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Moisture changes over the last millennium in arid central Asia: a review, synthesis and comparison with monsoon region

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A R T I C L E I N F O

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A B S T R A C T

There is a strong chance that 20th century warming will cause differences in precipitation distribution, hydrological cycle and effective moisture changes over the globe. Arid central Asia (ACA), a unique dryland area whose atmospheric circulation is dominated today by the westerlies, is one of the specific regions that are likely to be strongly impacted by global warming. An understanding of past variations in effective moisture in such regions is an important prerequisite for the prediction of future hydrological change. Here we evaluate spatial and temporal patterns of effective moisture variations documented by different proxies from 17 records in ACA, and synthesize a decadal-resolution moisture curve for ACA over the past millennium, using 5 of the 17 records selected on the basis of reliable chronologies and robust proxies. The high- and low-resolution data all show that, over the past millennium, ACA has been characterized by a relatively dry Medieval Warm Period (MWP; the period from ~1000 to 1350 AD), a wet Little Ice Age (LIA; from ~1500 to 1850 AD) and increasing moisture during recent decades. As a whole, the LIA in the ACA was not only relatively humid but also had high precipitation. Over the past millennium, the multi-centennial moisture changes in ACA show a generally inverse relationship with the temperature changes in the Northern Hemisphere, China, and western central Asia. The effective moisture history in ACA also shows an out-of-phase relationship with that in monsoon Asia (especially during the LIA). We propose that the humid LIA in ACA, possibly extending to Mediterranean Sea and Western Europe, may have resulted from increased precipitation due to more frequent mid-latitude cyclone activities as a result of the strengthening and equator-ward shift of the westerly jet stream, and the predominantly negative North Atlantic Oscillation conditions, coupled with a decrease in evapotranspiration caused by the cooling at that time.

1. Introduction

Studying climate variability of the recent past (e.g., last millennium) can help us to establish how the climate system varied under natural conditions and to improve projections of future climate. Large-scale temperature reconstructions carried out since the late 1990s (Jones et al., 1998; Mann et al., 1999, 2008; Briffa, 2000; Crowley and Lowery, 2000; Esper et al., 2002; Mann and Jones, 2003; Moberg et al., 2005; Oerlemans, 2005; D'Arrigo et al., 2006; Hegerl et al., 2007) have indicated that, although substantial differences exist in different regions during certain periods, Northern Hemisphere climate evolution over the last millennium could be roughly divided into three major episodes: "Medieval Warm Period" (MWP), "Little Ice Age" (LIA), and post-industrial warming. Unlike temperature, however, it has been more difficult to reconstruct large-scale spatial trends in moisture or precipitation, because of the heterogeneous nature of these hydroclimatic variables, which show variability at distinctly local or regional scales under different atmospheric circulation patterns. Given that the changes in moisture or precipitation are equally, if not more, important for human well-being and ecosystem dynamics as changes in temperature, understanding regional hydrological response to large-scale climatic change during the last millennium should be a crucial aspect of research in palaeoclimatology.

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The mid-latitude Asian continent can be divided into two distinct climatic regions (Dando, 2005): the humid eastern part of Asia, which is mainly controlled by monsoon circulation, and arid central Asia (ACA) in the western part, dominated by the mid-latitude westerlies (Fig. 1). ACA, a region extending from the Caspian Sea in the west to the modern Asian summer monsoon limit in the east, encompassing the newly independent central Asian countries, NW China, and southern Mongolian Plateau (Fig. 1), is one of the largest arid (desert) areas in the world. Climatically, local precipitation in ACA occurs when depressions, which develop over the eastern Mediterranean, bring moist air to central Asia during late spring and summer along a northeast trajectory through westerly circulation (Lioubimtseva et al., 2005). Water vapor can even be transported as far as the central and eastern Mongolian Plateau (Sato et al., 2007). The strength and trajectory of westerly circulation is therefore likely to be a major control on moisture in ACA.

The aim of this paper is to reconstruct moisture variations in ACA over the past millennium and to compare these with existing reconstructions for the monsoon domain. We focus our reconstruction only on the westerly dominated ACA, avoiding the transitional zone in the semi-arid and semi-humid region of central China where the westerlies and the monsoon interact, although several tree-ring based precipitation and soil moisture reconstructions on the NE Tibetan Plateau have been developed in recent years (e.g., Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005; Yin et al., 2008). The topography of ACA is characterized by high (normally > 2500 ~ 3000 m a.s.l.), relatively humid mountain ranges, which provide major water resources for this region, alternating with the much lower (normally < 1000 ~ 1500 m a.s.l.) and extremely arid desert/Gobi plains or basins. In ACA, the scarce water resources, the fragile ecosystems and the strong human impacts on the natural environment during its long history mean that the region is highly sensitive to changes in the hydrological cycle and characteristics of precipitation caused by temperature anomalies such as global warming (Trenberth et al., 2003; Narisma et al., 2007). Over the last 2000 years, a large number of lakes have dried out or are in the final stages of desiccation (Nihoul et al., 2004); oases have turned to deserts or are shrinking; kingdoms disappeared at various times in this region (Litvinsky et al., 1996; Soucek, 2000). During the last century, a marked decline in lake levels has occurred and even resulted in desertification at several large lakes such as the Aral Sea (Small et al., 2001) and Juyan Lake (Jin et al., 2005); such changes have attracted considerable attention around the world because of concerns about the shortage of water resources and related ecological problems (Qin and Yu, 1998; Ferronskii et al., 2003; Micklin, 2004). However, the recent expansion in volume for most lakes in arid NW China since the late 1980s suggests a climatic shift to wetter conditions possibly associated with recent global warming (Shi et al., 2007). In a previous study, we found that changes in effective moisture (ratio of precipitation to evaporation, P/E) in ACA during the Holocene were broadly out-of-phase with variations in the Asian summer monsoon (Chen et al., 2008b). Moreover, moisture variations reconstructed by tree-ring data over the past 100 years for the central Tien Shan Mountains in arid NW China (Li et al., 2006) were inconsistent with those from Helan Mountains along the present monsoon margin (Li et al., 2007), suggesting that the moisture histories of ACA and the monsoon domain have been out-of-phase over the past century as well. Instrumental data indicate that arid NW China has become more humid during the last decades (Jin et al., 2004; Ma and Fu, 2006), resulting in increased river runoff into the desert areas from the surrounding mountains and expansion of the terminal lakes in this region (Shi et al., 2007), while the Asian summer monsoon has generally weakened over the past half century (Sontakke et al., 1993; Li and Zeng, 2002; Ding et al., 2008; Zhang et al., 2008), implying that the asynchrony has persisted up to present. For the LIA, evidence for increased effective precipitation has previously been documented at Lake Bosten (Chen et al., 2006b) in the western part of arid NW China and Lake Sugan (Chen et al., 2009) in the eastern part as well as by various other proxy records (Chen et al., 2008a). In contrast, rainfall in the middle and lower reaches of the Yangtze catchment and in the South China, suggests decreased precipitation during the LIA (Wang and Dong, 2002). However, the moisture variability in ACA on a regional scale over the past millennium still remains poorly understood, despite attempts towards developing an integrated understanding of the late Holocene climatic changes for certain parts of this region (e.g., Boomer et al., 2009; Holmes et al., 2009; Yang et al., 2009). In the last decade, several well-dated, high-resolution palaeo-moisture records have been derived from widely-spaced sites across ACA (Thompson et al., 1995; Yao et al., 1996; 2009; Chen et al., 2006b;

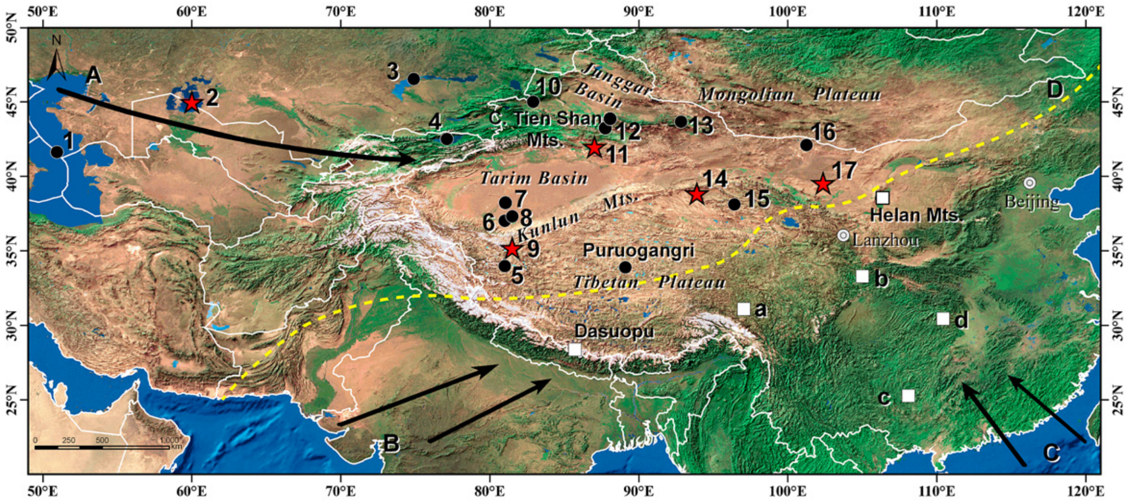

Fig. 1. Overview map showing the palaeoclimatic sites (dots marked with numbers for low-resolution records and stars for records used for synthesizing ACA moisture curve, same as in Table 1) selected in this study from ACA and some comparison sites selected from monsoon Asia (square with lower case letters), and the dominant circulation systems (arrows with upper case letters) of the westerlies (A), Indian monsoon (B) and East Asian monsoon (C). The modern Asian summer monsoon limit (thick dashed line D) is summarized from Gao (1962), Wang et al. (2005b,c), Tang et al. (2006), Wang et al. (2006), and Hu and Qian (2007).

