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Late Holocene climatic and environmental changes in arid central Asia

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Abstract

Late Holocene climate and environmental changes in arid central Asia were analyzed using various paleoclimate archives such as ice cores, tree rings, lake sediments, historical documents, glacial fluctuations and archeological data. Over the last 2000 years, arid central Asia witnessed three humid periods from AD 0–410, 650–890 and 1500–1820s. Dry periods occurred in 420–660 and in 900–1510s. Concerning temperature, the most striking features are the existence of the Medieval Warm Period (MWP) and the Little Ice Age (LIA). The MWP was recorded in the 9–12th centuries and was accompanied by an anomalously dry climate, whereas the LIA extended from the 15–18th centuries and was accompanied by pluvial conditions. Temperature and precipitation show significantly negative correlations on annual, decadal and centennial timescales. Temperature was generally above average when dry climate conditions predominated on decadal to centennial timescales during the last 1000 years. The coldest decades of the last millennium, the period 1630–1650s, matched with an anomalously wet episode. The combination of paleoclimatic evidence clearly suggests that the combination of cold and wet climate condition during the LIA was responsible for the strong glacial advances in several mountain systems of central Asia.

1. Introduction

The arid region of central Asia is mainly affected by two climatic systems, the mid-latitude westerlies and the Siberian High. Variations in intensity and locations of these two pressure systems and their interaction have a strong influence on climate change in various parts of arid central Asia (Aizen et al., 1997), between 70–95°E and 35–45°N. In the last decades, many paleoclimatic records from this area were derived from ice cores, tree rings, archeological data, lake sediments and glacier fluctuations (Thompson et al., 1995; Thompson, 1996; Yao et al., 1996a, b; Marchenko and Gorbunov, 1997; Yao, 1997; Esper et al., 2002, 2003; Narama, 2002a, b; Solomina and Alverson, 2004; Wu et al., 2004; Treydte et al., 2006). These climate reconstructions provide a chance to describe and understand the full range of natural climate system behavior of this region in the context of the past two millennia, a period that includes the so-called Medieval Warm Period (MWP) and the Little Ice Age (LIA).

Solomina and Alverson (2004) compiled paleoclimatic records derived from tree rings, glacier fluctuations, lake sediments and other proxies for the past 1500 years from high latitude Eurasia, including central Asia, the Arctic and Sub-Arctic, the Russian Plain, Caucasus, Eastern Siberia, and the Russian Far East. Unfortunately, all those proxy data come from the former Soviet Union territory, and exclude western China. In addition, little attention was paid to the relationship between temperature and precipitation at different timescales. In particular, it is still unclear how the MWP and LIA were accompanied by precipitation changes. A better understanding of variations of the temperature/precipitation combination at various timescales would be helpful to predict the future development of water resource evolution in a warming environment. This paper attempts to make a synthesis of the available proxy records in arid central Asia to highlight temperature and precipitation variations during the last 2000 years. It particularly focuses on the relationship

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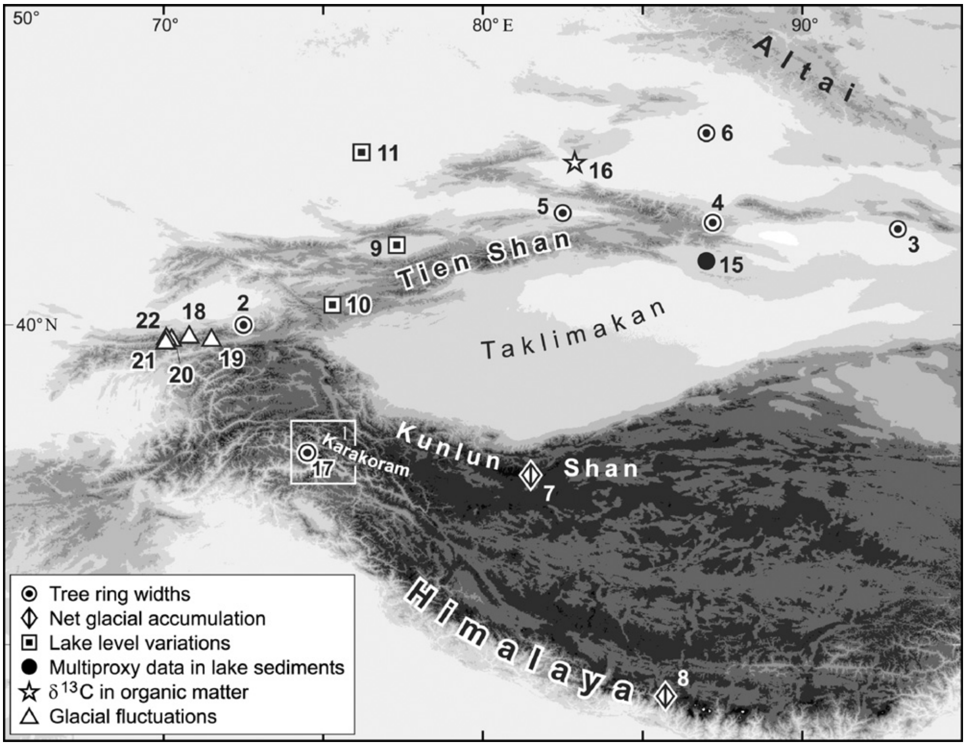

