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Tree-ring based reconstruction of precipitation in the Urumqi region, China, since AD 1580 reveals changing drought signals

Feng Chen*, Yujiang Yuan, Shulong Yu, Huaming Shang, Tongwen Zhang

Key Laboratory of Tree-ring Physical and Chemical Research of China Meteorological Administration/ Xinjiang Laboratory of Tree Ring Ecology, Institute of Desert Meteorology, China Meteorological Administration, 46 Jianguo Road, Urumqi 830002, PR China

ABSTRACT: In most cases, precipitation and drought records in central Asia extend only a few decades, hampering the detection of long-term decadal- to centennial-scale cycles and trends. However, long-term precipitation and drought series can be developed using tree-ring data, which offers researchers the ability to extend limited instrumental precipitation and drought data back several centuries. Water scarcity is the primary limiting factor in the sustainable development of Urumqi, the largest city in arid central Asia. In this study, a regional tree-ring chronology from *Picea schrenkiana* is used to reconstruct previous July–current June total precipitation for the Urumqi region and place the gauged precipitation (1957–2008) in a long-term, multi-century context. The precipitation reconstruction explains 52.1% of the actual precipitation variance during the common period (1957–2008) and contains a strong regional drought signal for the Tien Shan region. This reconstruction successfully captured the wetting trend that occurred from the 1980s to the 2000s and generally agreed with dry periods previously estimated from tree-ring records obtained from the surrounding areas. Moreover, a wavelet coherence analysis shows that significant common oscillations (11.5 and 60 yr) have occurred and suggests that precipitation variations across the Urumqi region were related to different climatic forcing mechanisms (i.e. solar activities and the NAO). Our precipitation reconstruction provides a long-term perspective on current wet and dry events in Urumqi, helps guide expectations of future variability, aids in sustainable water resource management and provides scenarios to address climate change planning.

KEY WORDS: Dendrochronology · Annual precipitation reconstruction · Urumqi · NAO · Solar activity

1. INTRODUCTION

There is a consensus that the 20th century was the warmest to occur in the past thousand years, and of that century, the last 3 decades were the warmest (IPCC 2007). Temperature increases have had a tremendous impact on global and regional precipitation, drought and water resources (Dai 2011). However, the responses of regional precipitation and water resources to this warming vary by location (Chen et al. 2011). For example, a clear tendency towards a more arid climate has prevailed in the eastern part of northwestern China and runs contrary to the moistening trend in the western part of northwestern China that has occurred since the 1980s (Shi et al. 2007). On longer timescales, the increasing precipitation in arid central Asia opposes a decreasing precipitation trend in the summer monsoon dominated regions of China and may be linked to the westerlies-dominated climate regime (Chen et al. 2008, 2011). However, meteorological records in many regions of arid central Asia are too sparse and

*Corresponding author: feng653@163.com

too short to investigate regional climatic patterns with any certainty. While there are some meteorological records going back around a century (from a few meteorological stations in Kazakhstan, Kyrgyzstan, Uzbekistan and Tajikistan), most of the precipitation data available throughout arid central Asia only extend 50–80 yr. This limits the analysis of long-term climate trends and the climate mechanisms affecting the region. Thus, we must turn to long-term climate reconstructions based on proxy data, such as tree rings (Sheppard et al. 2004, Allen et al. 2015), snow accumulation (Bromwich 1988), ice cores (Vance et al. 2013), lake sediment records (Chen et al. 2008, 2011) and stalagmites (Cheng et al. 2012), to place modern trends in a historical context. The precipitation reconstructions can both extend the record back in time and allow for an assessment of the range of natural precipitation variability and its relationship with dynamic climate features in arid central Asia.

Water scarcity has become the primary limiting factor for the sustainable development of Urumqi, the largest city in arid central Asia, in recent decades. The frequency and severity of droughts and other hydroclimatic events are of critical importance in the economic development of Urumqi and to the rapidly growing urban population. A careful and prudent plan to tackle climate change requires detailed and reliable knowledge of hydroclimatic conditions on annual to centennial timescales. However, instrumental climate records and historical documents in Urumqi are very limited. Tree-ring analysis is the best available method for extracting historical climate information. In the last decade, many tree-ring based hydroclimatic reconstructions have been developed for the areas surrounding Urumqi (Yuan et al. 2003, Li et al. 2006, Chen et al. 2013, 2015a, Zhang et al. 2013); however, the density of tree-ring research in Urumqi is still low, and high-quality precipitation and drought reconstructions are notably rare.

Here, we present a tree-ring based precipitation reconstruction for the Urumqi region that spans 429 yr. This precipitation reconstruction is representative of precipitation conditions in a large area of arid central Asia, which increases our understanding of the overall drought history in the region. The purposes of this study are therefore the following: (1) to reconstruct the precipitation variability of the Urumqi region for recent centuries using tree rings from central Tien Shan and (2) to investigate the relationships between precipitation records and natural forcings using wavelet analysis, such as solar activity and the NAO.