Ma and Edmunds, 2006; Sorrel et al., 2006; Austin et al., 2007; Gates et al., 2008b), providing the potential to investigate ACA-wide moisture evolution over the past millennium, to develop a synthesized moisture index curve, and to explore the relationships between moisture variability, temperature change and the history of the Asian monsoon.

2. Data sources and analytical methods

We set four criteria to select the proxy records to be included in our study. Firstly, study sites should be located in the main part of ACA, which is climatically controlled by westerly circulation. Accordingly, those sites in regions strongly influenced by summer monsoon circulation at the eastern margin of semi-arid China and along the southern margin on the Tibetan Plateau were excluded. Secondly, the proxy indicators should be indicative of changes in effective moisture or precipitation without ambiguous meaning. Furthermore, the moisture proxies should be able to reflect low-frequency (centennial or longer) variations, allowing the regional responses to MWP, LIA and post-industrial warming to be detected. Whereas tree-ring data can preserve high frequency (annual to decadal) information, the low-frequency signal is often lost as a result of the so-called “segment length curse” problem (Cook et al., 1995; Esper et al., 2002). Lacustrine sediments, in contrast, often show evidence for general characteristics of effective moisture, together with lake-level fluctuations and catchment vegetation history on the multi-centennial time scale by using different proxies. Thirdly, the record should span at least the last 1000 years without documented depositional hiatuses. Finally, the selected records should have reliable chronologies with decadal resolution or better. In certain cases, we have made corrections to published chronologies, as discussed below. A “site composite record” was generated for sites which have more than one proxy record, by using those data deemed to be most reliable. In addition to the high-resolution records, selected low-resolution data including lake-level variations, discontinuous historical documents and geomorphological evidence were used to provide complementary evidence, especially for regions where high-resolution materials are lacking. In total, 17 moisture proxy records (Table 1) are selected from ACA, five of which fulfill the criteria for them to be used to synthesize the ACA moisture curve.

Site composite records were generated for the Lake Bosten and for the multiple groundwater profiles of the Badain Jaran Desert. In each case, the selected proxy records were linearly interpolated to a uniform 10-year interval, standardized to have zero mean and unit standard deviation during the period from 1000 AD onwards, and then arithmetically averaged. Records from the other high-resolution sites (Aral Sea, Guliya ice core, and Lake Sugan) were interpolated and standardized in the same way. The synthesized ACA moisture sequence was produced by arithmetically averaging all of the standardized high-resolution moisture time series over the last millennium. The low-resolution moisture data such as lake level information were not included in the synthesized sequence. However, they are used to provide additional knowledge about the moisture conditions, particularly during the LIA in comparison with the MWP and post-industrial period.

3. Results and discussion

3.1. High-resolution records and temporal changes in arid central Asia over the last 1000 years

The five high-resolution records comprise three effective moisture proxies (Aral Sea, Lake Bosten, Lake Sugan), and two direct rainfall reconstructions (snow accumulation record from the Guliya ice cap and groundwater recharge record from the Badain Jaran Desert) (Table 1).

The Aral Sea was once the world’s fourth largest lake and the second largest lake in ACA. It has undergone a notable regression since the 1960s as a consequence of irrigation strategies using the inflow of its two main tributaries (Amu Darya and Syr Darya). Geomorphological investigations of lake levels, archeological surveys around the lake (Boomer et al., 2009) and the study of high-resolution cores (Sorrel et al., 2006; Austin et al., 2007), throw light on the water salinity and regression/transgression history over the last 1000 years. Records of diatom-inferred conductivity (Austin et al., 2007) and dinoflagellate cysts (Sorrel et al., 2006) from parallel cores (CH1/2) provided salinity reconstructions for the late Holocene (Fig. 2). The two proxies show a similar pattern of salinity changes over the last 1000 years, with high salinity and dry climate before ca 1380 AD but low salinity between 1380 and 1870 AD. In our synthesis, we use the conductivity time series inferred from diatoms (Austin et al., 2007) because of its relatively high sample resolution (approximately 8 years) and quantitative reconstruction over the past 1000 years. However, a new age model was established. We used the same ^{14}C dates as Austin et al. (2007) used except the one at 4.80 m (KSU3), which was obtained by correlating the magnetic susceptibility record of CH1 with material recovered by Nourgaliev et al. (2003). In the revised chronology, this was replaced by the TOC ^{14}C date at 4.97 m (POZ13511) (Sorrel et al., 2006). Subsequently, we made a 170-yr reservoir correction to the whole model as suggested by Kuzmin et al. (2007). The replacement is performed for the following two reasons: Firstly, POZ13511 was derived from the core Ch1/2, whereas KSU3 was from an earlier core Ar-8. Secondly, the inclusion of KSU3 in the age model made a nearly six-fold difference in the deposition rate for the interval before and after this control point, but when POZ13511 is used instead (Fig. 2), the deposition rate shows variations that are consistent with the lithology throughout the core. After the application of this new age model, the diatom-inferred and dinoflagellate cysts-based salinity records demonstrate broadly consistent variations: in summary, high salinity conditions prevailed during the MWP from 1000 AD to 1400 AD, which is in broad agreement with low water levels from ca 900 AD to 1350 AD, as reviewed by Boomer et al. (2009).

Lake Bosten, located on the southern foot of the central Tien Shan Mountains and mainly fed by Kaidu River, which is in turn sustained by precipitation over the Tien Shan Mountains, is the largest fresh water lake in this desert/Gobi region with an area over 1000 km^2 (Fig. 1). Lake Bosten has expanded since the mid-1980s under the influence of global climate change (Chen et al., 2006b), and provides a high-resolution palaeoclimatic record in this region. Cores from different water depths have been studied previously (Chen et al., 2006a,b; Wünnemann et al., 2006; Huang et al., 2009). The core BST04H, retrieved from the central part of the lake (at a depth of 16.1 m), has been well-dated by radiocarbon dating of terrestrial plant remains and bulk organic matter, by OSL dating of basal aeolian sands and by $^{210}Pb/^{137}Cs$ dating of the most recent sediments (Huang, 2006; Huang et al., 2009). The chronology is well established following reservoir correction (Huang, 2006), and the average deposition rate is ca 1.0 mm/year over the last 1000 years (Chen et al., 2006b). Various proxies were employed to reconstruct the moisture variability during the past millennium, including pollen A/C (ratio of *Artemisia* to Chenopodiaceae) to indicate the vegetation composition in the catchment (sample interval of ca 20 years), grain size to indicate river inflow intensity from Kaidu River (sample interval of ca 10 years), and carbonate content to indicate regional moisture (sample interval of ca 10 years) (Chen et al., 2006b). The consistent variations of these proxies revealed a marked episode of wet climate from the late 15th

Table 1
Palaeo-moisture records spanning the last millennium from ACA. Study sites are listed from west to east as in Fig. 1. High-resolution records used for synthesizing regional moisture curve are in bold.

Site No.	Site name	Lat. (°N)	Long. (°E)	Elev. (m a.s.l.)	Time Period (cal BP[a])	Sample Resolution (yr)	Dating Method	No. of Dates[b]	Proxies used	References
1	Caspian Sea	41.62	50.95	−28	Dis.[c]	–	^{14}C	2	Barrier complex	Kroonenberg et al., 2007
					Dis.	–	^{14}C	23	Sand bar and bays	Karpychev, 2001
2	**Aral Sea**	**45.00**	**60.00**	**53**	**ca 1600-0[d] ca 1400-0[e]**	**5–10**	**^{137}Cs, ^{14}C**	**2/6**	**Diatom**	**Austin et al., 2007**
					ca 2000-0[d] ca 1800-0[e]	ca 15	^{137}Cs, ^{14}C	3/8	Dinoflagellate cysts	Sorrel et al., 2006
3	Lake Balkhash	46.53	74.88	341	Dis.	–	^{14}C	N/A	Compiled archeological data	Solomina and Alverson, 2004
4	Issyk-Kul	42.50	77.10	1606	ca 1000-0	20–50	^{210}Pb	–	Pollen, monohydrocalcite	Giralt et al., 2004
					Dis.	–	^{14}C	N/A	Compiled archeological data	Solomina and Alverson, 2004
5	Sumxi Co	34.33	80.38	5058	ca 12000-0	100–200	^{14}C	0	Pollen	Van Campo and Gasse, 1993; Van Campo et al., 1996
6	Cele County	37.00	81.00	–	ca 4000-0	50–200	^{14}C	2/6	Sedimentological characteristics	Zhong and Xiong, 1999
7	Southern Tarim rivers	ca 37.00–39.00	ca 78.00–84.00	–	Dis.	–	–	–	Historical documents	Liu, 1976
8	Keriya River	37.30	81.50	–	Dis.	–	^{14}C	1	Terrace, historical documents	Yang et al., 2002b
9	**Guliya**	**35.20**	**81.50**	**6200**	**1700–10**	**10**	**Annual dust layer counting**	–	**Net accumulation rate**	**Thompson et al., 1995**; **Yao et al., 1996**
10	Aibi	45.02	82.9	189	ca 1500-0	ca 30	^{137}Cs, ^{210}Pb, ^{14}C,	–	$\delta^{13}C_{org}$, LOI	Wu et al., 2004
11	**Lake Bosten**	**42.00**	**87.02**	**1048**	**ca 1000-0**	**10–25**	**^{137}Cs, ^{210}Pb, ^{14}C**	**1**	**Pollen, grain size, carbonate content**	**Chen et al., 2006b**
12	Chaiwopu Lake	43.50	87.90	3000	Dis.	–	^{14}C	–	Compiled sedimentological, biogeological and geomorphological data	Qin and Shi, 1992
13	Balikun Lake	43.67	92.83	1585	Dis.	–	^{14}C	–	Compiled sedimentological, biogeological and geomorphological data	Qin and Shi, 1992
14	**Lake Sugan**	**38.85**	**93.90**	**2795**	**ca 1000-0**	**ca 10**	**Annual varve counting**	**–**	**Chironomid, $\delta^{18}O_{carb}$**	**Chen et al., 2009**
15	Dunde	38.10	96.40	5325	ca 12000-0	1–100	Annual layer counting	–	Pollen	Liu et al., 1998
16	East Juyan Lake	42.10	101.25	1060	ca 1500-0	ca 40	^{14}C	2/3	Soluble salt content	Zhang et al., 2004
					ca 2600-0	ca 50	^{14}C	1/3	Ostracod, pigment	Zhang et al., 1998
17	**Badain Jaran**	**39.55**	**102.37**	**–**	**ca 1200-0**	**5–10**	**Accumulative Chloride**	**–**	**Chloride concentrations in unsaturated zone**	**Ma and Edmunds, 2006**; **Gates et al., 2008b**