Fig. 1. Sketch map showing locations of paleoclimatic records in arid central Asia. 1, northwest Karakorum; 2, southern Tien Shan; 3, Hami region in eastern Tien Shan; 4, central Tien Shan; 5, Yili region in western Tien Shan; 6, northern Xinjiang region; 7, Guliya ice core; 8, Dasuopu ice core; 9, Issyk-Kul Lake; 10, Chatyr-Kel Lake; 11, Balkhash Lake; 15, Bosten Lake; 16, Aibi Lake; 17, northern Pakistan; 18, the Raigorodskogo Glacier; 19, the Abramova Glacier; 20, Asan-Usin Glacier; 21, Ak-Su Glacier; 22, Tokuzblak Glacier. Note that sites Shalkar Lake, Caspian Sea and Aral Sea (numbered 12–14) are not indicated in this map due to spatial constraint of this study region in this paper.

between temperature and precipitation changes on timescales ranging from annual to centennial. Fig. 1 illustrates the study area and proxy record sites used in this paper.

2. Precipitation changes during the last two millennia

2.1. Annual correlation between the Guliya ice-core accumulation data and precipitation

The Guliya ice cap is located in the western Kunlun Shan (35.3°N, 81.5°E) at an elevation of 6200 m. The timescale for the last 2000 years of the Guliya ice core-2 was established by counting visible annual dust layers, which allowed the reconstruction of net accumulation rates of snow for the last two millennia (Thompson et al., 1995; Thompson, 1996; Yao et al., 1996a, b). To examine the climatological significance and spatial representativeness of the Guliya net accumulation record (GA), a correlation between 3-year smoothed time series between the GA and precipitation data for the period of 1950–1989 was computed for this study region (Fig. 2), keeping in mind that a dating error of 1 year in the ice-core record may have a strong effect on the results (Thompson et al., 2000), which from practical experience is seen possible during the most recent 40-year period. The correlation period is restricted to 1950–1989 because almost all observational precipitation data in China start in 1950. GA has a close correlation, with highest values up to 0.5 ($p<0.01$), with precipitation data from the Xinjiang region of China and bordering areas to the west. This exercise suggests that GA is a reasonable proxy of precipitation change in arid central Asia on an annual timescale. It is noteworthy that the GA is negatively correlated with precipitation data from northern and central parts of India. Below study indicates that the GA is also negatively correlated with an ice-core accumulation record from Dasuopu Glacier on a decadal timescale during the last 600 years, and the latter reflects variations of the south Asian monsoon.

For the regions with high correlations between GA and precipitation outlined in Fig. 2, gridded precipitation anomalies (2.5° latitude × 3.75° longitude) that provide continuous precipitation records based on instrumental measurements back to 1900 (http://www.cru.uea.ac.uk/mikeh/datasets/global/) were considered (Hulme, 1996; Hulme et al., 1998). Fig. 3 illustrates that the precipitation anomalies for these two coordinates (42.5°N, 78.75°E; 37.5°N, 78.753°E) and GA show partly similar variations. Correlation coefficients between the 5-year smoothed data are 0.41 and 0.32, respectively. This provides further support that the GA is an indicator of precipitation change in arid central Asia on an annual timescale.

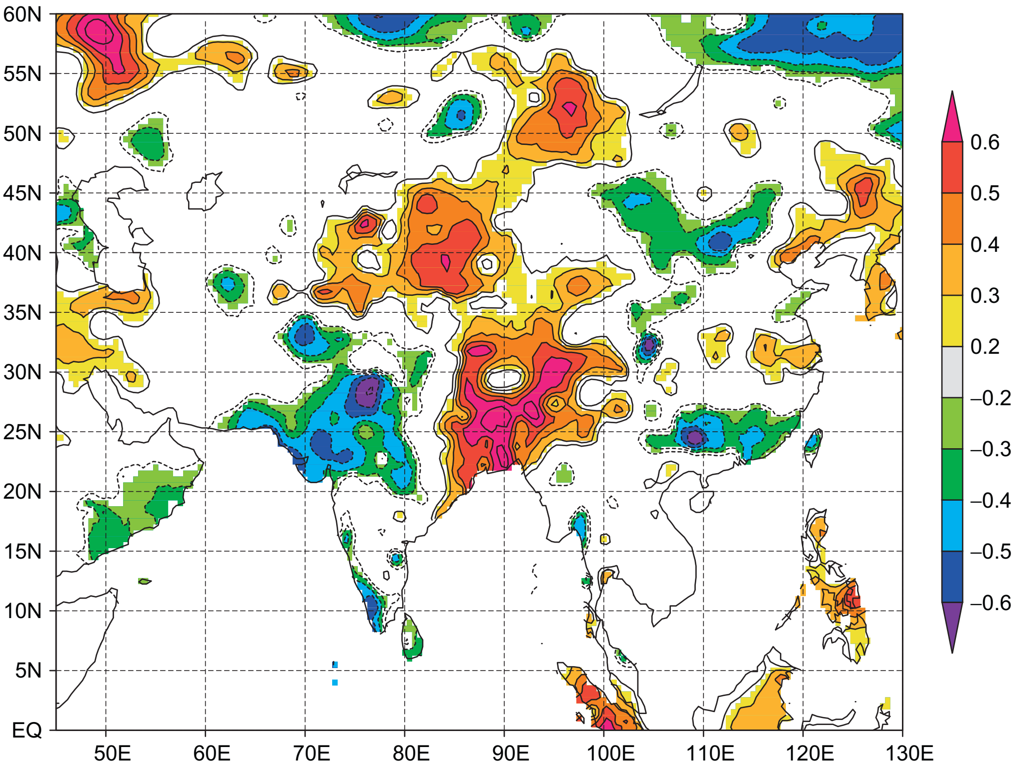

Fig. 2. Three-year running mean correlation between Guliya ice-core accumulation and precipitation observations from central Asia 1950–1989. The map is created with http://climexp.knmi.nl/.