2. MATERIALS AND METHODS

2.1. Study region and tree-ring data

The study area is characterized as having a semi-arid, continental climate (Xu et al. 2015) and covers Urumqi city's watershed (Fig. 1). Climate data from the nearest meteorological station indicate that annual (January–December) mean total precipitation is approximately 558 mm and mean daily average temperature is 2.4°C from 1956 to 2013. Fig. 2 shows that June is the wettest month of the year (mean total precipitation is 103 mm), while July is the hottest month (mean daily temperature is 15.1°C). The predominant tree species in the study area is Schrenk

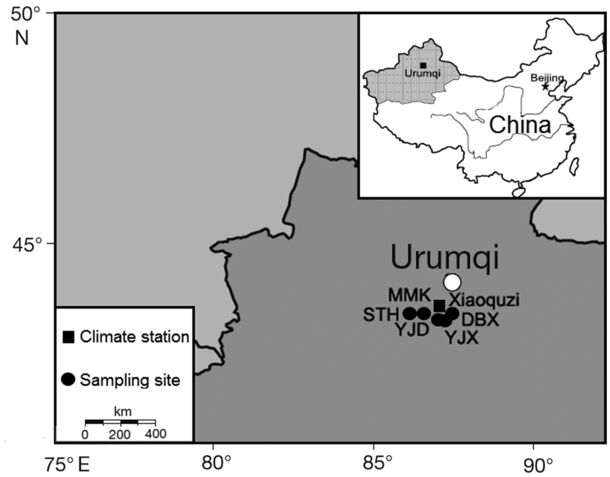

Fig. 1. Locations of sampling sites and meteorological station (Xiaoquzi) in the Urumqi region (city of Urumqi given by white circle)

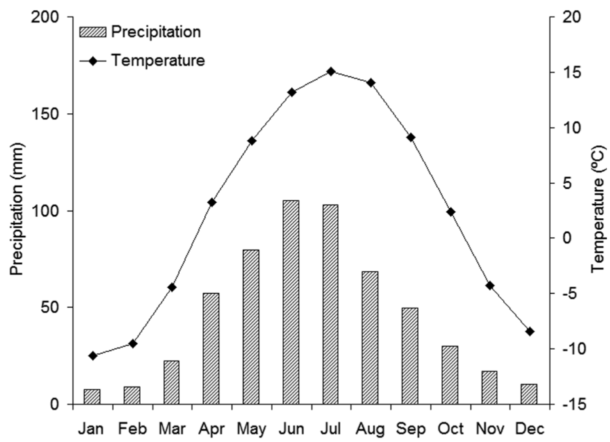

Fig. 2. Mean daily average temperature and mean total precipitation for each month for the climatological period AD 1956–2010 based on available records from the Xiaoquzi meteorological station

spruce, which is distributed between 1500 and 2800 m a.s.l. During autumn 2008, tree-ring increment cores from Schrenk spruce were sampled from 5 xeric sites located close to the Xiaoquzi meteorological station in central Tien Shan near Urumqi, where instrumental climate data are available for the period 1956–2013. These sites are characterized by sparse soil cover and very rapid drainage. The trees are characterized by their small stature, gnarled appearance, loss of apical dominance and cambial dieback.

A regional Schrenk spruce ring-width chronology was constructed using standard dendrochronological techniques (Fritts 1976). In general, 2 Schrenk spruce cores were sampled with an increment borer from each tree at breast height to measure tree-ring widths; 219 cores were sampled from 110 trees along an altitudinal gradient ranging from 2000 to 2550 m (Table 1). Cores were air dried, mounted and sanded, and then rings were measured to the nearest 0.001 mm using the TA UniSlide measurement system. The quality of the dating and measurement of each growth ring was verified using the software program COFECHA (Holmes 1983). To remove nonclimatic trends associated with age, size and stand dynamics, the cross-dated raw ring widths were detrended using conservative curves such as a negative exponential or linear curve (Cook 1985). Because of the high mean correlation (r = 0.62) of the individual cores with the master series, the first principal component of these tree-ring series over the 1900–2000 period accounts for 65.6% of the total variance. The detrended data from individual tree cores were merged into a regional standard (STD) tree-ring width chronology using the program ARSTAN (Cook 1985). The replication decline in the early portion of the chronology was addressed by employing the expressed population signal (EPS) (Wigley et al. 1984) to evaluate the reliable chronology with an arbitrary threshold value of 0.85. The reliable composite chronology used in the reconstructions described in the next section did not extend back beyond year 1580 based on this threshold value (Fig. 3).

