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Streamflow variability for the Aksu River on the southern slopes of the Tien Shan inferred from tree ring records

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ABSTRACT

Gauged river flow records from China generally span only a few decades, which hampers the detection of long-term, decadal- to centennial-scale cycles and trends in streamflow variability. New and updated tree-ring chronologies help reconstructed the water-year (October–September) streamflow for the Aksu River, which is an important river at the edge of the Taklimakan Desert that drains into the Tarim Basin. The reconstruction dates back to 1692 and has an adjusted r^2 of 0.61 (1957–2006). Based on frequency, intensity and duration of droughts and pluvial events, the lowest streamflows occurred in the 1920s. Since then streamflow has continuously increased, and was exceptionally rapidly after the 1960s, until today. The start and end of the 20th century to the present were the highest streamflow periods. The mid-20th century was the longest and driest period over the past 300 yr. The reconstructed streamflow series has a strong positive correlation with the North Atlantic Oscillation Index. Changes in mid-latitude circulation patterns influencing precipitation may have indirectly resulted in streamflow variations along the Aksu River over the past 300 yr. The rapid increase and the exceptional streamflows of the 1960s are likely linked with global warming and mid-latitude atmospheric circulation changes.

Introduction

The climate in northwestern China has been changing, most notably in Xinjiang, since the 1980s responding to human-induced global climate change. Precipitation, glacial meltwater, river runoff, and air temperature have all increased continuously over the past few decades (Shi et al., 2007). Increased river streamflow is beneficial to economic and societal development; however, it can also have disastrous consequences such as flooding. The Aksu River (40° 20′–41° 15′N, 80° 00′–81° 00′E) located on the southern slopes of the Tien Shan and the northwest edge of the Taklimakan Desert and is one of the main rivers in southern Xinjiang and an important tributary of the Tarim River, the largest inland river in China (Fig. 1). In terms of streamflow, the Aksu River is the largest of the three major tributaries (Aksu, Hotan, and Yarkant Rivers), providing up to 75% of the water for the Tarim River (Deng, 2011). Variations in the Aksu River's streamflow have an important impact on oasis agriculture, and the ecosystem and social stability of southern Xingjiang. Streamflow records in China are, in most cases, limited to the past few decades. Such relatively short records are conventionally used as a basis for planning and engineering design, but they are too short to properly determine true streamflow frequency, severity, and duration of dry and wet events. Tao et al. (2009) showed that the temperature, precipitation, and river streamflow in the Aksu River Basin have increased distinctly over the past 45 yr, but remarkably little is known about its possible driving mechanisms. Furthermore, it is not clear how the Aksu River's flow has changed over the past 300 yr as a consequence of human-induced global climate change. We must, therefore, use other proxy data to understand the long-term natural variability of streamflow for the Aksu River.

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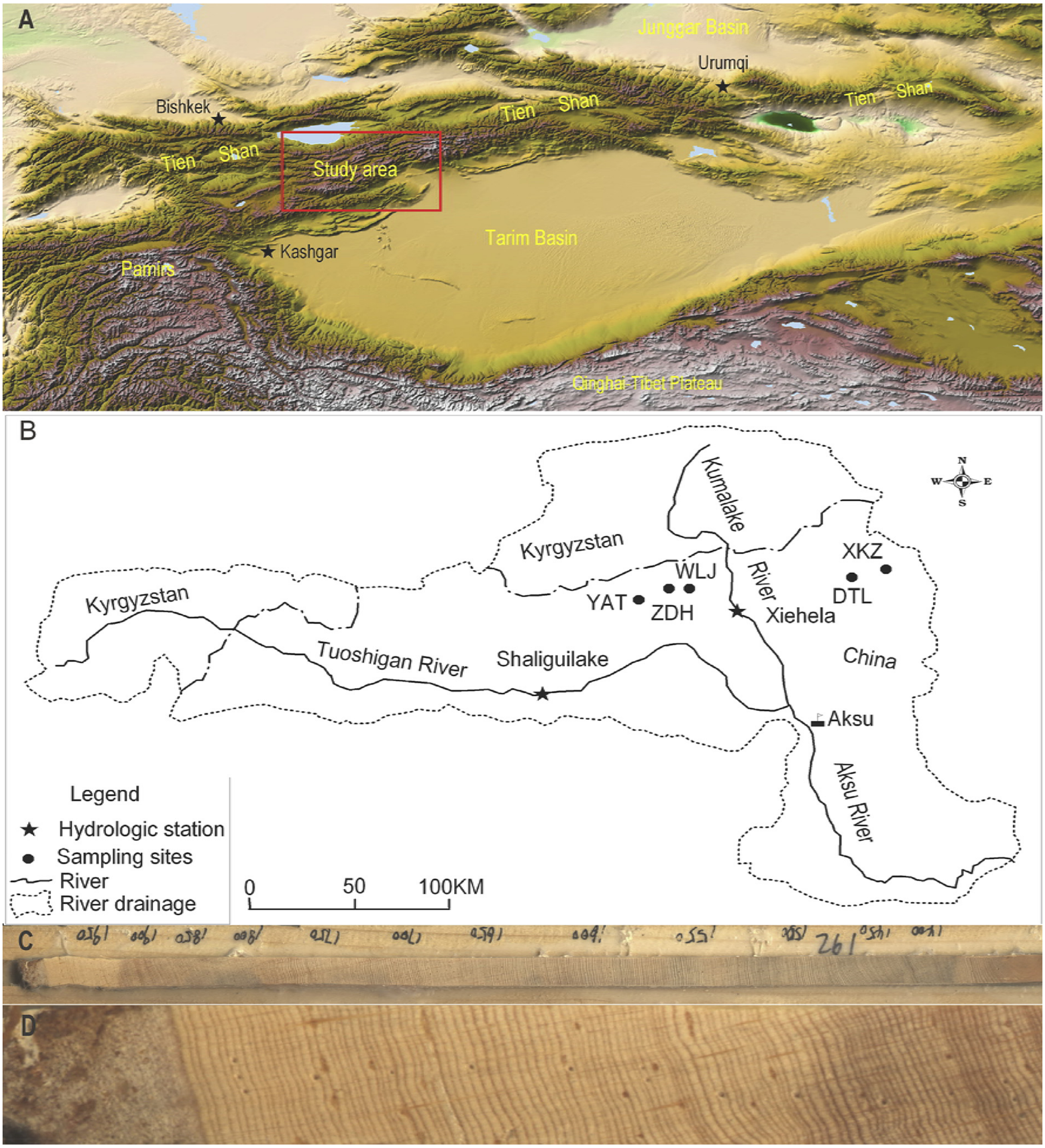