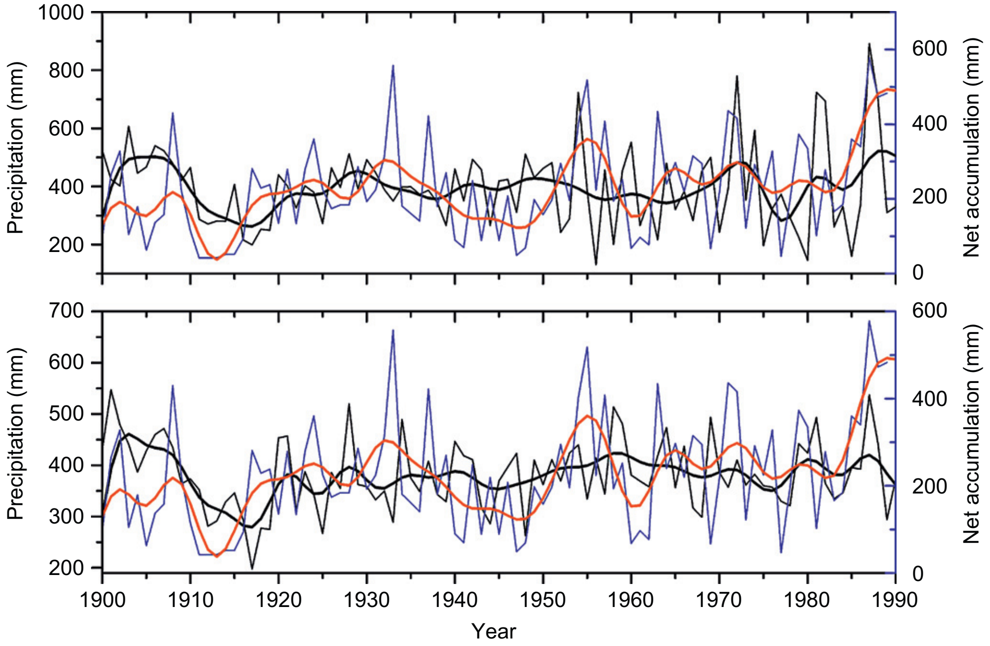

Fig. 3. Comparison of the GA and precipitation variation from two grids during 1900–1989. Heavy lines are 5-year FFT filter.

2.2. *Long-term calibration of the Guliya ice-core net accumulation record*

As stated above, GA can represent precipitation variations in arid central Asia on short-term (annual) timescales. In addition, there is evidence that the GA is also indicative of long-term precipitation variations over a broad region. According to Wang et al. (2004), GA shows good agreement with other regional precipitation records from Tien Shan Mountains and the northern Xinjiang region of

China (43–46°N, 82.5–93°E), which were established based on tree-ring width records. Decadal-scale correlations between the GA and these tree-ring based precipitation records for the last 500 years vary from 0.42 to 0.67, each significant at 95% confidence level (Table 1). A recent tree-ring based April–June Palmer Drought Severity Index reconstruction for central Tien Shan in China (Li et al., 2006) shows similar low-frequency variability to that of the GA record over the past 300 years.

Based on assembled Chinese historical documents Liu (1976) suggested that river flow at the southern fringe of the Tarim Basin increased during the AD 1–300, 650–800 and 1450–1850 periods, which is consistent with historical GA record for the last 2000 years (Fig. 4, Yao et al., 1996a, b; B. Yang et al., 2004).

Solomina and Alverson (2004) provided a summary on lake level fluctuations in central Asia reconstructed from archeological and radiocarbon data. According to their compilation, Lake Issyk-Kul was about 5–7 m below its present level during the 9–16th centuries whereas the lake level was 5–8 m above its present level during the 1–4th and 17–19th centuries. Chatyr-Kel Lake experienced a low lake level in the 11th and 16th centuries, and Lake Balkhash regressed around 1200–800 years BP and transgressed around 300 years BP. Additional evidence from radiocarbon dating of lacustrine macrophytes at 1623 m elevation indicates that Issyk-Kul Lake had another high stand with overflow between 1200 and 1400 years BP (Ricketts et al., 2001 and references therein). Therefore, lakes level was low during the Middle Ages throughout the Tien Shan Mountains.

North of 45°N, precipitation changes were different, as documented by higher levels of Shalkar Lake in the 1–3rd and 8–12th centuries and lower lake levels in the 13th and 14th centuries. In addition, the Aral and Caspian Seas to the west of arid central Asia exhibit different features in lake level fluctuations during the last 2000 years, except for a generally high lake level period during the 16–19th centuries and a low level condition during the late Medieval (the 13–14th centuries) period (Klige, 1990; Solomina and Alverson, 2004; Boroffka et al., 2006; Reinhardt et al., 2007). New evidence from geomorphological and sedimentological investigations also shows that there was a transgression of the Aral Sea around 200 AD (Reinhardt et al., 2007).