Table 1. Information about the *Picea schrenkiana* sampling sites and the climate station (Xiaoquzi) in the Urumqi region

Site code	Coordinates	Tree no.	Elevation (m)	Slope (°)	Aspect
DBX	43° 27′ N, 87° 17′ E	24	2000–2160	15–20	W
YJD	43° 08′ N, 87° 05′ E	20	2350–2550	15–40	NE
MMK	43° 26′ N, 86° 56′ E	22	2020–2134	15–25	N
STH	43° 28′ N, 86° 39′ E	22	2030–2075	20–35	NW
YJX	43° 09′ N, 87° 06′ E	22	2370–2530	20–30	NE
Xiaoquzi	43° 34′ N, 87° 06′ E		2161		

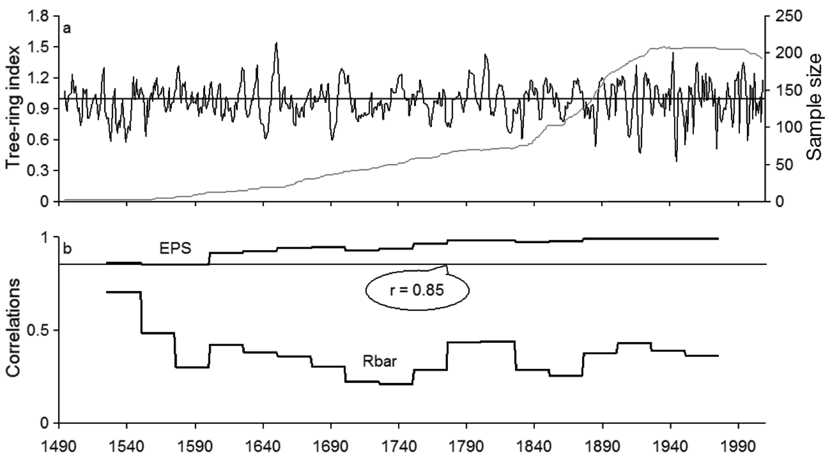

Fig. 3. (a) Plot of the standard tree ring index chronology of the Urumqi region and the sample size (gray). (b) Statistics of the inter-series correlation (Rbar) and the expressed population signal (EPS) (calculated over 50 yr lagged by 25 yr), indicating the robust signal strength of the standard chronology

2.2. Statistical analysis

The relationships between STD chronology and climate factors were analyzed for the common period (1956–2008) of tree rings and climate data using a correlation analysis. The climate factors analyzed include mean daily average temperature within each month and monthly total precipitation obtained from the Xiaoquzi meteorological station (43° 34′ N, 87° 06′ E, 2161 m a.s.l.). Because of the strong biological lag effect, as indicated by the high first-order autoregression value of 0.509, climate data taken from each previous July to September of the sample year were used for the correlation analysis. The calculations and significance tests were performed using the DENDROCLIM 2002 program (Biondi & Waikul 2004). This software allowed us to calculate the correlation coefficient using 1000 replicates for each data point in a random resampling.

A regression equation of annual precipitation was developed for the tree-ring chronology for the calibration period 1956–2008. The leave-one-out method was used to evaluate the model's reliability (Michaelsen 1987). The testing statistics used included the Pearson's correlation coefficient, the reduction of error (RE), coefficient of efficiency (CE) statistics, the sign test (ST) and the first-order sign test (FST) (Fritts 1976, Cook & Kairiukstis 1990). Based on the climate reconstructions, we defined dry years as the mean minus 1 SD and severely dry years as the mean minus 2 SD. To demonstrate that our reconstruction and instrumental records reflected regional-scale precipitation variability, we correlated these data with the CRU TS3.20 dataset (Harris et al. 2014) of all grid cells available for a user-defined region using the KNMI Climate Explorer application. We used a multi-taper method (MTM) analysis (Mann & Lees 1996) to reveal the frequency characteristics of the precipitation reconstruction of the Urumqi region. MTM provides a robust means for separating the noise and signal components of climatic time series, particularly in datasets that may contain both periodic and quasiperiodic behavior (Mann & Lees 1996). The use of MTM does not rely on *a priori* assumptions concerning the structure of the time series, and the method has been successfully employed in some paleoclimatic studies (Gray et al. 2004). We used $5 \times 3\,\pi$ tapers and a red noise background in the following analysis. The wavelet coherence analysis (Torrence & Compo 1998) was used to analyze the relationships between the precipitation reconstruction and the number of sunspots as well as the reconstructed NAO (Trouet et al. 2009). 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 right, antiphase pointing left).

3. RESULTS

3.1. Climate–growth relationships

The regional chronology is shown in Fig. 3. The EPS statistic indicates that the regional chronology was reliable for the timespan 1580–2008 (EPS > 0.85). The running EPS values were close to 0.90 from 1580 to 2008, further indicating the reliability of the chronology. The high signal-to-noise ratio (99.38), SD (0.17) and EPS (0.99) indicate a common signal in the trees. Moreover, the relatively high variance in the first eigenvector accounted for 65.6% of the total variance in the tree-ring width series.

As shown in Fig. 4, significant correlations with precipitation were found in July of the previous year (r = 0.32), August of the previous year (r = 0.38), April of the sample year (r = 0.40) and June of the sample year (r = 0.29); significant correlations (at 0.05 level) with temperature were found in August of the previous year (r = −0.37), April of the sample year (r = −0.37), May of the sample year (r = −0.42) and July of the sample year (r = −0.43). A detailed analysis revealed that a highest positive correlation (r = 0.722, $p < 0.01$) was found between tree rings and the previous July through the present year's June total precipitation. Therefore, previous July–current June total precipitation is the most appropriate predictand for the precipitation reconstruction.