[a] Calendar year before 2000 AD.
[b] No. of dating within the last 1000 years/total dates in the sequence, ^{210}Pb and/or ^{137}Cs dates are not included.
[c] Discontinuous record.
[d] Original time period.
[e] Time period after new age model applied.

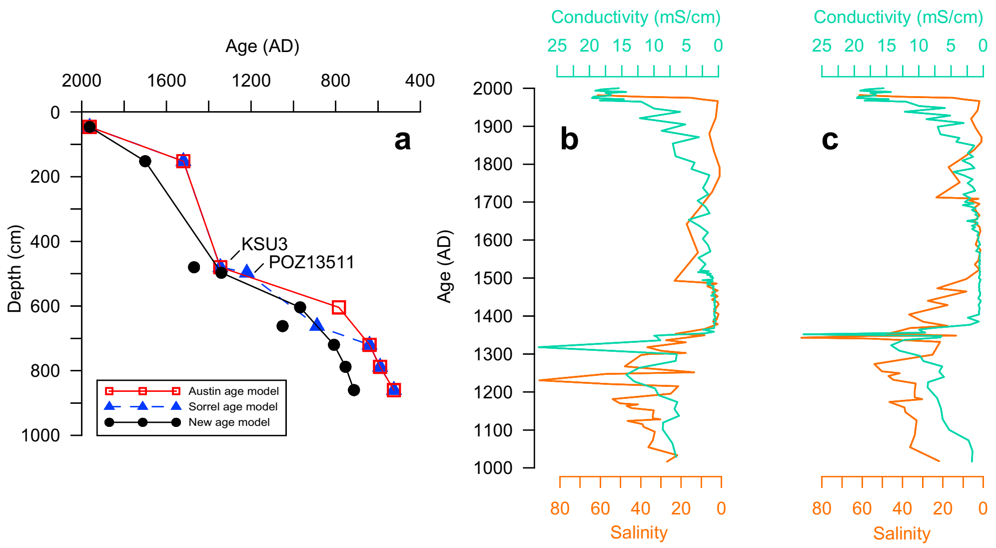

Fig. 2. (a) The new age-depth model (solid line with solid circle) and original ones used by Austin et al. (2007) (solid line with hollow square) and Sorrel et al. (2006) (dash line with solid triangle). 170-year reservoir correction ^{14}C dates are shown by solid circles for all measured ^{14}C dates; (b) variations of the diatom-inferred conductivity and dinoflagellate cyst-based salinity using the original age models without reservoir correction; (c) same as (b) but using the new age model after reservoir correction. Please note that the dinoflagellate cyst-based salinity reconstruction in (b) and (c) is estimated from the relative abundance of *L. machaerophorum* (Sorrel et al., 2006) and thus no unit is shown.

century to late 19th century in this area (Chen et al., 2006b), broadly coeval with the LIA. The humid LIA suggested by palaeolimnological investigations from Lake Bosten is supported by discontinuous historical documents in this region (Tian, 1993; Mahpir and Tursunov, 1996; Yang et al., 2004). For instance, great floods were frequent in the Lake Bosten catchment during the Qing Dynasty in 18th and 19th century (Tian, 1993). The relatively high-resolution grain-size and carbonate-content records were used to generate the composite record for this lake.

Lake Sugan, a small hydrologically-closed saline lake with an area of 104 km^2, located in the hyper-arid northern Qaidam Basin of NW China, is not strongly influenced by anthropogenic interactions and is recharged mainly by groundwater (Zhou, 2007). The laminated upper 5.5 m of core SG03I, taken from a depth of 4.5 m in the central part of the lake, was dated back to 670 BC by varve counting (Zhou et al., 2007). Recent studies have shown that the chironomid assemblages within the core are sensitive to salinity changes and a 1000-year chironomid-based salinity history (Fig. 3) has been reconstructed at decadal resolution for this lake (Chen et al., 2009). The variations in the abundance of low-saline-water taxa, together with the chironomid-inferred salinity reconstructions, are consistent with the variations in carbonate oxygen isotopes, especially at low frequency (Fig. 3), showing the freshening of the lake between 1500 AD and 1840 AD and at around 1200–1230 AD (Fig. 3), high salinities and hence drier climate during the period 990 to 1550 AD of the MWP (Chen et al., 2009). In the synthesis curve we used the chironomid-inferred salinity reconstruction for this lake.

The two chosen proxy records for precipitation amount in ACA are relatively straightforward. Net mass accumulation of an ice cap can normally provide a good indicator of past changes in precipitation. To date, the only suitable ice core record from ACA is that from the Guliya ice cap in western Kunlun Mountains, on the NW margin of the Tibetan Plateau. This core provides a 2000-year high-resolution natural archive of net mass accumulation (Thompson et al., 1995; Yao et al., 1996), which is shown to reflect precipitation changes over a broad area (Yao et al., 2000; Yang et al., 2009). Unfortunately, however, the accumulation data does not extend beyond the 1980s. The accumulation record has a 10-year resolution with an annual-layer-counting chronology over the last 1000 years (Fig. 4). It shows that higher precipitation in the mountain area occurred from ca 1450 AD to ca 1830 AD in LIA with accumulation rates higher than the average of the last 1000 years (Fig. 4), while the period from 800 AD to ca 1300 AD (Yao et al., 1996), corresponding to MWP period, was a time of much reduced precipitation. Low accumulation rates also prevailed from 1830s AD to 1960s AD. The increase of net accumulation since 1960s may reflect the high precipitation in mountain areas in ACA, consistent with a general expansion of lakes in the arid NW China since 1980s (Shi et al., 2007).

A single high-resolution record is available from the huge desert/Gobi areas over the last 1000 years, namely the groundwater unsaturated zone profile from the Badain Jaran Desert located on the southern Mongolian Plateau (Fig. 1). The record uses chloride mass balance within the unsaturated zone to reconstruct groundwater recharge rates, which strongly correlate with rainfall. The relationship of Cl-based recharge rates and local precipitation was demonstrated in Africa by an earlier study (Edmunds and Walton, 1980), and reapplied in the Badain Jaran Desert recently (Gates et al., 2008a). The history of the Cl-based groundwater recharge rates in the Badain Jaran Desert is quite consistent among different desert cores (Ma et al., 2003; Ma and Edmunds, 2006; Gates et al., 2008b). The longest one, core SW1, provides a 1200-year record at sub-decadal resolution. The record shows that the groundwater recharge rates were higher than average from 1290 AD to 1830 AD with three obvious peaks at around 1400 AD, 1550 AD and 1750 AD (Fig. 4), suggesting a relatively humid climate during this period. Low groundwater recharge rates are documented from 800 AD to 1300 AD in the MWP (Ma and Edmunds, 2006) and after 1830 AD during global warming. A recovery of the recharge rates since ca 1950 AD was clearly indicated in the recently studied core SWDA from the desert (Gates et al., 2008b). In this study we combine the SW1 record for the period before 1900 AD with the SWDA record for the post-1900 AD interval to form a synthesis, because the latter provides more reliable information for the last 100 years (Gates et al., 2008b).