In summary, during the 1–4th and 16–19th centuries, climate was wet in arid central Asia and in the Caspian Sea region except for the Aral Sea area. The Aral Sea area witnessed a short-term high lake level around AD 200. Sorrel et al. (2006, 2007) concluded that moisture variations in the Aral Sea region are directly associated with atmospheric circulation in the Eastern Mediterranean during the last 2000 years. This might explain the difference between arid central Asia and regions of the Aral Sea and

Table 1
Decadal-scale correlations for the last 500 years between the GA and other regional precipitation proxy records

Site name	Core site	Proxy type	Source	Corr.	*p*-Value
Hami region in eastern Tianshan	43.0°N, 93.0°E	Tree-ring widths	Li et al. (1989)	0.66	$p < 0.001$
Central Tianshan	43.2°N, 87.2°E	Tree-ring widths	Yuan et al. (2001)	0.69	$p < 0.001$
Yili region in western Tianshan	43.5°N, 82.5°E	Tree-ring widths	Yuan et al. (2000)	0.50	$p < 0.006$
Northern Xinjiang	46.0°N, 87.0°E	Tree-ring widths	Yuan and Han (1991)	0.42	$p < 0.03$

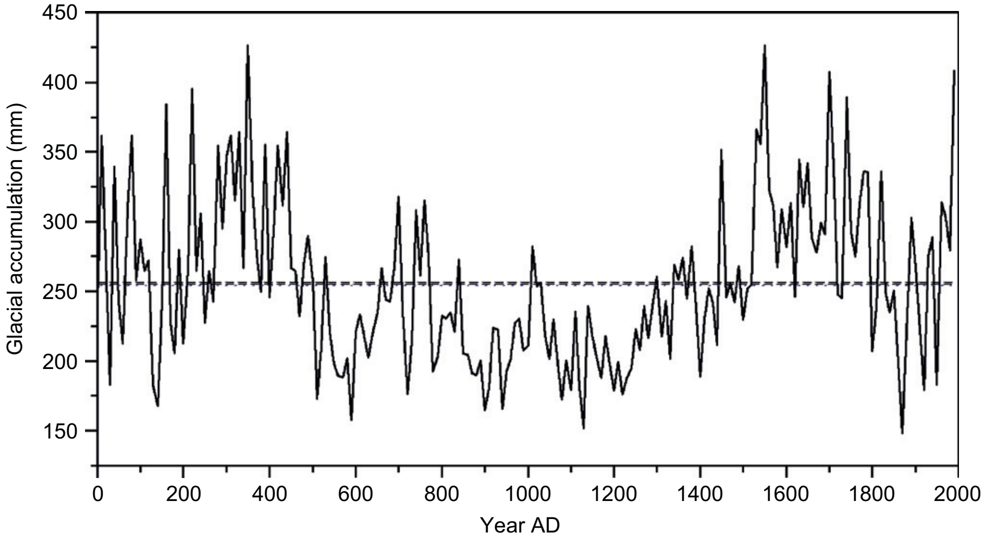

Fig. 4. The GA variations for the last two millennia.

Caspian Sea. West of 70°E, precipitation change patterns differ greatly.

A recent study has been carried out on sediments from Bosten Lake and Aibi Lake in western arid zone of northwest China. The variations of $\delta^{13}C$ in organic matter from Aibi Lake (44°54′–45°08′N, 82°35′–83°10′E) sediments, which is considered as a proxy of precipitation change, indicate that the AD 1460–1860 period witnessed extremely humid climate conditions, while climate was generally dry during AD 500–1460 (Wu et al., 2004). New paleoclimate evidence for the last 1000 years comes from a multi-parameter lake study from Bosten Lake (42°N, 87°E) in the southern Tien Shan. The studied parameters include carbonate content, grain size, and the ratio of Artemisia to Chenopodiaceae (A/C) pollen concentration. The results show that the region experienced the most arid period from AD 500 to 1500. Two obvious humid periods occurred AD 0–300 and during the LIA (AD 1500–1900) (Wünnemann et al., 2003; Chen et al., 2006). The timescale for Bosten Lake was determined based on the measurements of ^{210}Pb and ^{137}Cs using 14 AMS ^{14}C dates whereas the chronology for Aibi Lake sediments was derived from only one ^{14}C date.

The GA shows good agreement with the lake levels of the Tien shan Mountains (including the Issyk-Kul Lake, the Balkhash Lake, the Chatyr-Kel Lake and the Bosten Lake) and the northern Xinjiang region (the Aibi Lake) over the last 2000 years. The best agreement is achieved between level fluctuations of Issyk-Kul Lake and the GA during the last 2000 years. Periods of high lake level, such as the 1–4th and 16–19th centuries, and 1200–1400 BP, as well as low-level periods during the Middle Ages, correspond with the net accumulation record in GA. In particular, the wet period in the 1–4th century occurred in arid locations in northwest China from the Tarim Basin, the Junggar Basin, the Tien Shan and the Alaxa Plateau based on a compilation of ^{14}C-ages of different paleoenvironmental records, historical and archeological data given by Sheppard et al. (2004), B. Yang et al. (2002, 2004), X.P. Yang et al. (2002), and Q.B. Zhang et al. (2003), thus point to a wet climatic period of at least regional extent.