Figure 1. A) and B). Locations of tree-ring sampling sites and hydrologic stations. C). 600-year-old tree-ring in Wulijielike (WLJ) site. D). Tree-ring width changes of the previous 100 yr.

Tree-ring data are widely used as reliable proxies for streamflow, and they can be used to assess the long-term discharge behavior of a river and its management in various water resource sectors from the different regions of the world (e.g., Pederson et al., 2001, 2013; Davi et al., 2006, 2013; Akkemik et al., 2008; D'Arrigo et al., 2011; Margolis et al., 2011; Meko and Woodhouse, 2011; Leland et al., 2013; Cook et al., 2013; Shah et al., 2013, 2014). Dendroclimatology studies in China have mainly focused on the arid northwestern region and on the Tibetan Plateau (Zhang et al., 2015a,b). The field has also developed in the northeastern and subtropical regions in recent years (Duan et al., 2012; Chen et al., 2012). In terms of long-term climate reconstruction, Shao et al. (2010) developed the longest (3585 yr) tree-ring-width chronology for China. Yang et al. (2014) reconstructed a 3500-yr annual precipitation record for the northeastern Tibetan Plateau. Liu et al. (2011) analyzed amplitudes, rates, periodicities, causes, and future trends of the temperature variations for the past 2485 yr for the central-eastern Tibetan Plateau. Tree-ring based hydrometeorological reconstruction has been developed for many areas of China, such as the upper Yellow (Gou et al., 2007, 2010) and Heihe (Liu et al., 2010; Yang et al., 2011) rivers. The tree-ring response to climate is more sensitive in Xinjiang because it is located in central arid Asia, and precipitation and temperature series spanning more centuries have been reconstructed using dendroclimatological methods. Previous studies have shown the tree-ring width response to precipitation (Yuan et al., 2000, 2001, 2003; Wei et al., 2008; Zhang et al., 2009, 2015a,b, 2016; Gao et al., 2011; Chen et al., 2013; Qin et al., 2016) and the tree-ring density response to summer temperature (Chen et al., 2010, 2012; Yu et al., 2013; Yuan et al., 2013) in the Tien Shan. Yuan et al. (2007) reconstructed a 372-yr water-year (October–September) streamflow for the Manasi River on the northern slopes of the Tien Shan, and suggested that the analysis of Schrenk spruce could contribute significantly to the development of regionally explicit streamflow reconstructions. In a preliminary study, we established chronologies based on the spline detrending method, and reconstructed past streamflow for the Aksu River (Zhang et al., 2011). In this study, we recalculated the data and established five tree-ring width chronologies using three different detrending methods. We found the best response relationship between the tree-ring chronologies based on the detrending methods of negative exponential curve and streamflow. Then, we developed a more reliable 300-yr natural annual streamflow series for the Aksu River, analyzed the temporal variations in water discharge, and placed recent streamflow variations and trends into the context of the past three centuries. Finally, we compared the streamflow with global atmospheric circulation indices to identify the major climatic forcing factors of river discharge.