3.2. Precipitation reconstruction

The linear regression between the regional chronology and previous July–current June total pre-

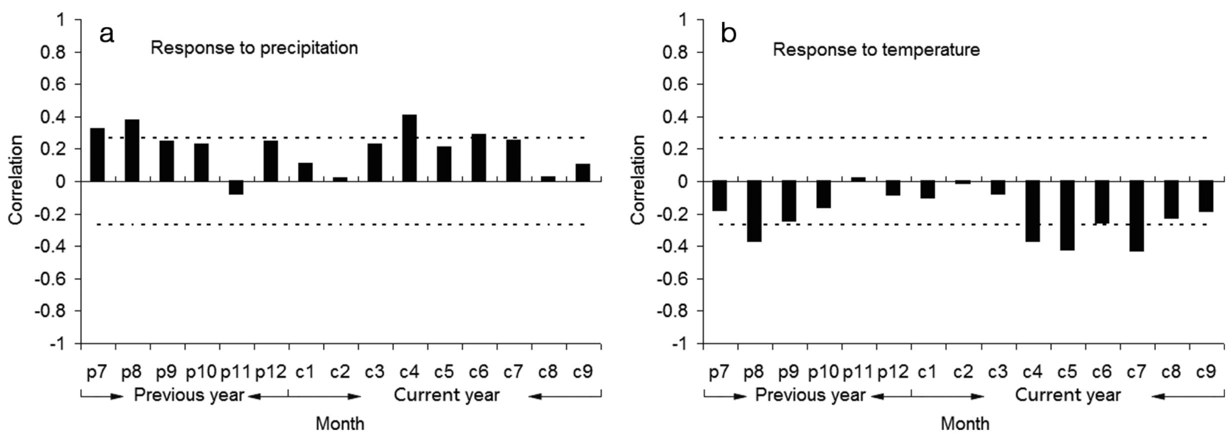

Fig. 4. Simple correlations (bars) of the standard chronology of the Urumqi region with (a) the monthly sum of precipitation and (b) the monthly mean temperature from previous July to current September (1957–2008). Dotted lines indicate 0.05 significance levels. p: previous year; c: current year

cipitation for the 1957–2008 calibration period was significant (F = 54.49, $p < 0.0001$, adjusted $r^2 = 0.51$). The calibration model explained 52.1% of the total variance of the instrumental records and 48.2% of the variance in the leave-one-out cross validation (Fig. 5). As shown in Table 2, the positive RE and CE values indicate the good predictive skill of the regression model. The high ST and FST values suggest that the developed model was able to track low- and high-frequency precipitation variability well.

Fig. 6 shows the interannual to multi-decadal variations of the reconstructed total July–June precipitation for the Urumqi region since AD 1580. Several extended dry periods were identified before the instrumental period (1957–2008) according to the 10 yr low-pass filtered precipitation reconstruction and the long-term mean (542 mm, 1580–2008). Dry periods occurred around 1588–1596, 1609–1622, 1635–1645, 1659–1674, 1686–1694, 1707–1732, 1759–1784, 1816–1833, 1856–1865, 1877–1887, 1908–1921, 1941–1955, 1972–1984 and 2002–2008. The SD is 59.4, which is within the scale of the defined normal status (precipitation = 542 ± SD). The values beyond the inner horizontal lines (±1 SD) indicate dry and wet years, and those beyond the outer horizontal lines (±2 SD) indicate extremely dry and wet years. Extremely dry years occurred in AD 1642, 1691, 1831, 1885, 1911, 1917, 1945, 1951, 1974 and 1997; 1917 and 1945 stood out as years in which 2 of the most severe central Asia droughts in recent centuries have occurred (Esper et al. 2001, Li et al. 2010), and 1974 was identified as the most extreme dry year to occur during the instrumental period. Severe drought events generally have strong effects on local social and agricultural activities, and those that have occurred have changed China's history. For example, severe and long-lasting drought and famine events occurred around western China in the late 1630s and early 1640s, precipitating the fall of the Ming dynasty (Parsons 1970).

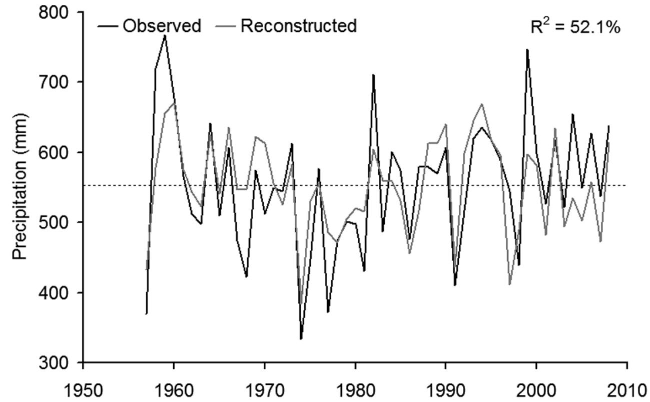

Fig. 5. Comparison between observed and estimated precipitation (July–June) from 1957 to 2008. Dotted line shows the mean of the observed values (553 mm)

