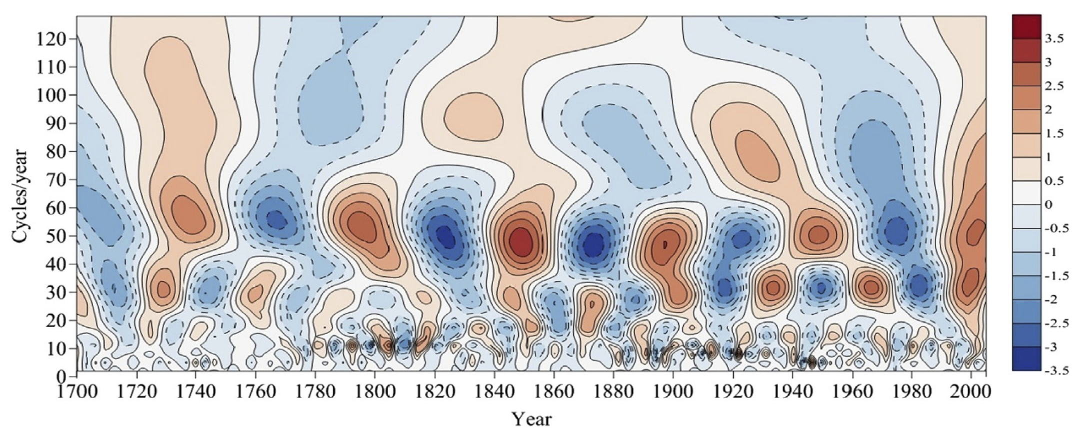

Fig. 8. Wavelet analysis of the reconstructed precipitation (dry/wet) index (1700–2003).

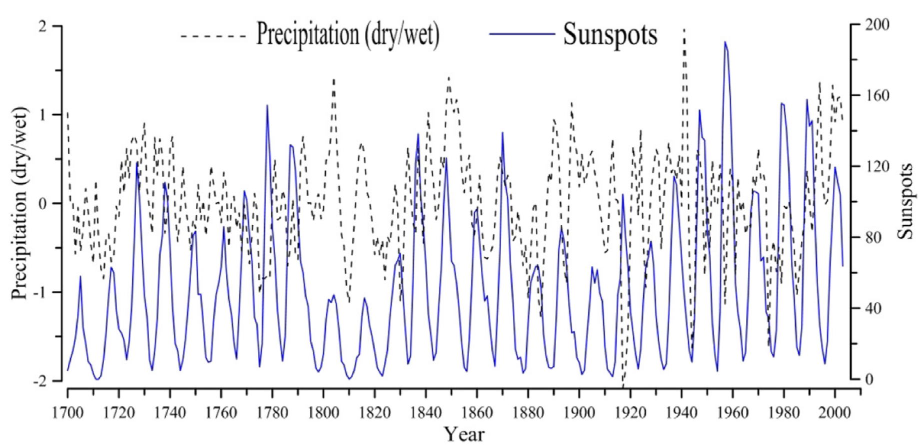

Fig. 9. Variation of the precipitation (dry/wet) index and sunspots relative number (1700–2003).

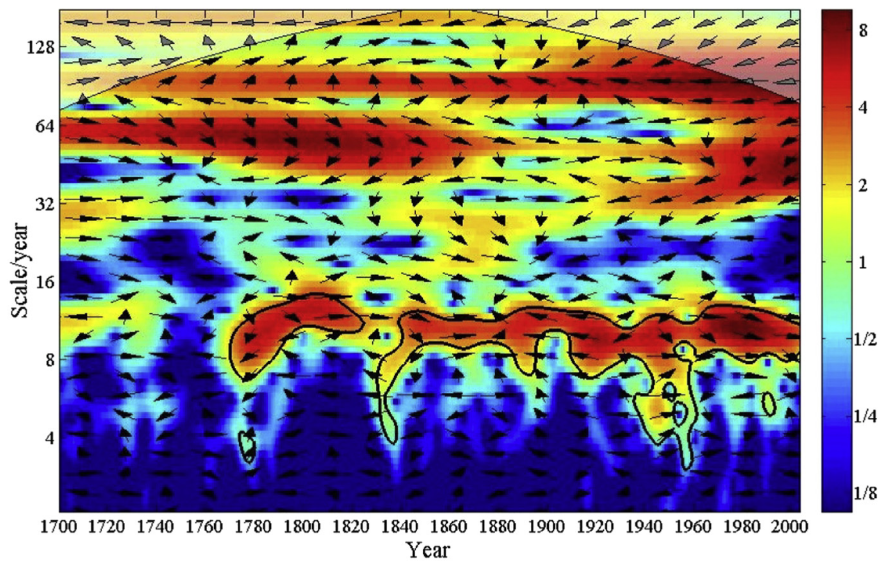

Fig. 10. Cross wavelet transform of the standardized reconstructed precipitation (dry/wet) index and sunspot relative number (1700–2003). The 5% significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing to right, anti-phase pointing to left).