In summary, the five high-resolution records show broadly similar moisture and precipitation changes as a whole over the last 1000 years. The synthesized moisture curve (Fig. 4) suggests that

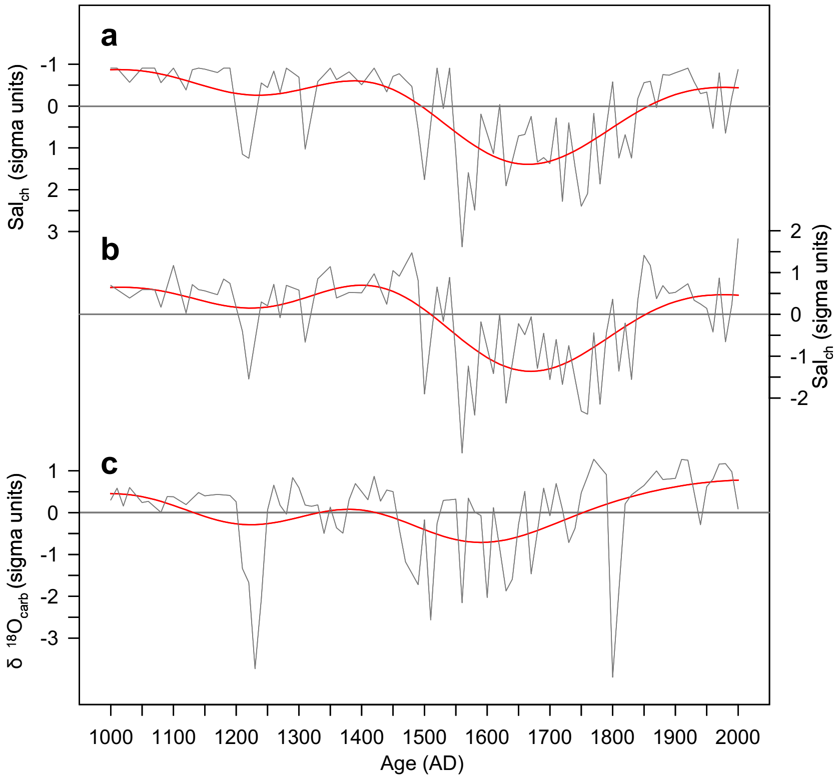

Fig. 3. Proxies indicated effective moisture changes at Lake Sugan during the past millennium. (a) low-saline-water taxa of chironomid (LSW_{ch}); (b) chironomid-inferred salinity (Sal_{ch}); (c) carbonate oxygen isotope ($\delta^{18}O_{carb}$). The time series have been standardized. Thick solid lines indicate a 320-year smooth using a low-pass filter (Mann, 2004).

climate in ACA was drier than average from 1000 AD to ca 1350 AD. This arid period probably started as early as 800 AD and persisted during the whole MWP according to records from Guliya ice cap (Thompson et al., 1995; Yao et al., 1996) and Badain Jaran Desert (Ma and Edmunds, 2006), although our synthesis curve does not cover the early part of MWP. From 1350 AD to 1500 AD, effective moisture was near average on this scale. A humid climate existed during ca 1500–1850 AD with a short interval of relatively dry conditions from 1600 to 1700 AD. There was a return to arid conditions after 1850 AD with evidence for increased humidity over the past 20 years in some records (Fig. 4). Because records from lake sediments in the Aral Sea (Austin et al., 2007) and Lake Bosten

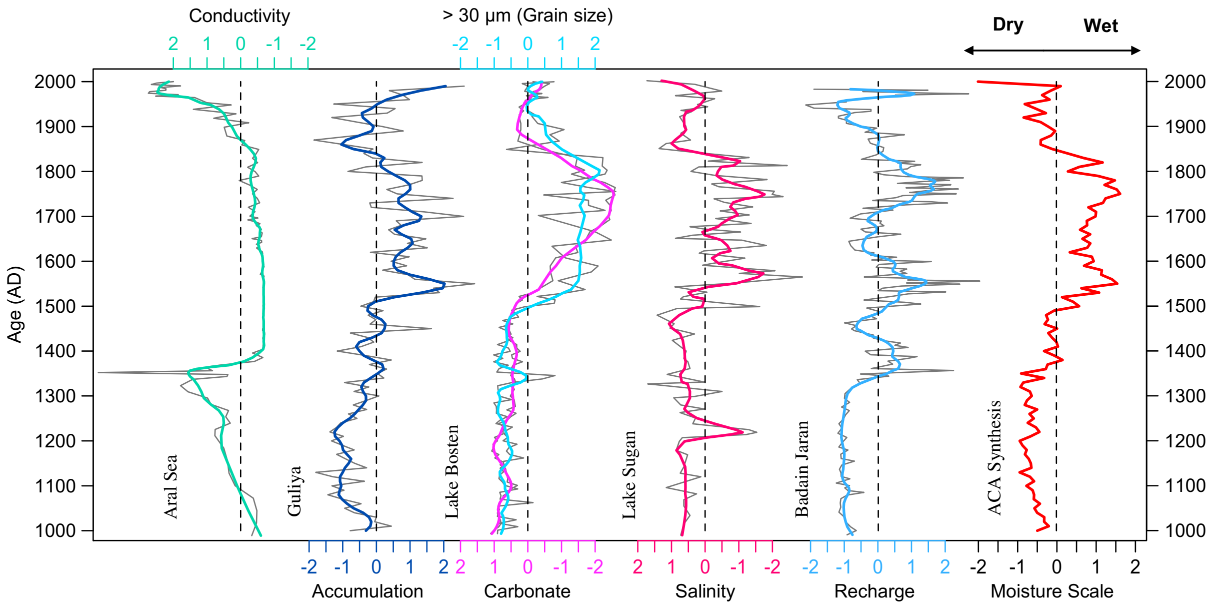

Fig. 4. Standardized high-resolution records from Aral Sea (Austin et al., 2007), Guliya ice core (Thompson et al., 1995; Yao et al., 1996), Lake Bosten (Chen et al., 2006b), Lake Sugan (Chen et al., 2009) and Badain Jaran Desert (Ma and Edmunds, 2006; Gates et al., 2008b). The synthesized moisture curve over the last millennium is also shown with high values indicating wet conditions. Thick solid lines indicate LOESS smoothers (span = 0.1). Dash lines indicate the mean values over the last 1000 years.

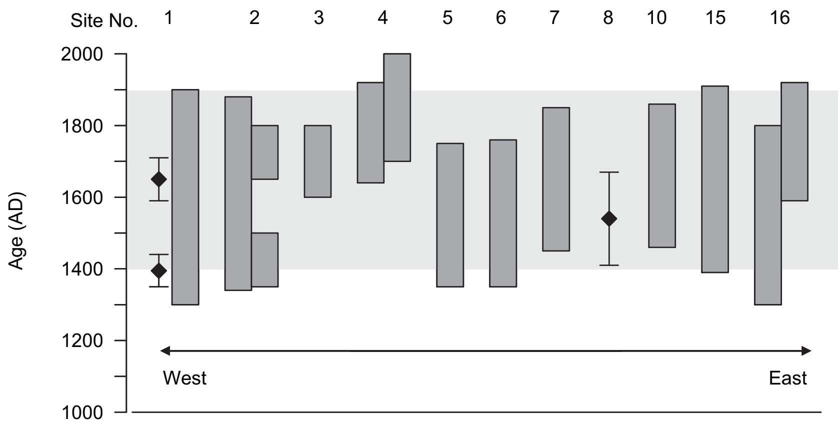

Fig. 5. Sketch map showing humid period over the last 1000 years documented by low-resolution data in westerly dominated ACA. Detail information for each site is listed in Table 1.

(Chen et al., 2006b) are strongly influenced by human activities with increases in irrigation using the recharging river water, the synthesis curve for the past 100 years, especially for the time since the 1960s, must be regarded with caution. In general the climate of ACA in the warm MWP tended to be dry, whereas in the cold LIA it tended to be humid.

3.2. Low-resolution records and humid Little Ice Age in arid central Asia

The lower resolution records complement the synthesis discussed above, especially for periods of increased effective moisture and times of very high precipiation and consequent flooding. Such evidence includes geomorphology, sedimentology, archaeology and historical data. These low-resolution data are portrayed in Fig. 5. During the LIA generally high lake levels were found in the Caspian Sea (Karpychev, 2001; Kroonenberg et al., 2007). Combining evidence of shorelines (Boomer et al., 2000), settlement and archaeology (Boroffka et al., 2006), high lake levels (humid climate) were inferred in the Aral Sea catchment from ca 1350 AD to 1500 AD and from ca 1500–1600 AD (taking the dating uncertainties into consideration) to ca 1800 AD during the last millennium (Boomer et al., 2009). The high lake level periods generally coincide with low salinities deduced from the high-resolution proxy records from core CH1/2 in the Aral Sea (Sorrel et al., 2006; Austin et al., 2007). Further to the east, low-resolution data from Issyk-Kul document a high lake level starting from the mid-17th century (Giralt et al., 2004), while a high lake level in Lake Balkhash existed between ca 1600 AD and 1800 AD (Solomina and Alverson, 2004). Therefore, low-resolution data all show that a humid climate prevailed during the LIA whereas very little, if any, evidence has been reported for a humid climate for the period 1000 to 1300 AD. This suggests that the MWP was characterized by dry conditions compared to the LIA in the western part of ACA. Differences in the timing of onset and termination of humid conditions can be attributed, at least in part, to dating uncertainties.