Material and methods

Study areas and streamflow data

The Aksu River Basin covers an area of 50,000 km^2, the main part of which is on the southern slope of the Tien Shan in China, and the remaining part (19,000 km^2) in southeastern Kyrgyzstan (Fig. 1). Two major tributaries, the Kumalake and Tuoshigan rivers, flow into the Aksu River. The Kumalake River originates from Tomur Peak and Khan Tengri Glacier, and has a total length is 293 km. The total length of the Tuoshigan River is 457 km, and the length of the mainstream of the Aksu River is 132 km. The Aksu River's hydrograph is characterized by a single peak, which occurs in the rainy season (June–August) due to precipitation and snowmelt in its upper catchment (Fig. 2).

The streamflow data are from the Xiehela Hydrologic Station (79° 37′E, 41° 34′N, elevation 1427 m, 1957–2006) on the Kumalake River and the Shaliguilan Hydrologic Station (78° 36′E, 40° 57′N, elevation 1909 m, 1957–2006) on the Tuoshigan River, and were provided by the Hydrological and Water Resources Bureau of Xinjiang. The location and type of gauge at the two hydrological stations have not changed over the study period and the streamflow data are expected to be homogenous. The station data records natural streamflow because the quantity of water flowing in any watercourse before 2006 was not affected by human activity. The total observed streamflow data from 1957 to 2006 from both hydrological stations were used to analyze the relationship between tree-ring chronology and the streamflow for the Aksu River. The streamflow from the October to September is defined as the water-year streamflow (Case and MacDonald, 2003). The average water-year streamflow (1958–2005) for the Aksu River is 242 m^3/s. The source of streamflow is mainly from snow and glacier meltwater, precipitation, and groundwater. Precipitation and baseflow in the basin is very important to the streamflow (Fan et al., 2014).

Development of the tree-ring chronologies

Trees were sampled according to the standards of the International Tree-Ring Data Bank. The tree ring chronologies used in this study were obtained from five sampling sites. Location information and basic chronology statistics are provided in Figure 1 and Table 1. At all sites the tree species that was sampled was Schrenk spruce (*Picea schrenkiana Fisch*. et Mey.). These trees grow in poor soil conditions in virgin forests.

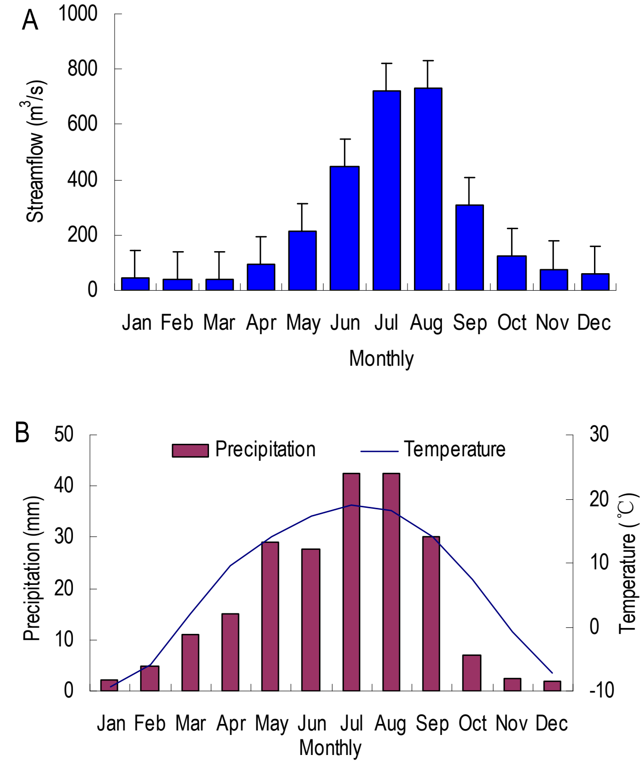

Figure 2. Streamflow and climate variability in Aksu River Basin. A). Monthly variability of streamflow in the Aksu River (1958–2006). B). Mean temperature and precipitation of Aheqi meteorological station (1957–2013).

All tree-ring samples were prepared and cross-dated according to standard dendrochronological procedures (Stokes and Smiley, 1968). Each individual ring was thus accurately assigned a calendar year. The cross-dated tree rings were measured on a tree-ring-width measuring system with a precision of 0.001 mm. The quality control of cross-dating was carried out using COFECHA (Holmes, 1983). Cores with any ambiguities were excluded from further analyses. In total, 279 cores were used for further analysis (Table 1).

Each individual ring-width measurement series was detrended and standardized to ring-width indices using the ARSTAN_41d program (2003, Dendrochronology Program Library, http://www.ltrr.arizona.edu/software.html). Undesirable growth trends related to age and stand dynamics unrelated to climatic variations were removed from each series during the detrending process. We used a negative exponential curve fitting with and without application of an adaptive power transform (NEP) (Cook and Peters, 1997). After all these processes, we obtained standard, residual, and ARSTAN chronologies. Subsample signal strength was used to assess the adequacy of replication in the early years of the chronology, which can ensure the reliability of the reconstructed streamflow (Wigley et al., 1984). We restricted our analysis to the period with subsample signal strength of at least 0.85 to use the maximum length of the tree-ring chronologies and ensure the reliability of the reconstructions (Fig. 3).