The GA is significantly negatively correlated with an ice-core accumulation record from the Dasuopu glacier that spans the last 600 years. Correlations are −0.34 and −0.54 (both significant at $p<0.05$) after smoothing the decadal resolved series with a 3-point running mean. The Dasuopu ice-core accumulation record is recovered from the south central rim of the Himalayas and is linked with intensity variations of the south Asian monsoon (Thompson et al., 2000). Therefore, it seems that the GA is out of phase with variations of the intensity of the south Asian monsoon during the last six centuries. This makes it easy to understand why the GA is also weakly correlated with an annually resolved (October–September) precipitation reconstruction from the high mountains of northern Pakistan during the last millennium. The latter record was obtained from $\delta^{18}O$ measurements of tree rings (Treydte et al., 2006). Northern Pakistan is affected both by the south Asian monsoon and westerlies.

In summary, GA is a good indicator of precipitation change at annual to centennial timescales, and might represent a large fraction of arid central Asia extending from 70 to 90°E and 35 to 45°N.

3. Temperature changes during the last two millennia

The northwest Karakorum (35–37°N, 74–76°E) and southern Tien Shan (40°N, 72.5°E) are located in the western part of central Asia. Two tree-ring chronologies have been established from these two regions, both covering the last 1000 years were established that retain and retaining low-frequency variability (Esper et al., 2002, 2003, 2007). The tree-ring chronology from the Karakorum region was derived from 17 trees aging over 1000 years by the use of a mean 'average division' method. The Tien Shan chronology was developed by calculating differences between the ring-width measurements and their long-term means using 51 ring width series with lengths >500 years (for details see Esper et al., 2002, 2003). Preliminary correlation analysis of ring-width series and climate data from nearby meteorological stations indicated that both chronologies contain temperature signals.

Solomina and Alverson (2004) made a comparison between the Karakorum tree-ring record and other paleotemperature records from central Asia, including ring widths records from Pamir-Alay, evidence from a number of moraines in the Tien Shan Mountains dated by lichenometry, two radiocarbon dates from peat profiles reaching back to 1000 BP, reconstructed permafrost depth distributions and ground temperature variations in Zailiisky Altau (Tien Shan). The independent proxy temperature records show generally good agreement. They indicate a cool period from 6th to 7th centuries and a warm climate period between the 9 and 11th century, which corresponds to the MWP. Cold condition prevailed from 12th to 19th centuries that is correlative to the LIA. This period was interrupted by a brief warm episode centered on the early 15th century.

Analysis of the Raigorodskogo Glacier variations provided further evidence of temperature changes during the late Holocene. According to Narama (2002a, b), the fluctuations of the Raigorodskogo Glacier are mainly caused by summer temperature change as recorded in the nearby Fergana meteorological station on a decadal timescale. According to Esper et al. (2003), the June–September temperatures recorded at Fergana correlate with the Tien Shan tree-ring width record over the last 100 years. A composite Tien Shan/Karakorum tree-ring record can be compared with Raigorodskogo Glacier variations. Narama (2002a, b) suggested that two large glacier recessions occurred in 1911–1934 and 1977–1998, a significant advance occurred in 1960–1976, and a stationary or recession period occurred in 1935–1959. The glacier recession rate was 27 m/year in 1911–1934, 13 m/year in

1977–1990, and 21 m/year in 1990–1998. In comparison, the largest values from 1890 to 1916 correspond to the highest glacier recession period whereas the decreasing values during 1958–1976 match the maximum glacier advance. The final increase in the tree-ring chronology is in line with recent glacier recession is noted.

The conformity among tree ring, observational temperature and glacier variation records indicates that fluctuations of the Raigorodskogo Glacier in the Pamir-Alay can provide complementary evidence of temperature change for the past 2000 years. According to ^{14}C-calibrated ages of wood samples from moraine deposits and buried soil layers in terrace exposures, the glacier expanded before 3215 cal. BP, after 1545 cal. BP, and at 310 cal. BP (AD 1630–1650; Narama 2002a). The latter date was derived by the dating of the outermost ring of a toppled *Juniperus turkestanica* that was destroyed during a glacier advance. It indicates the onset of the glacier advance of the maximum expansion of Raigorodskogo Glacier during the LIA.

Two obvious warm periods in which the glacier retreated, occurred immediately before 1545 and 500 cal. BP. Further evidence for these warm periods comes from two ^{14}C dated buried soils with a horizon in the Alay range of the Tien Shan Mountains. Soils developed on the lateral moraine of the Abramova Glacier (39.6°N, 71.5°E) at 2030 ± 60 and 986 ± 60 BP, indicating warmth resulting in interruptions of glacier activity (Zech et al., 2000). These findings provide further evidence that the Tien Shan and Karakorum tree-ring widths represent temperature variations in arid western central Asia on decadal to centennial timescales.

Since the Tien Shan and Karakorum ring widths show similar decadal variations with correlations at 0.27 ($p < 0.05$; Table 2) at this timescale, and since both series respond to a common forcing associated with temperature variations, they were combined into a composite chronology. The composite should be of broader spatial representativeness and more reliable to reflect regional temperature variations. The common features between the two series can be emphasized by computing empirical orthogonal functions (EOFs). In the case of only two series, EOF analysis results in a decomposition in which the first EOF component expresses the dominant similarity (Meeker et al., 1995; Meeker and Mayewski, 2002). Analysis results show that the first EOF shares 64% of the variance of both tree-ring records (Table 3). According to the composite, a warm period during the 11–12th centuries was followed by a cold interval in the 13th century. Warmth is recorded during the 14th century, and a prolonged LIA cool period characterized the 15–18th centuries with the coldest stage from AD 1600 to 1660. Finally, a transition period during 18–19th century with frequent temperature fluctuations was followed by a warm period in the 20th century (Fig. 5). Especially, the LIA maximum AD 1600–1660 matched with the age of 310 ± 10 cal. years BP (AD 1630–1650) of Raigorodskogo Glacier.