Table 2. Leave-one-out cross-validation statistics for reconstruction of total July–June precipitation in the Urumqi region based on tree rings. r: correlation coefficient; ST: prediction sign test; FST: first-order sign test; RE: reduction of error; CE: coefficient of efficiency; +: pair of actual and predicted temperatures showed same sign of departures from their respective mean values; –: pair of actual and predicted temperatures showed different sign of departures from their respective mean values. *Significant at the 1% level

r	ST	FST	RE	CE
0.694*	$45^+/7^{-*}$	$44^+/7^{-*}$	0.481	0.410

The spatial correlation analysis shows that the instrumental and reconstructed July–June precipitation in the Urumqi region correlates significantly with gridded surface total July–June precipitation and have similar spatial correlation fields, albeit the signal strength of the latter is lower (Fig. 7). Signifi-

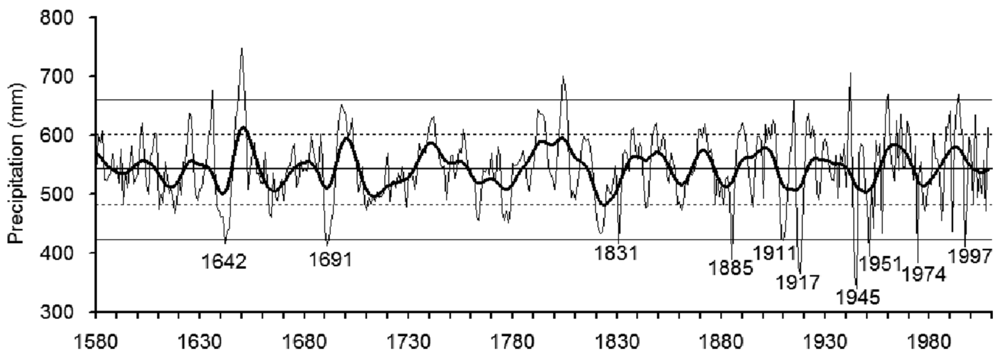

Fig. 6. Estimated (thin line) and 10 yr low-pass filter (thick line) values of total July–June precipitation of the Urumqi region. Central horizontal line shows the mean of the estimated values, inner horizontal lines (dotted) show the border of 1 SD and outer horizontal lines (solid) show the border of 2 SD

cant positive correlations are found in Tien Shan, with the highest correlations occurring in central Tien Shan. The results confirm that the precipitation reconstruction captures broad-scale regional climatic signals. The MTM spectral analysis indicates the existence of some decadal (60 and 11.5 yr) and interannual (8.3, 6.6, 5.8, 5.3, 4.9, 4.5, 3.3 and 2.1–2.3 yr) cycles. Both high- and low-frequency peaks exceeded the 95% significant confidence level based on a red noise null continuum.

4. DISCUSSION

4.1. Climate–growth response

The climate response analysis results indicated that precipitation variation was a major factor limiting the radial growth of spruce trees in the Urumqi region. Above-average precipitation during summer may ease the threat of summer drought and promote storage of carbohydrates and bud formation, thus enhancing spruce growth during the following year (Fritts 1976, Chen et al. 2013). Moreover, we also found significant positive correlations between tree growth and precipitation in April and June. In Tien Shan, dry conditions before the onset of the rainy season cause drought stress in spruce trees and thus limit growth. Tree growth benefits from current spring precipitation and snow, which increase soil moisture content during the early phase of the growing season. After the onset of the rainy season, enough moisture is available to satisfy the water demand of the trees. Both our study sites and the meteorological station used are located at mid-elevations, far from the approximately 2800 m a.s.l. upper tree line in the central Tien Shan. Thus, tree-ring widths responded very well to total July–June precipitation.

Most of the correlations between the radial growth of spruce trees and temperature were negative, especially in summer. High temperatures during the growing season enhance evapotranspiration and thus decrease soil moisture availability (LeBlanc & Terrell 2001). This growth response is not surprising for trees growing on steep slopes in an arid climate.

4.2. Comparison with other precipitation and drought reconstructions

Several tree-ring based drought and precipitation reconstructions for surrounding areas have recently been developed. Chen et al. (2013) developed a drought reconstruction for the last 426 yr for western Tien Shan, capturing 36% of the variance in the calibration period (1925–2005). Chen et al. (2014) developed 6 Siberian spruce (*Picea obovata*) tree-ring width chronologies and reconstructed annual (prior July–June) precipitation in the Altay Mountains for the period 1825–2009. The calibration model explained 72% of the actual precipitation variances for the period from 1962 to 2009. Chen et al. (2015a) presented a drought reconstruction for the Hutubi River near central Tien Shan. Using a tree-ring width series from Siberian larch, Chen et al. (2015b) developed a drought reconstruction (r^2 = 0.458 for 1957–2009) for eastern Tien Shan. To meet the replication criterion, we truncated their climate series, eliminating data prior to AD 1825. For a better visual compar-