Statistical analyses

The relationships between streamflow and tree-ring width were analyzed using simple Pearson correlation analysis with the Statistical Product and Service Solutions (SPSS) program. All statistical procedures were evaluated at $p < 0.05$ level of significance. Tree

Table 1
Location information and basic chronology statistics.

Sampling sites	Site	Location (°N, °E)	Elevation (m asl)	Cores	Chronology interval SSS > 0.85
Yingate River	YAT	41°33′, 79°05′	2800 m	46	1607–2005
Zhendan River	ZDH	41°40′, 79°14′	3100 m	72	1608–2005
Wulijielike	WLJ	41°39′, 79°17′	3000 m	47	1616–2005
Datailan	DTL	41°47′, 80°23′	3000 m	56	1692–2005
Xiaokuzibayi	XKZ	41°49′, 80°37′	3200 m	58	1556–2005

growth may be affected by the hydrological conditions of the previous season as well as those of the current growing season (Fritts, 1976). Therefore, the streamflow data used for the response function and the correlation analysis included monthly streamflow over a 15-month period (previous July to current September). Annual streamflow modeling was conducted using the transfer function approach (Fritts, 1976; Cook and Kairiukstis, 1990). Multiple stepwise linear regression was used to develop a linear model to estimate the dependent streamflow variable, e.g., total annual streamflow, from a set of potential tree ring predictors (Fritts, 1974).

The calibration model was evaluated based on the variance in the instrumental record explained by the model after adjustment for loss of degrees of freedom (R^2 cal). We examined all streamflow subsets for successive months from the previous October to the current September. The data set from 1958 to 2005 was too short for a meaningful division into two subsets for calibration and verification (Fritts et al., 1990), so the leave-one-out cross-validation method (Michaelsen, 1987) was used to verify our reconstruction. Several statistics, including sign tests of both the first-differencing data and the raw data, the reduction of error (RE), and correlation coefficients were calculated to evaluate the similarity between the observed data and the estimated data. Sign tests measure the degree of association between series (or variables) by counting the numbers of agreements and disagreements in the two series. The series are correlated if the number of similarities is significantly larger than the number of dissimilarities. The RE statistic provides a rigorous test of the association between actual and estimated data, and any positive value is considered to indicate the predictive ability of the model. A positive RE is evidence for a valid regression model (Fritts, 1976).

Finally, if the developed model passed the verification tests in the previous step, it was applied to the pre-industrial tree ring index series to estimate a long-term record of streamflow.

Results and discussion

Correlation analysis and reconstruction

Correlation and response analyses show that there is a higher correlation coefficient between the five standardized tree-ring chronologies and streamflow from the previous October to current September of the Aksu River. The highest correlation coefficient between the chronology in ZDH and streamflow from the previous October to current September is 0.689 ($p < 0.001$, $n = 48$). Based on the results, the streamflow from the previous October to current September was reconstructed. A transfer function was designed as:

$$Q_{L10-9} = 102.7 - 40.5 \times WLJ + 18.4 \times YAT + 80.6 \times ZDH + 127.4 \times DTL - 42.3 \times XKZ, \quad (1)$$

where $Q_{L10\text{-}9}$ is the water year streamflow of the previous October to current September. During the calibration period (1958–2006), the reconstruction tracks the observation very well, with an explained variance of 65.1% (61.0% after adjustment for loss of degrees of freedom) in the observed streamflow data. In model (1), $n = 47$, $r = 0.807$, $F = 15.7$, and $p < 0.01$. The Durbin–Watson value (Durbin and Watson, 1951) is 1.616 for $n = 48$. During the calibrated period (1958–2005), the reconstructed streamflow from the previous October to current September tracked the observation very well (Fig. 4). The reconstructed series reveals streamflow variability over the past 314 yr for the Aksu River.

Validation of the reconstruction

The model passed all calibrations. The cross-validation test yielded a positive RE (0.56), thus indicating the predictive skill of the regression model. The statistically significant sign test (30+, 17−, $p < 0.10$) and correlation ($r = 0.751$, $p < 0.0001$), and the first difference sign test (35+, 13−, $p < 0.01$) and correlation ($r = 0.517$, $p < 0.001$) between the recorded data and the leave-one-out-derived estimates, respectively, also indicate the validity of the reconstruction. In addition, the first-order differential has a higher correlation ($r = 0.6$, $p < 0.001$, $n = 47$, Pearson) between the reconstructed and observed. The reliability of the reconstruction was further validated because high-frequency change is consistent between the reconstructed and observed.