The nearby Asan-Usin Glacier experienced a maximum LIA expansion AD 1645–1665, based on a radiocarbon date (250 ± 15 BP) derived from the outermost rings of a tree in a moraine (Narama and Okuno, 2006). Therefore, it is inferred that the cold period during AD 1600–1660might have been responsible for the maximum glacial expansion. In addition, two radiocarbon dates of 470 ± 15 and 370 ± 15 BP, which were obtained from outer rings of pieces of wood found in two moraines Ak-Su Glacier and Tokuzblak Glacier, indicate that these two glaciers experienced maximum expansion during AD 1425–1445 and 1460–1520, respectively (Narama and Okuno, 2006). Considering the uncertainty of radiocarbon dates (the dated material is wood that provides maximum dates for the respective glacier advance), the two glacier advance periods are reasonably consistent with corresponding cold periods indicated by the ring-width composite.

A comparison between the composite tree-ring width record and several temperature reconstructions for China over the last millennium is made. A decadal resolved mean annual temperature record was established by B. Yang

Table 3
Empirical orthogonal functions (EOFs) analysis of the Tien Shan and Karakorum ring-width series (both series was normalized before computing EOFs)

Eigenvector 1	Eigenvector 2	Eigenvector 1	Explained variance
0.71	0.71	0.71	0.64
0.71	−0.71	0.71	0.32

Table 2
Correlation between the Karakorum and the Tien Shan ring width chronologies, the Karakorum/Tien Shan ring-width composite and the GA and temperature reconstructions for China

	Tien Shan tree ring	Karakorum tree ring	The Karakorum/Tien Shan ring-width composite	China temperature reconstruction	GA
Tien Shan tree ring	1				
Karakorum tree ring	0.27	1			
The Karakorum/Tien Shan ring-width composite	0.80	0.80	1		
China temperature reconstruction	0.41	0.39	0.50	1	
GA	−0.44	−0.16	−0.38	−0.33	1

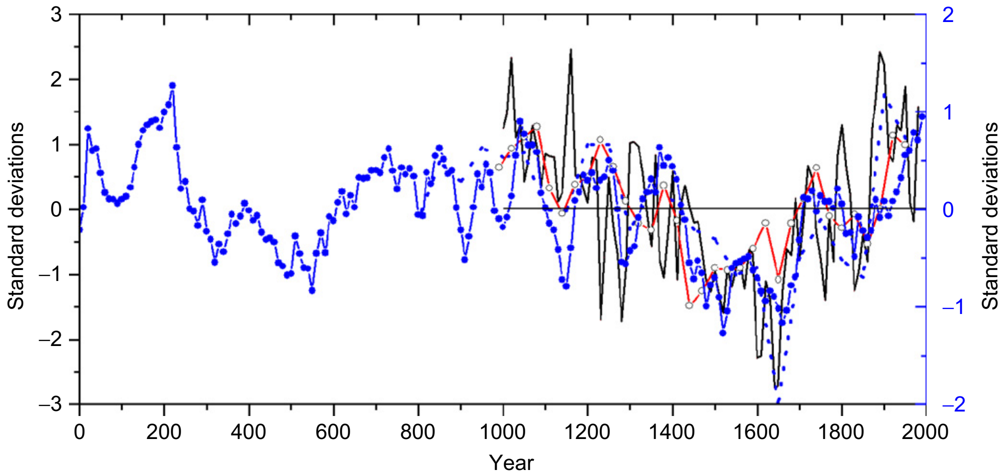

Fig. 5. Comparison between the composite of the Karakorum and Tien Shan ring-width chronologies and several temperature reconstructions for China over the last millennium. Solid line indicates the central Asian ring-width composite, solid circle line is the China temperature reconstructions of B. Yang et al. (2002) and X.P. Yang et al. (2002) open circle line the EC-new for East China formed by averaging the Ge et al. (2003) and Tan et al. (2003), and dashed line represents the Wang et al. (2001) temperature reconstruction for East China.

et al. (2002) by combining multiple paleoclimate records from ice cores, tree rings, lake sediments and historical documents, and is described to represent temperature change for the whole of China. Based on historical documentary proxy data, Wang et al. (2001) and Ge et al. (2003, 2007) established two temperature series for East China spanning the AD 800–2000 and 1–2000 periods, respectively. The Wang et al. (2001) reconstruction has a 50-year resolution and characterizes annual temperature variations whereas the Ge et al. (2003) reconstruction has a 10–30-year resolution and reflects October–April temperatures. Another temperature reconstruction by Tan et al. (2003) was derived from an annually resolved thickness record of a stalagmite near Beijing and is indicative of warm season (May–August) temperature variations in East China during the past 2000 years. Here, an annual temperature series with 30-year resolution for East China (referred as EC-new) is shown that was formed by averaging the Ge et al. (2003) and Tan et al. (2003) series for comparison (Fig. 5).