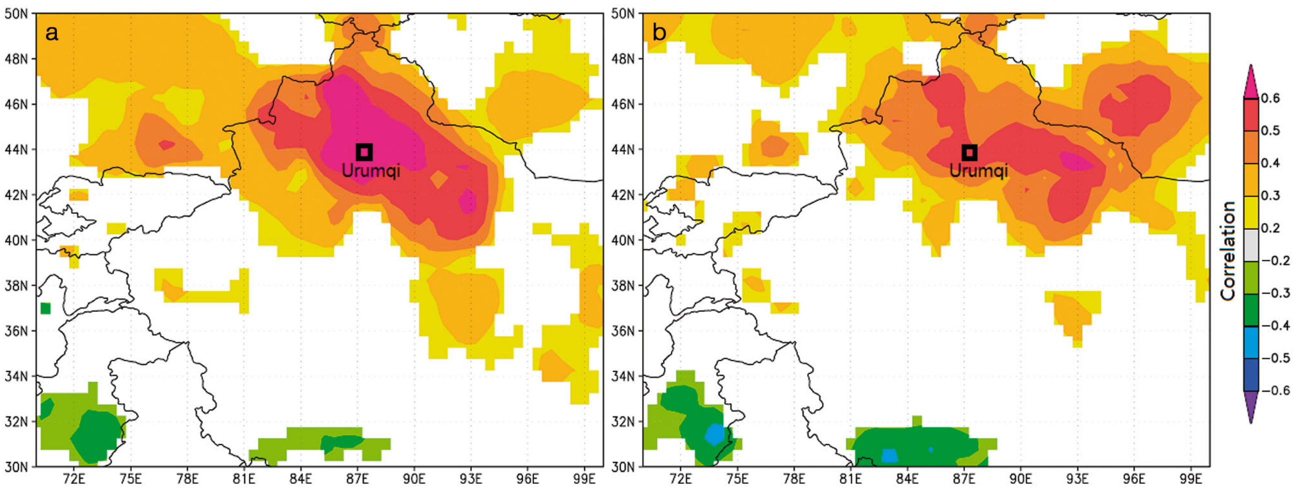

Fig. 7. Spatial correlation fields of (a) instrumental and (b) reconstructed July–June precipitation for the Urumqi region with regional gridded July–June precipitation for the period 1957–2008

ison, all reconstructions were scaled to a mean of zero and smoothed with a 20 yr low-pass filter to highlight low-frequency climate signals. Our precipitation reconstruction reflects similar dry/wet intervals in the nearby regions as drought and precipitation reconstructions (Fig. 8). Regional dry conditions during the 1820s–1830s, 1850s–1860s, 1870s–1880s, 1900s–1910s, 1940s and 1970s found in this study occurred synchronously in western Tien Shan and the Hutubi River basin (Chen et al. 2013, 2015a). Dry conditions in the 1870s–1880s, 1940s and 1970s are also reported for the Altay Mountains (Chen et al. 2014). The drought and precipitation reconstructions from the Altay Mountains and west-central Tien Shan exhibit an upward trend during the 1980s–2000s. The common large-scale climate signals found in our reconstruction and the compared records suggest that our reconstruction represents broad-scale regional climatic variations.

As shown in Fig. 8, some differences between the drought reconstructions for eastern and western Tien Shan (i.e. in the 1820s–1830s, 1910s–1920s, 1940s, and 1980s–2000s) were found, and these may reflect the local influence of different geographic features or differences in seasonality of the various precipitation/drought reconstruction sites (Chen et al. 2015b). In particular, the drought reconstruction for eastern Xinjiang exhibits a downward trend during the 1980s–2000s, which is in contrast to a consistent moisture increase in west-central Tien Shan. Fig. 9 presents the spatial distribution of the reconstruction values over northern Xinjiang during the 8 extremely dry years shown in our precipitation reconstruction. The drought severity level declined from west-central Tien Shan to the eastern edge of the Xinjiang region. Even during the most severe drought year (1917) of the last 500 yr in the western part of central Asia (Esper et al. 2001, Chen et al. 2013), eastern Xinjiang remains in a wet state. Meanwhile, the correlation between the drought reconstructions for eastern Tien Shan and the western edge of the East Asia monsoon area is far stronger than that between eastern and west-central Tien Shan (Chen et al. 2015). Based on the instrumental records, both arid central Asia and Xinjiang, China (36°–54° N, 50°–90° E), define the Urumqi region as the core region influenced by westerly winds, and the records indicate an opposing pattern in precipitation variations between arid central Asia–Xinjiang, China, and mid-latitude, monsoon-dominated Asia (Huang et al. 2015). Thus, the opposing trends may be linked to an out-of-phase relationship between the Asian summer monsoon and the westerlies (Chen et al. 2008).