The reconstructed series was further compared with historical records. Few documentary records are available for validating our reconstruction before the 1950s. Zhang (2000) reported an extremely dry period from 1784 to 1787 across a large area of China. In our reconstruction, there was a dry period from 1784 to 1787 with the streamflow at about 8.5% below normal. Historical documents show flooding in Yarkant River (+30.0%) in July 1804. In

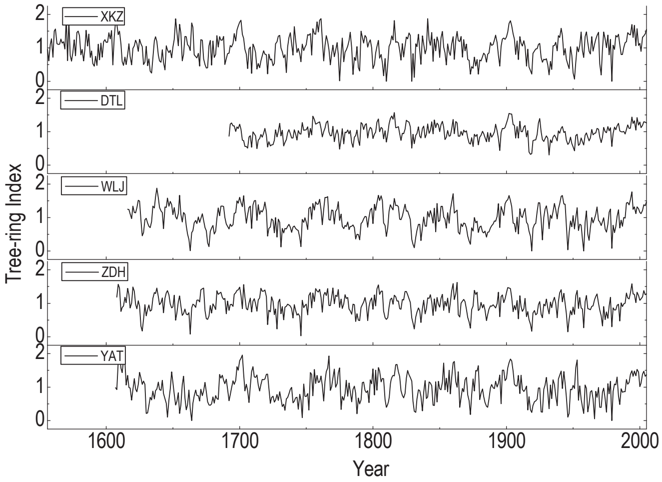

Figure 3. Five standardized (STD) tree-ring width chronologies for the Aksu River Basin. These chronologies are reliable because the subsample signal strength (SSS) of the chronologies were restricted at least 0.85. XKZ represents Xiaokuzibayi standardized tree-ring width chronology, DTL represents Datailan standardized tree-ring width chronology, WLJ represents Wulijielike standardized tree-ring width chronology, ZDH represents Zhenda River standardized tree-ring width chronology and YAT represents Yingate River standardized tree-ring width chronology.

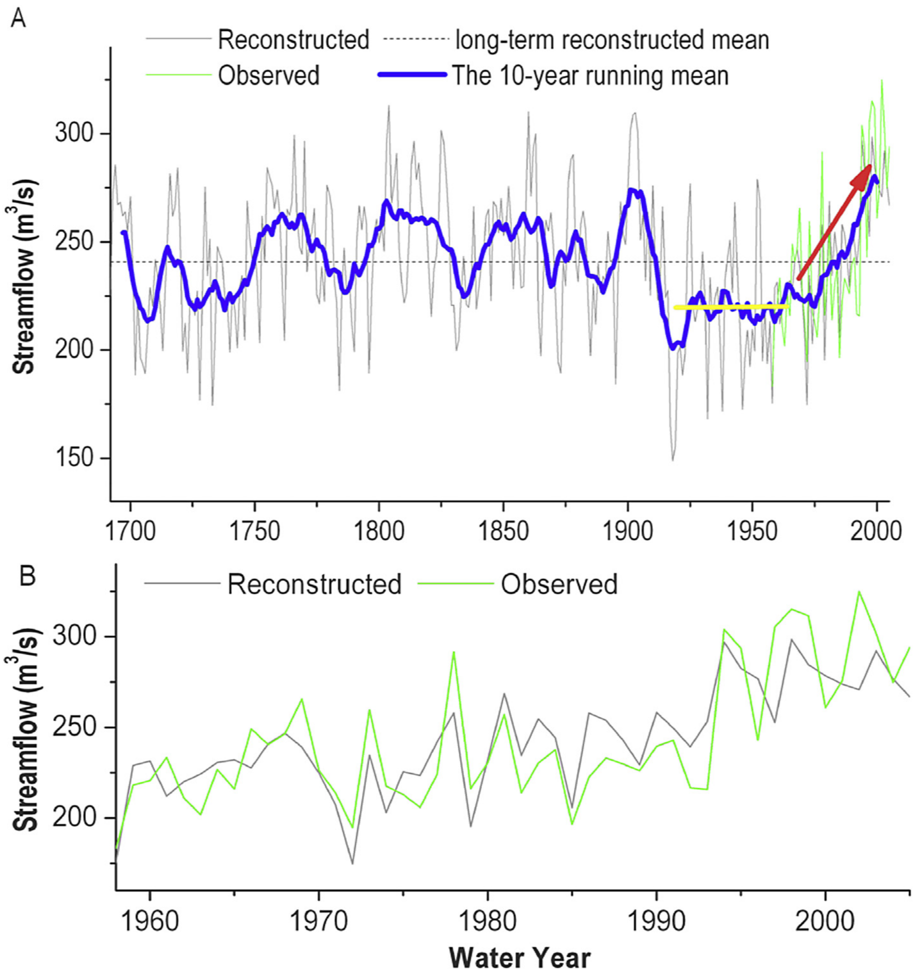

Figure 4. Historic streamflow variability for the Aksu River. A). The reconstructed the water-year (October–September) streamflow for the Aksu River (1692–2005). B). Comparison between the observed and reconstructed streamflow for the Aksu River (1958–2005). Reconstructed annual streamflow for the Aksu River is shown in gray. The 10-yr running mean of the reconstructed streamflow (blue). Observed Streamflow (green) and mean long-term reconstructed (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

addition, the Tarim River rose and broke its banks in Shaya (+20.8%) in 1807, in Bachu (+7.0%) during 1851–1861, rose rapidly in Aksu (+28.9%) in May 1860, flooded in Spring 1900 in Tarim River (+14.2%), became more arid in 1917–1929 in Xinjiang (−15.0%), became drier in 1916 (−5.4%), 1917 (−31.3%), 1918 (−38.3%), 1919 (−35.4%), and 1920 (−17.5%) in Xingjiang, and experienced severe drought from Summer to Autumn in 1932 (+30.2%) in most parts of Xinjiang (Editorial Committee of XinJiang Chorography, 1998). The historical hydrological and climatic records are consistent with the results of this reconstruction.