In the central part of ACA, there have been many previous studies concerning the effective moisture changes in the Tarim Basin, covered by the Taklamakan Desert, the largest desert both in China and in ACA, in the Junggar Basin and in surrounding mountains such as the Tien Shan Mountains. A layer of greyish–black organic deposits inter-bedded by eolian sand at two sections at Damugou and Tagle in Cele County, on the southern margin of the Taklamakan Desert (Fig. 1) was dated to the period from ca 1350 to 1760 AD (Zhong and Xiong, 1999), indicating a relatively humid climate with increased discharge from nearby rivers during that time, which is further supported by the geochemical investigation of these two sections. In fact, the lowest terrace of the Keriya River formed during the LIA, in response to the increased river-flow (Yang et al., 2002b). Historical documents indicate that the runoff of rivers on the southern fringe of the Tarim Basin was generally high between 1450 AD and 1850 AD (Liu, 1976), partly supported by the fact that the Keriya River penetrated the Taklamakan Desert to join the Tarim River during the 16th and the beginning of the 19th centuries (Yang et al., 2002b). The high runoff during LIA may simply be a response to the high precipitation in surrounding high mountains and plateaux, as documented by high net mass accumulations of the Guliya ice cap (Yao et al., 1996) and also suggested by high pollen A/C ratio and thus favorable conditions for *Artemisia* growth in Sumxi Co catchment on the dry NW Tibetan Plateau (Van Campo and Gasse, 1993; Van Campo et al., 1996). Low-resolution proxy records from sedimentological, biogeological and geomorphological data also suggest that a higher lake level occurred during the LIA in Balikun Lake in the eastern Tien Shan Mountains and Chaiwopu Lake on the southern margin of the Junggar Basin (Qin and Shi, 1992). Humid conditions during the LIA are also documented by Aibi Lake, presently the largest lake in Junggar Basin (Wu et al., 2004). High organic matter content and low organic $\delta^{13}C$ values together indicate a generally wet period from 1460 AD to 1860 AD in a 1500-year palaeoenvironmental reconstruction of this lake (Wu et al., 2004).

In the eastern part of ACA, there are few proxy records for moisture variability over the last 1000 years. A pit section dug at East Juyan Lake, a presently dry lake in western Inner Mongolia (Fig. 1), documented a 2600-year moisture history (Zhang et al., 1998). The ostracod assemblage dominated by *Cypridopsis* sp. and *Limnocythere dubiosa*, together with the low carbonate content and low Sr/Ba ratio suggested a significant decrease in salinity of the lake water from 1300 AD to 1800 AD (Zhang et al., 1998). The peak values of chlorophyll and its derivatives during this period also point to an increase in catchment-derived, exogenic organic material. The recent investigation of dominant soluble salt contents in core sediments from this lake also suggested a gradual expansion of the lake between 1590 AD and 1920 AD. This most likely resulted from increased discharge into the lake of the Heihe River from the Qilian Mountains during part of LIA (Zhang et al., 2004). The freshening and expansion of the lake is unlikely to have resulted from less irrigation for farmland because the population in the catchment has tended to increase since the Ming dynasty, from 1368 AD onwards (Committee on Compilation of 'Zhangye Annals', 1995). Bearing in mind the dating uncertainties, these two records both point to humid conditions during the LIA in the East Juyan Lake catchment. In the Qilian Mountains from where the Heihe River originates, the Dunde ice core provides an archive of climate change for the past millennium. Unfortunately, the high-resolution snow accumulation data only extend back to 1600 AD. The record shows lower accumulation from 1600 AD to 1700 AD (Yao et al., 1991), possibly reflecting a relatively dry period during LIA in our synthesized curve (Fig. 4). The result of the ice-core pollen analysis at an average sample resolution of ca 50 year indicated that high pollen concentration, a proxy of vegetation density and productivity in surrounding area, occurred in the interval 1390–1910 AD (Liu et al., 1998), suggesting wet conditions during the LIA.

In summary, low-resolution records (Fig. 5) indicate a humid and probably high-precipitation LIA commonly in ACA. Most of the records indicate that humid conditions lasted from 1400 AD to 1900 AD, taking the dating uncertainties and different proxies into consideration. The low-resolution records (Fig. 5) support our proposal that the moisture synthesis derived from the five high-resolution records is representative of the whole ACA region (Fig. 4). Both low- and high-resolution records show that there is a uniform moisture change pattern at least on a multi-centennial time scale over the last millennium in this region.

3.3. Contrasting pattern of millennium moisture histories between ACA and monsoon Asia

High- and low-resolution records generally show consistent moisture changes in ACA on a multi-centennial time scale. The prominent feature is that wet climatic conditions prevailed during the LIA from the 16th to early 19th century, and dry climatic conditions prevailed during the MWP before the 14th century. The humid climate during the LIA (dry climate during the MWP) (Figs. 4 and 5) most likely resulted not only from lower evaporation, because of lower temperatures during the LIA (higher evaporation because of approximately 1 °C higher temperature during the MWP) as indicated by both salinity changes in the Aral Sea and Lake Sugan, but also from higher precipitation during the LIA (lower precipitation during the MWP) as indicated by snow accumulation rates in the Guliya ice cap, runoff of the Keriya River in the Tarim Basin, and groundwater recharge rates in the Badain Jaran Desert (Figs. 4 and 5).

Records derived from historical documents (e.g., Zhang et al., 1997; Jiang et al., 2005; Zheng et al., 2006; Shen et al., 2009), lake sediments (e.g., Adhikari and Kumon, 2001; Li et al., 2002; Jin and Wang, 2003; Liu et al., 2003; Mingram et al., 2004; Chen et al., 2005), tree rings (e.g., Linderholm and Braeuning, 2006) and speleothems (e.g., Hou et al., 2003; Wang et al., 2005a; Hu et al., 2008; Zhang et al., 2008) in eastern and southern China provide evidence for changing monsoon circulation over the past millennium. In some cases, a lack of accurate and reliable chronologies, ambiguous moisture proxies and strong human impacts have made it difficult to investigate the correlations between different records, although climate (moisture or precipitation) change over the last 1000 years has been previously reviewed (e.g., Zhang, 1991; Wang et al., 2001b; Wang et al., 2003). Here we selected three absolutely-dated and sub-decadal resolution speleothem records in monsoon China from Wanxiang Cave (Zhang et al., 2008), Dongge Cave (Wang et al., 2005a) and Heshang Cave (Hu et al., 2008), to summarize the major changes in Asian summer monsoon intensity. A 1000-year tree-ring index record potentially indicating monsoon strength variations on the SE Tibetan Plateau (Linderholm and Braeuning, 2006), and a Dry–Wet Index record inferred from historical documents in eastern China (Zheng et al., 2006) are also referenced in Fig. 6.

Although it is hard to make inter-site comparisons among these monsoon intensity (precipitation) reconstructions on the decadal to sub-centennial scale, they share some common features (Fig. 6). According to the proxy records from Wanxiang Cave, Heshang Cave, and SE Tibetan Plateau, the summer monsoon was generally moderate to strong and variable before ca 1400 AD (Fig. 6). In addition, low-resolution records, including ostracod assemblages recovered from sediment in Chen Co Lake (29.43°N, 90.53°E), southern Tibetan Plateau (Li et al., 2002), pollen assemblages recovered from sediment in Foyechi Pond (33.95°N, 107.73°E),