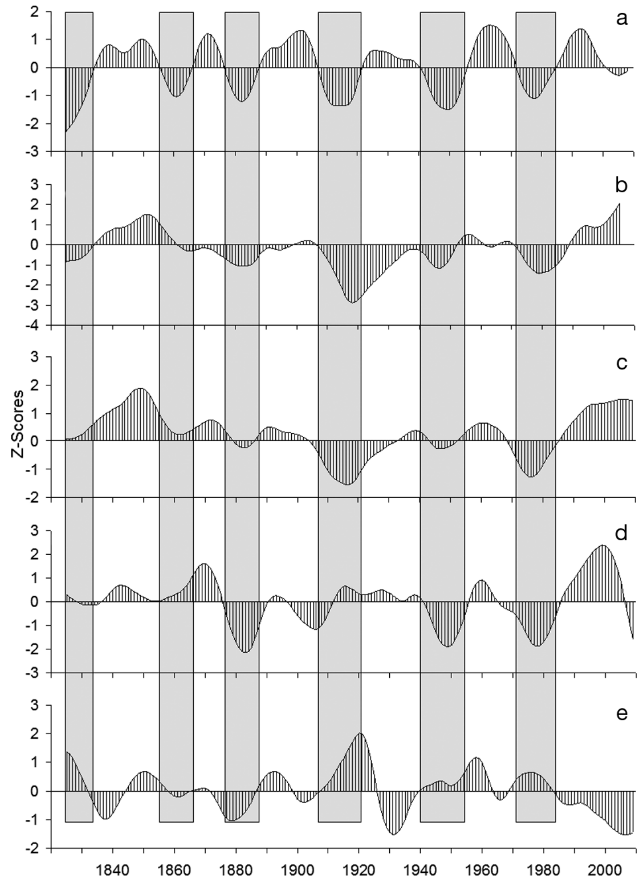

Fig. 8. Comparison of various precipitation/drought reconstructions for arid central Asia derived from tree-ring records (gray shading: dry periods of the Urumqi region). (a) Annual (July–June) precipitation reconstruction in the Urumqi region (this study); (b) drought reconstruction in western Tien Shan (Chen et al. 2013); (c) drought reconstruction in the Hutubi River basin (Chen et al. 2015a); (d) annual (July–June) precipitation reconstruction in the Altay Mountains (Chen et al. 2014); (e) drought reconstruction from eastern Tien Shan (Chen et al. 2015b). All series were adjusted for their long-term means over the period 1825–2009 and smoothed with a 20 yr low-pass filter to emphasize long-term fluctuations

4.3. Periodicities and natural forcings

The 11.5 yr cycle in the precipitation reconstruction for the Urumqi region is possibly influenced by solar forcing (Hale 1924). In arid central Asia, the influence of solar activity on drought variations has been revealed by many dendroclimatic studies (Li et al. 2006, Wang et al. 2015). The relationships between reconstructed precipitation and the number of sunspots were examined by applying correlation and wavelet coherency analyses over the period 1700–2009. A comparison of the precipitation reconstruction and the sunspot relative number series reveals

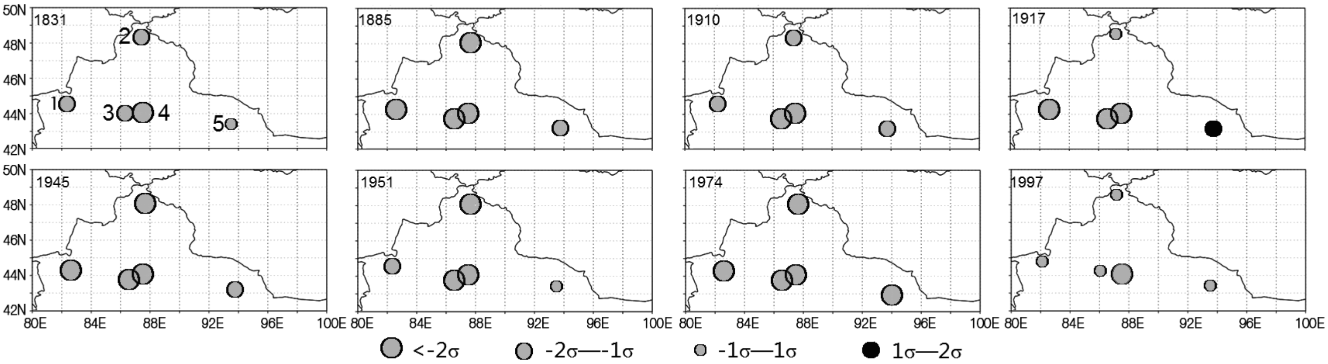

Fig. 9. Spatial distribution of the reconstruction values over northern Xinjiang during the 8 extremely dry years revealed by the precipitation reconstruction of the Urumqi region. σ: SD. The numbers 1, 2, 3, 4 and 5 denote western Tien Shan (Chen et al. 2013), the Altay Mountains (Chen et al. 2014), the Hutubi River basin (Chen et al. 2015a), Urumqi and eastern Tien Shan (Chen et al. 2015b), respectively

no significant relationship between the 2 variables on an annual or inter-annual scale, which is likely related to the regional nature of both the precipitation reconstruction of the Urumqi region and the forcing data. However, as shown in Fig. 10a, a significant relationship was found at the 11.5 yr scale from the 1770s to the 2000s. The arrows show an in-phase relationship from the 1800s to the 1850s and after the 1930s. An anti-phase relationship is identified from the 1770s to the 1800s and the 1870s to the 1930s on an approximately 11.5 yr timescale, and an in-phase relationship is identified from the 1700s to the 1800s on timescales of 50–60 yr. The 2 time series share some significant common oscillations, implying that solar activity has a large impact on the precipitation variation of the Urumqi region on decadal to multidecadal timescales.