To examine whether there is a connection between our reconstruction and other reconstructions in the Tien Shan, four precipitation reconstructions based on tree-ring width, including the Aksu River Basin (Zhang et al., 2011), western Tien Shan (Zhang et al., 2016), Tien Shan (Wei et al., 2008), and central Tien Shan (Gao et al., 2011) were selected for comparison. After applying an 11-yr moving average, the droughts and pluvial periods of our reconstruction correspond well with other precipitation reconstructions (Fig. 5). The Pearson correlation coefficients between the reconstructed streamflow and four precipitation reconstructions are 0.436 ($p < 0.01$, $n = 314$), 0.343 ($p < 0.01$, $n = 120$), 0.247 ($p < 0.01$, $n = 235$), and 0.141($p < 0.05$, $n = 312$), respectively. Fan et al. (2014) suggested that precipitation plays a decisive role in the streamflow for the Aksu River. Therefore, there is a positive correlation between streamflow and precipitation in the Tien Shan. The high correlation between streamflow and precipitation further validates our reconstructed streamflow series.

Long-term streamflow change of Aksu River

The reconstructed streamflow series for the Aksu River (1692–2005) show important inter-annual to multi-decadal variability, with common transitions from dry to wet, or wet to dry, intervals throughout the reconstruction (Fig. 4). A list of the lowest and highest reconstructed streamflow for the Aksu River since 1692 shows that all of the five lowest stream flows occurred during the 20th century, with the lowest in 1918, which was the driest year over the past 300 yr (Table 2). The four 5-yr lowest streamflow periods were 1915–1919, 1945–1949, 1955–1959, and 1920–1924. The three 5-yr highest streamflow periods were 1900–1904, 1995–1999, and 2000–2004. In terms of the 10-yr averages, the 1930s, 1910s, and 1950s were the driest among the five lowest streamflow events over the past 300 yr, while the periods of the 2000s, 1900s, and 1990s were at the top of the highest streamflow over the past three centuries. We also analyzed the frequency of single- to multiple-year droughts. The periods at the beginning and the end of the 20th century until present had the highest streamflow, and the mid-20th century period was the longest and driest

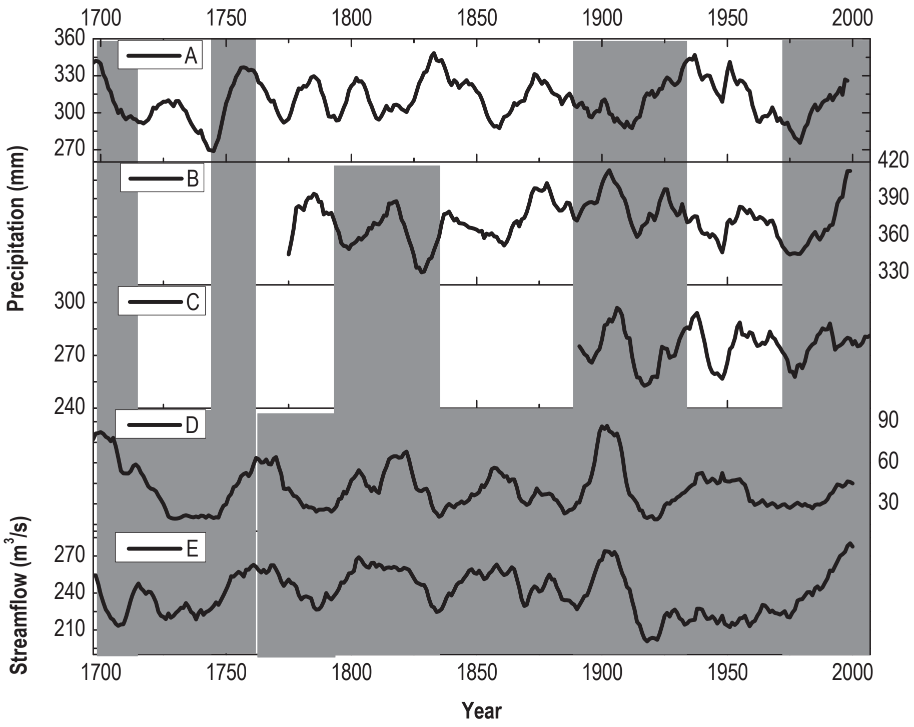

Figure 5. Comparison of the streamflow with four precipitation series in Tien Shan (11-yr moving average). A) Reconstructed precipitation in central Tien Shan (Gao et al., 2011). B) Reconstructed precipitation of Tien Shan (Wei et al., 2008). C) Reconstructed precipitation in Issyk-Kul Basin (Zhang et al., 2016). D) Reconstructed precipitation in the Aksu River Basin (Zhang et al., 2009). E) Reconstructed streamflow for the Aksu River.

period over the past 300 yr. The two periods of significantly increased streamflow coincide with glacial fluctuations. This shows the most rapid glacial retreat at the beginning of the 20th century on the southern slopes of Tien Shan, and the rapid glacier retreat since the 1970s in Xinjiang (Zhang and Zhang, 2007).