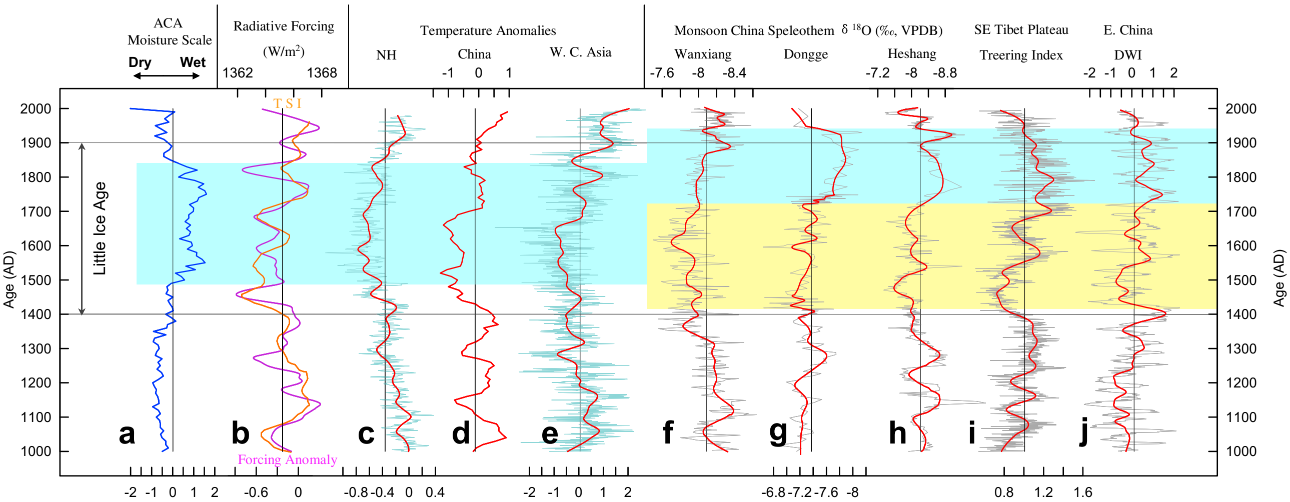

Fig. 6. Comparison of the synthesis effective moisture history of the last millennium in ACA (a) with total solar irradiance (b-orange curve, Bard et al., 2007), solar and volcanic forcing anomalies (b-purple curve, Crowley, 2000), temperature anomalies in the North Hemisphere (c, Moberg et al., 2005), standardized temperature anomalies in China (d, Yang et al., 2002a) and western central Asia (e, Esper et al., 2007), and selected moisture records from monsoon China including speleothem oxygen isotope time series from Wangxiang Cave (f, Zhang et al., 2008), Dongge Cave (g, Wang et al., 2005a), and Heshang cave (h, Hu et al., 2008), tree-ring index record from SE Tibetan Plateau (i, Linderholm and Braeuning, 2006), and Dry–Wet Index record inferred from historical documents in eastern China (j, Zheng et al., 2006). Thick lines indicate LOESS smoothers (span = 0.1), except for (a) and (d) in which only the original data are shown. Black vertical line indicates average value for each record over the last 1000 years. Wet period suggested by our synthesis moisture curve for ACA are marked by green band, together with North Hemisphere, China and western central Asia temperature reconstructions. Wet periods within the LIA in monsoon China are also marked by blue band, and dry periods by yellow band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Qinling Mountains (Liu et al., 2003), speleothem carbon isotope data from Shihua Cave (39.83°N, 115.67°E), Beijing (Hou et al., 2003), and pollen concentration data from Maili Bog (42.87°N, 122.88°E), NE China (Ren, 1998), consistently indicate an intensified summer monsoon (or increased rainfall) from ca 1000 AD to 1300/1400 AD. It should be noted that the oxygen isotope record from Dongge Cave and Dry–Wet index from eastern China suggest a weak summer monsoon (low precipitation) before ca 1250 AD. However, this discrepancy could be, at least partly, attributed to relatively poor age control for the Dongge Cave record before 1400 AD (Wang et al., 2005a), and dramatically decreased documentary material before 1470 AD (Zheng et al., 2006). From ca 1400 AD to 1700 AD, a weaker summer monsoon prevailed, coherently indicated by these three speleothem records, the tree-ring record, and the documentary record from southern and eastern China shown in Fig. 6. Therefore, it is reasonably deduced that the summer monsoon was generally moderate to strong and variable before ca 1400 AD, whereas a weaker monsoon prevailed from ca 1400 AD to ca 1700 AD. All records indicate the strongest monsoon occurred in 19th-early 20th centuries, and a declining monsoon in the last 50 years, which is also suggested by different monsoon indices (Li and Zeng, 2002; Ding et al., 2008). However, the monsoon history documented by the Wanxiang Cave speleothem record is slightly different from other records in recent centuries (Fig. 6): the summer monsoon became stronger after 1870 AD, later than other records in monsoon areas, although it has a more reliable chronology and its oxygen isotope record has better correlation with precipitation (Liu et al., 2008). This could be partly because Wanxiang Cave is located on the margin of the Tibetan Plateau and closer to the monsoon limit. The oxygen isotope variations of the Wanxiang Cave speleothem may be influenced not only by monsoon circulation but also local circulations on the Tibetan Plateau and the westerlies.

The best example of the contrasting conditions between monsoon history of the last millennium and moisture (precipitation) evolution in ACA is during the LIA (Fig. 6). Moisture in ACA was moderate at the start of the LIA from 1400–1500 AD, whereas a notably weak monsoon began at that time and lasted until ca 1700 AD. A wet climate in ACA prevailed during 1500–1850 AD, while a strong monsoon and high rainfall only started after ca 1700 AD, about 200 years later than in ACA, but lasted until the early 20th century. Therefore, during the last 1000 years until the recent global warming, the climate in ACA and monsoon domain also experienced generally out-of-phase changes (more so during the LIA), similar to that during the Holocene (Chen et al., 2008b).

The synthesis curve is less reliable for the last 100 years than for the earlier period for two main reasons. First, the records from Aral Sea and Lake Bosten become strongly influenced by human activities, especially the use of river water for irrigation, and second, because the snow accumulation data for the Guliya ice core only extend up until the 1980s. The synthesis moisture curve conflicts with the fact that there were generally high amounts of river runoff and expansion of inland lakes in arid NW China since the late 1980s (Shi et al., 2007). However, two records of tree-ring reconstructed summer Palmer Drought Severity Index (PDSI) (Palmer, 1965), a widely used meteorological drought index and most suitable for describing soil moisture and consequently climate moisture for much of the globe (Briffa et al., 1994; Cook et al., 2004; Dai et al., 2004) and also China (Zou et al., 2005), may provide better understanding of the moisture variability in both ACA and monsoon China during this interval. One record from the central Tien Shan Mountains in ACA began 1675 AD (Li et al., 2006), while another from 1788 AD in Helan Mountains (Li et al., 2007) lies within the monsoon domain, close to the modern monsoon limit. It is shown that a relatively wet climate (high PDSI) prevailed before 1810 AD at Tien Shan Mountains, followed by a dry climate until 1920 AD (Fig. 7), which is similar to the moisture fluctuations in our synthesis curve (Fig. 4). The PDSI has a trend of increasing moisture from 1920 AD to present day, broadly consistent with the records of net snow accumulation from the ice cores from Guliya (Yao et al., 1996) and Dunde (Davis et al., 2005), although a number of drought events interrupted the trend. In contrast to the PDSI time series at Tien Shan Mountains, the PDSI record at Helan Mountains fluctuated between 1788 AD and 1930 AD, and then jumped to a wet peak at ca 1940 AD. A general decreasing trend of PDSI (decreasing moisture) prevailed subsequently until recent years, reflecting the weakening Asian monsoon over the last 50 years (Fig. 7). The tree-ring index from the SE Tibetan Plateau even suggests that monsoon rainfall has reduced since 1900 AD (Fig. 6). The two annual PDSI records, therefore, also show the contrasting trends of moisture changes even during the last 100 years, especially since the 1930s. The out-of-phase or anti-phase relationship in precipitation or moisture changes has also been reported to exist in net snow accumulation changes between the northern Tibetan Plateau, which is controlled climatically by the westerlies, and the southern Tibetan Plateau, which is mainly influenced by the Indian monsoon circulation (Wang et al., 2007). When net snow accumulation at the Dasuopu ice cap on the southern Tibetan Plateau (Fig. 1) was low, the net snow accumulations at the Dunde and Puruogangri ice caps on the northern Tibetan Plateau (Fig. 1) were generally high (Fig. 7). This inverse relationship has existed throughout the past 500 years (Wang et al., 2007), the post-industrial period (Davis et al., 2005), and even the last 50 years, as indicated by the instrumental precipitation records (Duan et al., 2008). This supports the view that precipitation or effective moisture changes in the westerly dominated ACA have been broadly out-of-phase over the past 1000 years with those in the monsoon domain, not only on the multi-centennial time scale but also on the decadal to centennial time scales.

3.4. Possible forcing mechanism for the moisture changes in ACA during the pre-industrial LIA/MWP

The moisture synthesis curve from the high-resolution records (Fig. 4) and the low-resolution records (Fig. 5) all show that a wet climate (high precipitation) prevailed during the typically cold LIA period from ca 1500–1850 AD, while a dry climate existed during the typically warm MWP period. The synthesized temperature anomalies from the North Hemisphere (Moberg et al., 2005), China (Yang et al., 2002a) and western central Asia (Esper et al., 2007), which are smoothed by a LOESS function (span = 0.1) to remove the high frequency noise (Cleveland and Devlin, 1988), are in broad agreement over the past 1000 years, especially on the multi-centennial time scale (Fig. 6). The relatively warm MWP, the cold LIA from ca 1400–1900 AD and recent global warming are all documented clearly by these temperature reconstructions (Fig. 6). Simple visual inspection of the temperature changes and the synthesized ACA moisture curve (Fig. 6) reveals that the relationship between temperature and precipitation variations is inverse on the multi-centennial time scale (high/low temperature, low/high effective moisture or precipitation), which was also noted by earlier studies (Chen et al., 2006b; Yang et al., 2009). This relationship exists over the last millennium until the 20th century global warming, when moisture (precipitation) rises along with increasing temperature (Fig. 7). One open question arising from the relationships among temperature changes, moisture evolution in ACA, and monsoon history during the pre-industrial LIA/MWP, taking LIA period as an example, is why the cold LIA resulted in wet climate (high precipitation) in ACA, but a dry climate in the monsoon-dominated eastern China.