These high-amplitude interannual cycles (i.e. 3, 3.1, 2.9, 2.3, 2.1 yr) may correspond to the quasi-biennial oscillation (Brönnimann et al. 2007) (Fig. 10b). Similar to the sunspots variable, the arrows in Fig. 10c show an in-phase relationship between the reconstructed NAO index (Trouet et al. 2009) and our precipitation reconstruction from the 1620s to the 1850s. They indicate an anti-phase relationship from the 1850s to the 1880s on timescales of 50–60 yr and an anti-phase relationship after the 1900s at an interval of 30 yr. Instrumental records support a proposed mechanism for the significant correlations between precipitation in Xinjiang and the NAO (Dai et al. 2013). During the negative NAO phase, precipitation increases in central Asia as a result of increased eastward water vapor transport (strong westerlies) from Europe to central Asia, which causes an increase in water column vapor content in these areas (Dai et al. 2013). The anti-phase relationship between the reconstructed NAO index (Trouet et al. 2009) and our precipitation reconstruction supports this connection. However, different relationships appeared during the Little Ice Age, and the recent warming period

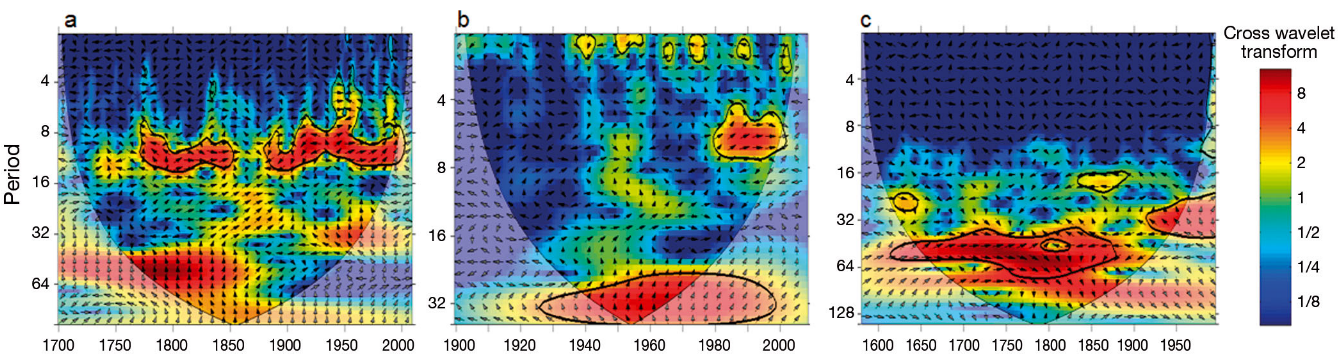

Fig. 10. Cross-wavelet transform of the reconstructed precipitation of the Urumqi region with (a) sunspot number (www.sidc.be/silso/datafiles), (b) quasi-biennial oscillation and (c) NAO (Trouet et al. 2009). The 5 % significance level against red noise is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left)

reveals that the impacts of solar activities and large-scale climate factors on regional precipitation in arid central Asia are more complicated than expected. As a result, some unknown physical processes at various timescales await further investigation.

5. CONCLUSIONS

Our study found that the tree-ring widths of spruce trees in the Urumqi region were sensitive to previous July–current June total precipitation. The precipitation reconstruction was developed using a model calibrated with instrumental precipitation. The model accounts for 52.1% of the instrumental precipitation variance during the period 1957–2008. Spatial correlation fields using instrumental and reconstructed precipitation data reveal similar patterns, indicating that our reconstruction represents a high degree of regional precipitation variability over the Urumqi region. A comparison with other precipitation and drought reconstructions from the surrounding areas shows a high correlation in the timing of dry/wet periods at the decadal scale across northern Xinjiang (i.e. dry during the 1820s–1830s, 1850s–1860s, 1870s–1880s, 1900s–1910s, 1940s and 1970s). The spatial discrepancies between eastern and west-central Tien Shan may reflect the influences of different geographic features.

We identified periodic trends (60, 11.5, 8.3, 6.6, 5.8, 5.3, 4.9, 4.5, 3.3 and 2.1–2.3 yr) in the precipitation reconstruction of the Urumqi region, suggesting the possible influence of large-scale ocean–atmosphere–land circulation systems on the study area. Possible natural forcings of the precipitation variation in the region, as detected in the wavelet coherence analysis, include solar activity and the NAO. However, the climate mechanisms are more complicated than expected, and unexplained patterns might be associated with many unknown physical processes. Key challenges for future research include linking precipitation variability in the Urumqi region over various timescales to regional physical processes, and separating the impacts of natural climatic regimes from the effects of anthropogenic forcing.

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