There is a significant correlation between the central Asian ring-width composite and the China temperature reconstructions of B. Yang et al. (2002), Wang et al. (2001) and EC-new during the last millennium, with correlation coefficients of 0.50 ($n = 99$, $p < 0.01$), 0.53 ($n = 20$, $p < 0.05$) and 0.49 ($n = 32$, $p < 0.01$), respectively. The central Asian ring-width composite is significantly positively correlated ($r = 0.66$, $n = 32$, $p < 0.001$) to the Tan et al. (2003) series whereas it has a weak correlation ($r = 0.03$, $n = 32$) to the Ge et al. (2003) reconstruction. All curves display the warming periods during the 11th and 20th centuries and the cooling in the 15–17th centuries. This similarity suggests a close connection of temperature changes in eastern China and in arid central Asia. It is noteworthy that the China temperature reconstructions are higher correlated with the ring-width composite than with the single Tien Shan or Karakorum series (Table 3), suggesting that the ring-width composite is a good indicator of temperature change in arid central Asia. However, the ring-width composite has a weak correlation with the $\delta^{18}O$ record of the Guliya ice core, although the latter correlates closely ($0.2 \leqslant r \leqslant 0.4$) with annual temperatures of Xinjiang for the common period from 1951 to 1996 (Wang et al., 1998; B. Yang et al., 2004). A possible explanation is that the ice-core $\delta^{18}O$ record in the special site (which is 6200 m high) may be a poor indicator of large-scale long-term temperature change.

4. Temperature/precipitation relationship during the last millennium

Fig. 6 shows the correlation fields between annual mean temperature and total precipitation on the basis of CRU data set for the period 1901–2002 (Hulme, 1996; Hulme et al., 1998). For comparison, the temperature/precipitation correlation in western Asia and eastern China was also included. Areas within 95% confidence limits are shaded. A general feature is that negative correlations dominate the north and central arid Asia, inferring that temperature is above (below) average when dry (wet) conditions predominated in this region. However, positive correlations are found in the regions 40–45°N (western Asia) and 55–70°E (eastern arid region of northwestern China and Mongolia), inferring the predominance of warm–wet conditions. It is noteworthy that analysis of correlations between annual mean temperature and total precipitation during the last 50 years came to the same conclusion. Therefore, the characteristics of climate change in central Asia may vary from west to east at an annual timescale. The relationship between precipitation and temperature will be tested by the use of proxy data in the context of historical background on decadal to centennial timescales.

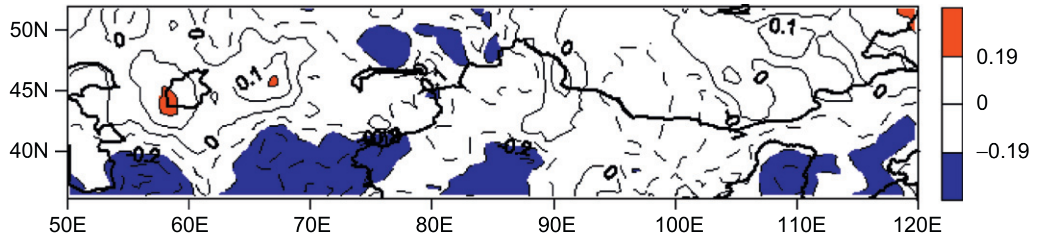

Fig. 6. Map showing the correlation between annual mean temperature and total precipitation on the basis of CRU data set for the period 1901–2002.

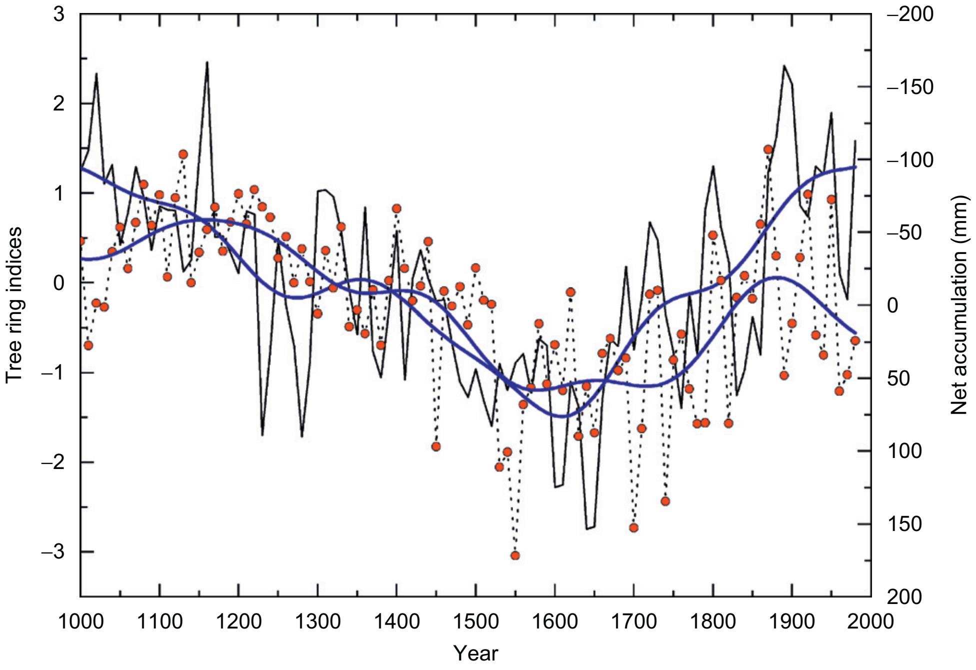

Fig. 7. Comparison of temperature (solid line) and precipitation (dashed dotted line) records in arid central Asia during the last millennium. Note that temperature and precipitation are shown as deviations from the 1000-year mean. The superimposed smoothed curves are derived by Fast Fourier Transform (FFT) filtering to emphasize long-term fluctuations (the FFT smoothing is accomplished by removing Fourier components with frequencies higher than 1/100). For a better comparison of the time series, precipitation scales are inverted.