region varied with time on a decadal scale. Therefore, the impacts of solar activities on annual precipitation in the Tianshan Mountains are more complicated than expected, and the complexity might be associated with a number of unknown physical processes. Further investigation is needed to better understand the associations and the mechanism.

5. Conclusions

(1) The reconstructed precipitation (dry/wet) index series well captured the climatic signals of inter-annual variability and the long-term increasing trend of annual precipitation in the study region for the instrumental period, and the reconstruction is also comparable to the previous studies for the region in terms of decadal to multi-decadal variability.

(2) The frequencies of dry and wet years were approximately equal over the past 300 years, and six dry stages (1707–1719, 1768–1782, 1822–1832, 1880–1886, 1913–1924 and 1973–1989) and five wet stages (1723–1741, 1843–1857, 1893–1907, 1933–1940 and after 1990) were identified. The dry period of 1973–1989 and the after-1990 wet period were among the driest and wettest ones during the 304 years.

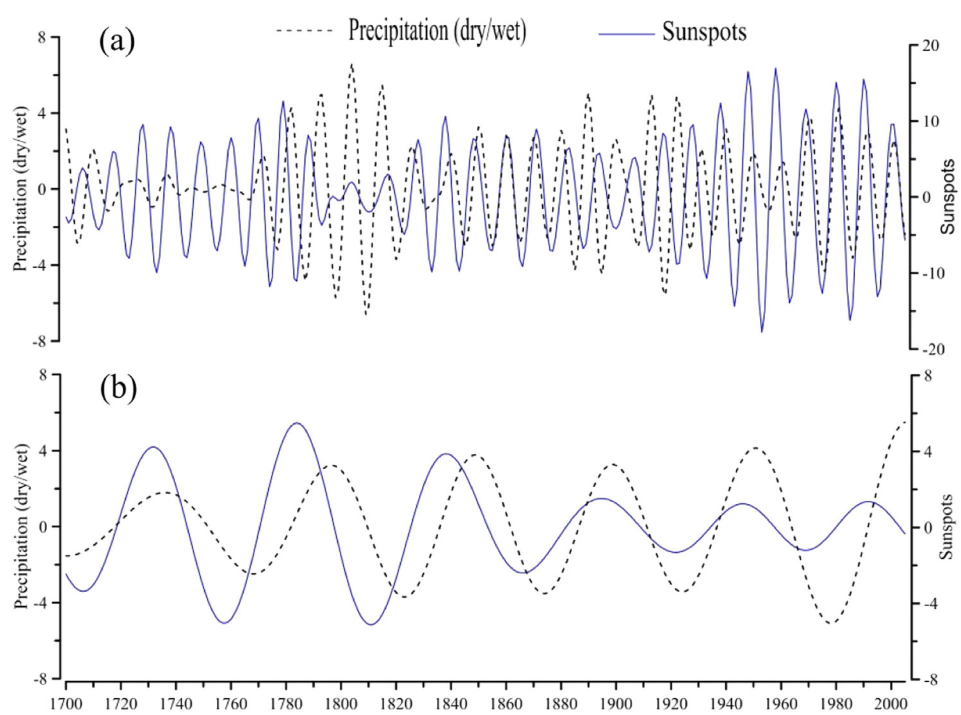

Fig. 11. Wavelet coefficient changes of the precipitation (dry/wet) index and the sunspots from 1700 to 2003 on 10 yr scale (a) and 50 scale (b).

(3) Quasi-periodicities of 2–5 y, 7–8 y, 11 y, 30 y, 50 y and 80 y were detectable, with the 11 y, 30 y and 50 y quasi-periodicities being more significant statistically. Climatic shifts from dry to wet condition occurred in 1720, 1779, and 1886, and those from wet to dry condition in 1741, 1854, and 1904.

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