We used the Modulus ratio coefficient (K_p = annual streamflow/mean annual streamflow) to differentiate pluvial, normal, and drought years (Kang et al., 2002). The extreme dry years ($K_p < 0.84$) were not evenly distributed throughout the complete reconstruction period, and were slightly more frequent during the 20th than the previous two centuries (Table 3). Particularly interesting is the clustering of extreme dry years during the 1700s and 1910–1950s with two consecutive years of extreme drought in 1704–1706 and 1917–1919. The extreme drought in 1917–1919 is a universal precipitation reconstruction based on tree rings in Xinjiang (Yuan et al., 2001, 2003; Wei et al., 2008; Zhang et al., 2011, 2012, 2016; Gao et al., 2011). A study of the tree-ring-based, water-year (October–September) streamflow reconstruction for the Manasi River in the northern Tien Shan shows that the driest period was 1917–1921 and the longest extended dry period lasted 14 yr (1911–1924) (Yuan et al., 2007). This result is consistent with our study. The extreme drought period is also evident in the Yili River, Guxiang River in Hami (Li et al., 2000) and Tongtian River in Tibetan Plateau (Qin et al., 2004). The historical documents also show that Xingjiang was dry between 1917 and 1920 (Shi et al., 1991).

Over the past centuries, the streamflow has clearly decreased rapidly over the first two decades of the 20th century. Subsequently, the streamflow was relatively stable and maintained a low level from the 1930s to the 1950s. The streamflow clearly increased rapidly from the beginning in the 1960s until present (Fig. 4). There is a similar trend in the precipitation of the central Tien Shan (Li et al., 2006), western Tien Shan (Aizen et al., 2001), northern Pakistan (Treydte et al., 2006), and Mongolia (Pederson et al., 2001).

Possible factors of historical streamflow

The ultimate goal of this study is to better understand the role of large-scale climate-forcing mechanisms in the hydroclimatic variability of the Aksu River Basin. To this end, we obtained the values of atmospheric teleconnections shown to be related to the streamflow for the Aksu River for analysis.

Airflow from the west predominates in the middle and upper troposphere (from 3 to 12 km) in middle Asia (Aizen et al., 1995), and is one of the main sources of moisture. Aizen et al. (2001)

Table 2
Lowest and highest n-year averages of the reconstructed streamflow (1692–2005). Events are non-overlapping averages of the mean streamflow in the Aksu River streamflow (m^3 s^{-1}) for n-year periods. Events ranked 1–5 are the most severe reconstructed events and “actual” indicates the most severe observed event.

Rank	Droughts			Pluvials		
	1 yr	5 yr	10 yr	1 yr	5 yr	10 yr
1	148.6 (1918)	184.3 (1915–1919)	214.9 (1930S)	313.1 (1804)	299.0 (1900–1904)	276.5 (2000S)
2	155.6 (1919)	195.7 (1945–1949)	215.1 (1720S)	310.0 (1860)	279.0 (1995–1999)	273.0 (1900S)
3	165.3 (1917)	206.0 (1955–1959)	215.7 (1910S)	309.7 (1903)	278.6 (1860–1864)	269.2 (1990S)
4	168.1 (1932)	208.0 (1705–1709)	216.0 (1700S)	308.6 (1902)	278.4 (2000–2004)	267.5 (1800S)
5	171.8 (1938)	208.1 (1920–1924)	218.2 (1950S)	301.5 (1825)	276.0 (1755–1759)	263.2 (1810S)

Table 3
Comparison of high-flow years and low-flow years from the past 300 yr. K_p represents the modulus ratio coefficient (K_p = annual streamflow/mean annual streamflow).

	Extreme high-flow years	High-flow years	Normal years	Low-flow years	Extreme low-flow years
Modulus ratio coefficient year (a)	$K_p > 1.16$ 29	$1.16 > K_p > 1.06$ 77	$1.06 > K_p > 0.95$ 97	$0.95 > K_p > 0.84$ 73	$K_p < 0.84$ 38
Percentage (%)	9.2	24.5	30.9	23.2	12.1