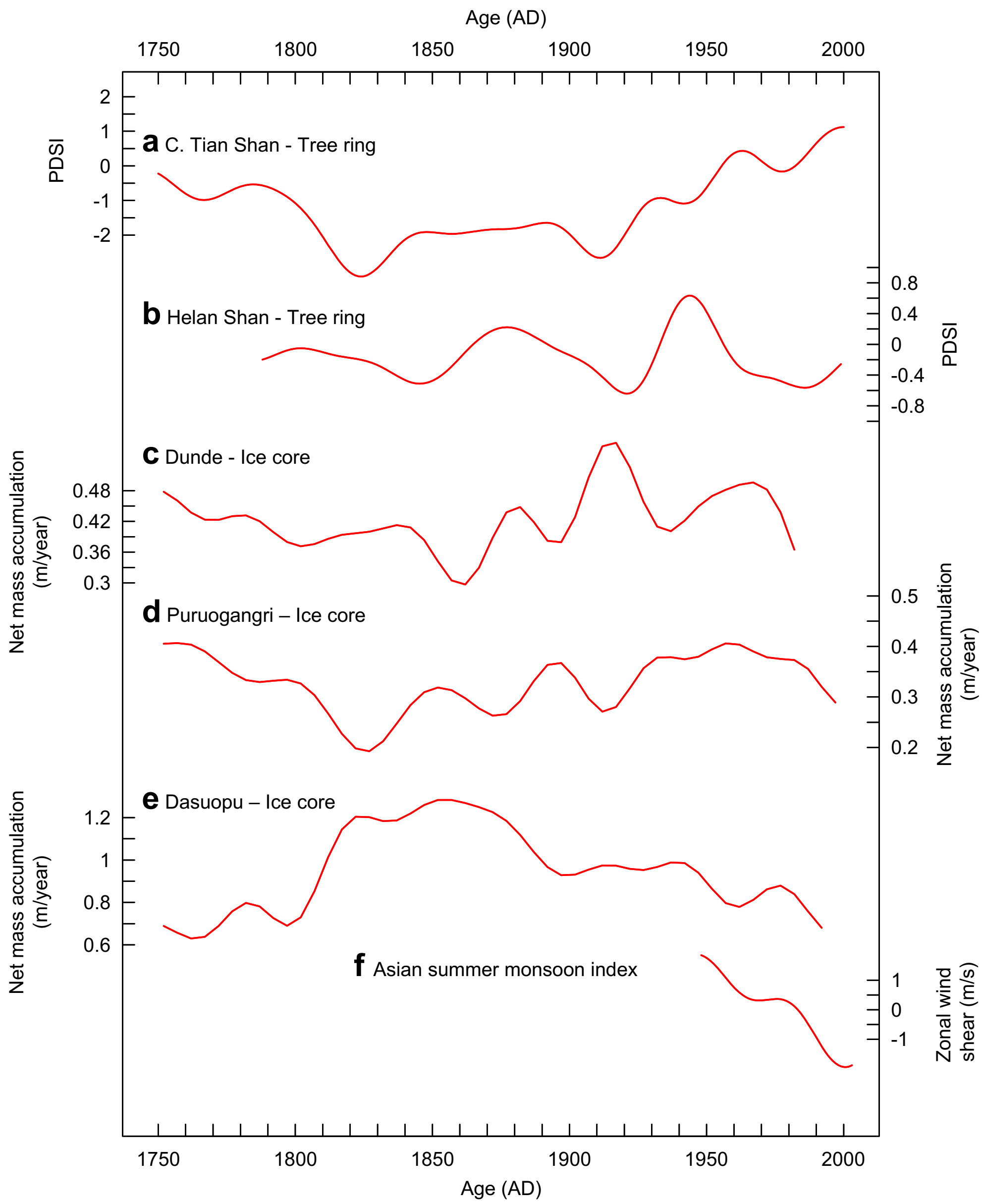

Fig. 7. High-resolution moisture (precipitation) records in the recent 250 years. Tree-ring reconstructed summer PDSI records at central Tien Shan Mountains in ACA (a) (Li et al., 2006) and Helan Mountains in the summer monsoon margin (b) (Li et al., 2007), high-resolution net snow accumulation records at Dunde ice cap (c) (Yao et al., 1991), at Puruogangri ice cap (d) (Thompson et al., 2006) and at Dasuopu ice cap (e) (Wang et al., 2007). The Asian monsoon index (f) (Ding et al., 2008) over the recent half century is also shown. All records have been smoothed with a 30-year filter (Mann, 2004) to show the general trend.

It is possible that the low temperature, approximately 1–2 °C lower during LIA than during MWP (Fig. 6), could have resulted in relatively high effective moisture in the mid-latitude Asian continent including ACA, by decreasing evapotranspiration. However, this alone would not fully explain the high net snow accumulations in the Guliya ice cap (Yao et al., 1996), increased runoff of the rivers on the south fringe of Tarim Basin (Liu, 1976; Yang et al., 2002b), and of Amu Darya and Syr Darya in central Asia (Boomer et al., 2000), and high groundwater recharge rates in Badain Jaran Desert (Ma and Edmunds, 2006; Gates et al., 2008b), all of which suggest that higher precipitation occurred widely across ACA during the LIA. In the mid-latitudes of the North Hemisphere, cold and humid climate (high precipitation) were also reported to exist in Mediterranean Europe and the North Atlantic (Grove, 1996, 2001; Dragoni, 1998), possibly forming a wet mid-European zone south of approximately 50°N during cold-event phases of the Holocene (Magny et al., 2003).

Combining this with our findings of the wet climate (high precipitation) in ACA, a wet climate (high precipitation) zone in mid-latitude Eurasia, except for monsoon-dominated eastern China, probably existed during the LIA. The existence of a wet mid-latitude zone during the LIA points to altered atmospheric circulation patterns, among which the southward shift of the westerlies is the most likely. Simulations using the Community Climate System Model (CCSM) have shown that the southward shift of westerlies during the cold LIA led to an increase in the occurrence of cyclones and extreme precipitation events in all seasons, but especially during winter in the North Atlantic and particularly in the Mediterranean, due to a stronger meridional temperature gradient and an increase in lower tropospheric baroclinicity (Raible et al., 2007). At present, mean precipitation in mid-latitude central Asia is primarily a result of the transportation into ACA of depressions and cyclone storms formed over the eastern Mediterranean by the westerly jet stream (Lioubimtseva et al., 2005). This mechanism also applies to rain falling in the surrounding high mountains in ACA, where moisture normally condenses and falls as snow (Lioubimtseva et al., 2005). The high frequency of cyclonic activity in the North Atlantic and Mediterranean sectors during LIA, which was simulated by the CCSM, would consequently result in elevated precipitation in ACA through moisture transported by the westerly jet stream. Furthermore, the increase in the precipitation in ACA could be partially attributed to the predominantly negative North Atlantic Oscillation (NAO) conditions during the LIA (Trouet et al., 2009), as suggested by the inverse association between the NAO index and precipitation at mid-latitudes of continental Asia revealed by statistical analyses of meteorological data from 57 to 88 hydroclimatic stations in this region (Aizen et al., 2001). In contrast to precipitation levels in ACA, variations in the strength of the Asian monsoon are thought to be forced by changes in Northern Hemisphere summer solar insolation caused by the precessional cycles of earth orbital change over long time scales, including the Holocene interglacial (Kutzbach, 1981; Clemens et al., 1991; Wang et al., 2001a; Wang, 2009), and by solar irradiance changes over shorter time scales (Wang et al., 2005a; Zhang et al., 2008). For example, during the Maunder Minimum (1640–1715 AD) within the LIA, reduced solar activity, coupled with the effects of a series of volcanic eruptions, resulted both in cooling and in weakening of the Asian monsoon. It is found that a weak summer monsoon generally correlated with cold climate and weak solar irradiance over the past 2000 years until the recent global warming (Zhang et al., 2008). Therefore, we would expect that moisture changes in ACA during the pre-industrial LIA/MWP should have an inverse relationship with variations in the strength of the Asian summer monsoon. This study further supports the hypothesis that, climatically speaking, there are two different parts of Asia with out-of-phase moisture (precipitation) variability in responding to global change, i.e., monsoon-dominated Asia and westerlies dominated ACA during the Holocene (Chen et al., 2008b).

4. Conclusions

In this study we used five high-resolution unambiguous proxy records, with relatively reliable chronology, to synthesize a 10-year resolution moisture curve for ACA over the last 1000 years. This was complemented by low-resolution records. The general patterns of the reconstructions indicate that the ACA, a dry inland zone in central Asia from the Caspian Sea in the west to the southern Mongolian Plateau in the east and alternating with high mountains, has experienced a relatively dry MWP, a wet LIA and increasing humidity during the recent period of global warming. As a whole, the LIA in the ACA was not only relatively wet (high P/E) but also had high precipitation. The wet LIA climate may have extended to the Mediterranean Sea and Western Europe possibly to form a humid zone throughout the mid-latitudes of Eurasia. The effective moisture (precipitation) in ACA has a generally inverse relationship with the temperature of the Northern Hemisphere, China, and central Asia as reconstructed by different proxies at a multi-centennial time scale over the last 1000 years until the 20th century global warming, i.e., wet (dry) climate in ACA correlates with low (high) temperature. We also propose that the effective moisture history in ACA as a whole had an out-of-phase relationship with that in monsoon Asia (more so during the LIA), as documented by numerous palaeoclimate records. Furthermore, we propose a possible mechanism to explain the wet and high-precipitation LIA in ACA, namely, that cold temperature during LIA would cause a southward shift of the westerly jet stream as the meridional temperature gradient increased, resulting in increased occurrences of mid-latitude cyclone activity and extremely events of precipitation, as simulated by a CCMS model (Raible et al., 2007). In addition, persistent negative NAO conditions could have attributed to the high precipitation during the LIA in ACA as well. The Asian monsoon is supposed to be driven by Northern Hemisphere summer insolation at long time scales and solar irradiance at decadal to multi-centennial time scales, such that strong (weak) solar irradiance results in both high (low) temperature and a strong (weak) summer monsoon. Therefore, low temperatures during LIA would eventually result in high precipitation and a wet climate in ACA but a weak summer monsoon and dry climate in the monsoon-dominated region, leading to an out-of-phase or even anti-phase relationship of moisture changes between ACA and monsoon Asia.

The synthesis moisture curve for ACA can be only considered as preliminary because we have used only five records to synthesize moisture evolution over the last 1000 years in this vast region. However, at present there are only a few suitable proxy records in ACA, and we think it would be better to have such a synthesis curve than not. Secondly, in this study we only discuss the multi-centennial-scale moisture changes over the last 1000 years. Imprecise chronologies hamper further attempts to investigate the secondary oscillations of wet and dry climates on a multi-decadal to centennial time scale within LIA and MWP, which may either be documented by the original proxy records or by the synthesis moisture curve (Fig. 4). Thirdly, the limited number of available proxy records also prevents us from exploring the spatial heterogeneities of moisture variations within ACA, and hinders efforts to identify the exact spatial boundaries within which the moisture evolutions share similar patterns at least on the multi-centennial time scale (such as a wet LIA) in ACA. Thus, it is crucial that additional well-dated, temporally highly-resolved and spatially extensively-distributed moisture records over the last millennium are recovered in the future. In addition, more modeling efforts are needed to test the mechanism proposed here, to study the relationship between the ITCZ shifts, causing global monsoon changes (Wang, 2009), and the westerly jet stream shifts, causing moisture changes in ACA, and to achieve a better understanding of moisture (precipitation) and hydrological changes in ACA.