Fig. 7 illustrates a comparison between temperature and precipitation records during the last 1000 years. The correlation between the decadal resolution time series is -0.38 ($p<0.05$). After smoothing these decadal resolved time series with a 10-point running mean, their correlation coefficient increased to -0.72. For temperature, there is a tendency for above (below) average when dry (wet) conditions predominated on decadal to centennial timescales. An example in case is that the warm period around the 11–12th centuries corresponded with an anomalously dry period, whereas the cold LIA coincided with extremely wet conditions. Also, the warm period in the 9–10th centuries (Esper et al., 2002) was consistent with dry conditions at that time as indicated by low glacial accumulation rate in the Guliya ice core, and low lake levels and low river runoff records derived from historical documents. In a simplified way one can characterize MWP climate as being dominated by warm and dry conditions, whereas LIA climate was cold and humid. Here it is noteworthy that the coldest decades 1630–1650s during the last 1000 years matched with concurrent anomalously high precipitation episodes (Fig. 7). The cold–wet LIA period might have been responsible for the glacial advances that occurred in central Asian mountains, including the Tien Shan and Pamir-Alay, at that time. It can be inferred from the presently available limited data that the extremely cold–wet episode of the 1630–1650s accounted for the maximum LIA glacier advance.

Nevertheless, there are some exceptions concerning the general anticorrelation of temperature and precipitation records. The most significant is that temperature was above the long-term average in the late 18th and 20th centuries when precipitation fluctuated around its average. Another example is that the cold 13th century corresponded to a below-average precipitation event.

5. Conclusions

Proxy data such as tree rings, ice cores, lake sediments, archeological data related to lake level variations, and glacier fluctuations were used to examine climatic and environmental change in arid central Asia during the late Holocene, particularly to climatic features during the two periods of MWP and LIA and the relationship between temperature and precipitation changes during the late Holocene. Cross-validation of various proxies shows that the Guliya ice-core accumulation record can represent precipitation changes in arid central Asia on annual to centennial timescales while the composite from Tien Shan and Karakorum tree-ring width chronologies is indicative of temperature changes over a broad region on decadal to centennial timescales.

According to the Guliya ice-core accumulation record, six periods of precipitation variation, including a wet period during AD 0–420, a dry interval between 420 and 650, a return to pluvial conditions from 650 to 900, an extended dry period 900–1500 including the Middle Ages (1000–1300), and a humid period 1500–1830 during LIA, followed by a period of frequent precipitation variations can be identified. Here it is noteworthy that the dry interval during AD 420–650 also extended to northeastern Tibetan Plateau (J.W. Zhang et al., 2003; Sheppard et al., 2004), and central Mongolia (Fowell et al., 2003), Badain Jaran Desert and Tengger Desert in the Alaxa Plateau (Chen et al., 1999, 2001; Herzschuh et al., 2004; Yu et al., 2006), and even to eastern China (Yang and Shi, 2001), indicating a broad-scale drought event. Limited studies of the unsaturated zone groundwater suggest that the LIA (1500–1830) featured wet climate conditions in the Alaxa Plateau (Ma and Edmunds, 2006), but inconclusive evidence was found in the northeastern Tibetan Plateau (Liu et al., 1998; Morrill et al., 2003; Q.B. Zhang et al., 2003; Zhang et al., 2004; Ji et al., 2005; Shao et al., 2005; Liu et al., 2005, 2006). In contrast, climate in the Middle Ages featured spatial and temporal variability. The northeastern Tibetan Plateau was characterized by wet climate during 9–11th centuries and by dry conditions during 13–14th centuries (Liu et al., 1998; Sheppard et al., 2004).

The comparison between the tree-ring data and several temperature reconstructions from China reveals significant positive correlations between on decadal timescales. Furthermore, various records show similar low-frequency trends, such as the warming period during the 11th century that was indicative of the MWP, as well as a recent warming trend into the 20th century. LIA cooling occurred in the 15–17th centuries in arid central Asia, eastern China and the whole of China. These coincidences suggest a close connection of temperature changes in China and arid central Asia on decadal to centennial timescales.

Several lines of evidence from proxy records of ice cores, glacial fluctuations, lake level variations and paleosols indicate that arid central Asia witnessed warm–wet climate conditions during the first two or three centuries in the first millennium AD. At that time, various paleo-environmental records, historical documents and archeological data show that similar climate condition also occurred in the arid zones of northwest China and eastern China. Concerning the temperature/precipitation relationship, a solid negative correlation indicates that temperature was usually above/below average when dry/wet climate conditions predominated on decadal to centennial timescales. Especially, the MWP during the 9–12th centuries corresponded to an anomalously dry period whereas the cold LIA coincided with an extremely wet condition.

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