showed that annual and seasonal precipitation at the mid-latitudes of Asia can be linked to the major components of the mid-latitude atmospheric circulation. They supposed that between 1931 and 1990 in the central Asian mountains, the zonal circulation patterns predominated from 1931 to 1960, and the meridional circulation patterns predominated from 1961 to 1990. The North Atlantic Oscillation (NAO) is one of the main atmospheric circulation patterns from the west influencing the amount of rainfall at mid-latitudes in continental Asia (Aizen et al., 2001). A change of circulation patterns, the manifestation of which is NAO variability, may impact precipitation, indirectly affecting streamflow. For example, the predominant zonal circulation patterns may have led to the extreme dry period of 1910–1950 in the Aksu River Basin. The meridional circulation patterns dominant from the 1960s until present may be one of the reasons that the climate is becoming warmer and wetter in northwestern China. In the long term, the reconstructed streamflow series has a significant positive correlation with the annual (4-yr lag) and winter (4-yr lag) NAOI (Li and Wang, 2003). The highest correlation coefficient is between the NAOI in winter (December–February) and our reconstructed streamflow, reaching 0.45 ($n = 54$, $p < 0.01$) from 1952 to 2005. A study by Xu et al. (2014) showed that the regional drought variability is linked with the NAO on the long-term scale. Much of the observed interannual-decadal variability in middle eastern streamflow is physically linked to a large-scale atmospheric circulation pattern such as the NAO (Tabari et al., 2014). Burt and Howden (2013) found that the hydroclimatology of rainfall and river flow in upland areas is closely coupled with the strength of atmospheric circulation. Li et al. (2009) also showed that the winter NAO has a lag-effect on runoff for the Aksu River catchment. When the NAO is in its positive phase, the westerly flow over the North Atlantic is strengthened (Hurrell, 2001; Visbeck et al., 2001). Stronger westerly winds may lead to abundant precipitation in Tien Shan and increase the streamflow for the Aksu River. This suggests that the atmospheric circulation may indirectly influence the streamflow for the Aksu River on both short- and long-term scales by affecting precipitation.

In addition, a positive trend in precipitation could be the result of a global air temperature increase over recent decades. If so, as the Siberian High is weakened or displaced, a strengthened or displaced westerly could bring more moisture-laden air masses to regions (Aizen et al., 2001). At the same time, a global air temperature increase can lead to accelerated melting of snow and glaciers in the western Tien Shan. Hence, the change in streamflow is synchronized with the change in air temperature and precipitation. Coincidence of positive trends in precipitation and accelerated melting of snow/glacier may be a direct reason for a clear and rapid increase of streamflow during the 1960s. We suggest that the recent streamflow anomalies in the Aksu River are strongly linked to human-induced global climate change and mid-latitude atmospheric circulation transformation.

Strong inter-annual streamflow variability was identified in the Aksu River using the multi-taper method (Thomson, 1982). There are significant 2.0-yr (99%), 2.8-yr (95%), 3.1-yr (99%), and 12.0-yr (95%) cycles in the annual streamflow. The reconstruction by Liu et al. (2010) based on tree-ring width analysis shows that the average runoff for the Heihe River from 1430 to 2007 has 2-yr cycles, which is consistent with the results of our study. The reconstruction of Gou et al. (2010) based on tree-ring width analysis shows that the streamflow for the Upper Yellow River over the past 1234 yr also has 2- to 5-yr cycles. The 2.0- to 3.1-yr cycles indicate that our reconstructed streamflow variation may have some teleconnections with the oscillations of land-atmospheric-ocean circulation systems because this cycle may be related to the El Niño–Southern Oscillation and the Quasi Biennial Oscillation in the stratosphere (Meehl, 1987). Chen et al. (2011) argued that the Troposphere Biennial Oscillation signal of westerly circulation is the decisive factor associated with precipitation in arid Central Asia. The 12.0-yr (~11-yr) cycle corresponds with Schwabe cycles in solar activity (Rind, 2002). The peaks resemble other findings in surrounding areas, which suggested that solar activity may affect historical streamflow variability (Pederson et al., 2001; Liu et al., 2003; Li et al., 2006). This suggests that changes in the streamflow for the Aksu River may be related to solar activity and large-scale oscillation of the climate system.

Conclusions

This study developed a long hydrological series combining tree-ring and natural hydrological data. The 1700s–1740s had a relatively low streamflow value, the 1750s–1900s had a higher streamflow value, the 1910s–1980s had a lower streamflow value, and the streamflow value has then remained relatively to the present. Over the past hundred years, the streamflow has fluctuated, decreasing rapidly and clearly over two decades at the beginning of the 20th century, then stabilized and maintained a low level during the 1930s–1950s, and finally increased rapidly from the 1960s to present. The 20th century contains some of the driest and wettest annual- to decadal-scale events over the past 300 yr. In the long term, the reconstructed streamflow series was significantly positively correlated with the NAOI in winter. This suggests that the atmospheric circulation (NAO) may indirectly influence the streamflow for the Aksu River on both short- and long-term scales by affecting precipitation. The recent streamflow anomaly (rapid and clear increase during the 1960s) is strongly linked with human-induce global climate change and mid-latitude atmospheric circulation. The 2.0- to 3.1-yr and 12-yr cycles suggests that the streamflow variation may be the result of teleconnections with land-atmospheric-ocean circulation systems and solar activity.

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