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References

Adhikari, D.P., Kumon, F., 2001. Climatic changes during the past 1300 years as deduced from the sediments of Lake Nakatsuna, central Japan. Limnology 2, 157–168.

Aizen, E.M., Aizen, V.B., Melack, J.M., Nakamura, T., Ohta, T., 2001. Precipitation and atmospheric circulation patterns at mid-latitudes of Asia. International Journal of Climatology 21, 535–556.

Austin, P., Mackay, A., Palagushkina, O., Leng, M., 2007. A high-resolution diatom-inferred palaeoconductivity and lake level record of the Aral Sea for the last 1600 yr. Quaternary Research 67, 383–393.

Bard, E., Raisbeck, G., Yiou, F., Jouzel, J., 2007. Comment on "Solar activity during the last 1000 yr inferred from radionuclide records" by Muscheler et al. (2007). Quaternary Science Reviews 26, 2301–2304.

Boomer, I., Aladin, H., Plotnikov, I., Whatley, R., 2000. The palaeolimnology of the Aral Sea: a review. Quaternary Science Reviews 19, 1259–1278.

Boomer, I., Wünnemann, B., Mackay, A.W., Austin, P., Sorrel, P., Reinhardt, C., Keyser, D., Guichard, F., Fontugne, M., 2009. Advances in understanding the late Holocene history of the Aral Sea region. Quaternary International 194, 79–90.

Boroffka, N., Oberhansli, H., Sorrel, P., Demory, F., Reinhardt, C., Wünnemann, B., Alimov, K., Baratov, S., Rakhimov, K., Saparov, N., Shirinov, T., Krivonogov, S.K., Rohl, U., 2006. Archaeology and climate: settlement and lake-level changes at the Aral Sea. Geoarchaeology – An International Journal 21, 721–734.

Briffa, K.R., 2000. Annual climate variability in the Holocene: interpreting the message of ancient trees. Quaternary Science Reviews 19, 87–105.

Briffa, K.R., Jones, P.D., Hulme, M., 1994. Summer moisture variability across Europe, 1892–1991: an analysis based on the Palmer drought severity index. International Journal of Climatology 14, 475–506.

Chen, J., Wan, G., Zhang, D.D., Chen, Z., Xu, J., Xiao, T., Huang, R., 2005. The 'Little Ice Age' recorded by sediment chemistry in Lake Erhai, southwest China. The Holocene 15, 925–931.

Chen, F.H., Huang, X.Z., Yang, M.L., Yang, X.L., Fan, Y.X., Zhao, H., 2006a. Westerly dominated Holocene climate model in arid central Asia: case study on Bosten Lake, Xinjiang, China. Quaternary Sciences 26, 881–887 (in Chinese with English Abstract).

Chen, F.H., Huang, X.Z., Zhang, J.W., Holmes, J.A., Chen, J.H., 2006b. Humid Little Ice Age in central Asia documented by Bosten Lake, Xinjiang, China. Science in China, Series D 49, 1280–1290.

Chen, J.H., Chen, F.H., Zhang, J.W., Yang, B., 2008a. Humidity variability in the arid Northwest China during LIA derived from different proxy records. Acta Geographica Sinica 63, 23–33 (in Chinese with English Abstract).

Chen, F.H., Yu, Z.C., Yang, M.L., Ito, E., Wang, S.M., Madsen, D.B., Huang, X.Z., Zhao, Y., Sato, T., Birks, H.J.B., Boomer, I., Chen, J.H., An, C.B., Wünnemann, B., 2008b. Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. Quaternary Science Reviews 27, 351–364.

Chen, J.H., Chen, F.H., Zhang, E.L., Brooks, S.J., Zhou, A.F., Zhang, J.W., 2009. A 1000-year chironomid-based salinity reconstruction from varved sediments of Sugan Lake, Qaidam Basin, arid Northwest China, and its palaeoclimatic significance. Chinese Science Bulletin 54, 3749–3759.

Clemens, S., Prell, W., Murray, D., Shimmield, G., Weedon, G., 1991. Forcing mechanisms of the Indian-ocean monsoon. Nature 353, 720–725.

Cleveland, W., Devlin, S., 1988. Locally weighted regression: an approach to regression analysis by local fitting. Journal of the American Statistical Association 83, 596–610.

Committee on Compilation of 'Zhangye Annals', 1995. Zhangye Annals. Gansu Culture Publishing House, Lanzhou (in Chinese).

Cook, E.R., Briffa, K.R., Meko, D.M., Graybill, D.A., Funkhouser, G., 1995. The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. The Holocene 5, 229–237.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the western United States. Science 306, 1015–1018.

Crowley, T.J., 2000. Causes of climate change over the past 1000 years. Science 289, 270–277.

Crowley, T.J., Lowery, T.S., 2000. How warm was the medieval warm period? Ambio 29, 51–54.

D'Arrigo, R., Wilson, R., Jacoby, G., 2006. On the long-term context for late twentieth century warming. Journal of Geophysical Research 111, D03103. doi:10.1029/2005JD006352.

Dai, A., Trenberth, K.E., Qian, T., 2004. A global dataset of Palmer drought severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. Journal of Hydrometeorology 5, 1117–1130.

Dando, W.A., 2005. Asia: climates of Siberia, central and east Asia. In: Oliver, J.E. (Ed.), Encyclopedia of World Climatology. Springer, Dordrecht, pp. 102–114.

Davis, M.E., Thompson, L.G., Yao, T., Wang, N., 2005. Forcing of the Asian monsoon on the Tibetan Plateau: evidence from high-resolution ice core and tropical coral records. Journal of Geophysical Research 110. doi:10.1029/2004JD004933.

Ding, Y., Wang, Z., Sun, Y., 2008. Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. International Journal of Climatology 28, 1139–1161.

Dragoni, W., 1998. Some considerations on climatic changes, water resources and water needs in the Italian region south of 43°N. In: Issar, A.S., Brown, N. (Eds.), Water, Environment and Society in Times of Climatic Change. Kluwer Academic Publishers, Dordrecht, pp. 241–271.

Duan, K.Q., Yao, T.D., Wang, N.L., Tian, L.D., Xu, B.Q., 2008. The difference in precipitation variability between the North and South Tibetan Plateaus. Journal of Glaciology and Geocryology 30, 726–732 (in Chinese with English Abstract).

Edmunds, W.M., Walton, N.R.G., 1980. A geochemical and isotopic approach to recharge evaluation in semi-arid zones, past and present. In: Arid Zone Hydrology: Investigations with Isotope Techniques. International Atomic Energy Agency, Vienna, pp. 47–68.

Esper, J., Cook, E.R., Schweingruber, F.H., 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. Science 295, 2250–2253.

Esper, J., Frank, D., Wilson, R., Büntgen, U., Treydte, K., 2007. Uniform growth trends among central Asian low- and high-elevation juniper tree sites. Trees – Structure and Function 21, 141–150.

Ferronskii, V.I., Polyakov, V.A., Brezgunov, V.S., Vlasova, L.S., Karpychev, Y.A., Bobkov, A.F., Romaniovskii, V.V., Johnson, T., Ricketts, D., Rasmussen, K., 2003. Variations in the hydrological regime of Kara-Bogaz-Gol Gulf, Lake Issyk-Kul, and the Aral Sea assessed based on data of bottom sediment studies. Water Resources 30, 252–259.

Gao, Y.X., 1962. Some Questions About the East Asian Monsoon. Science Press, Beijing (in Chinese).

Gates, J.B., Edmunds, W.M., Ma, J.Z., Scanlon, B., 2008a. Estimating groundwater recharge in a cold desert environment in northern China using chloride. Hydrogeology Journal 16, 893–910.

Gates, J.B., Edmunds, W.M., Ma, J.Z., Sheppard, P.R., 2008b. A 700-year history of groundwater recharge in the drylands of NW China. The Holocene 18, 1045–1054.

Giralt, S., Julià, R., Klerkx, J., Riera, S., Leroy, S., Buchaca, T., Catalan, J., De Batist, M., Beck, C., Bobrov, V., Gavshin, V., Kalugin, I., Sukhorukov, F., Brennwald, M., Kipfer, R., Peeters, F., Lombardi, S., Matychenkov, V., Romanovsky, V., Podsetchine, V., Voltattorni, N., 2004. 1000-Year environmental history of Lake Issyk-Kul. In: Nihoul, J.C.J., Zavialov, P.O., Micklin, P.P. (Eds.), Dying and Dead Seas: Climatic Versus Anthropic Causes. Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 253–285.

Grove, J.M., 1996. The century time-scale. In: Driver, T.S., Chapman, G.P. (Eds.), Timescales and Environmental Change. Routledge, London, pp. 39–87.

Grove, A.T., 2001. The "Little Ice Age" and its geomorphological consequences in Mediterranean Europe. Climatic Change 48, 121–136.

Hegerl, G.C., Crowley, T.J., Allen, M., Hyde, W.T., Pollack, H.N., Smerdon, J., Zorita, E., 2007. Detection of human influence on a new, validated 1500-year temperature reconstruction. Journal of Climate 20, 650–666.

Holmes, J.A., Cook, E.R., Yang, B., 2009. Climate change over the past 2000 years in Western China. Quaternary International 194, 91–107.

Hou, J.Z., Tan, M., Cheng, H., Liu, T.S., 2003. Stable isotope records of plant cover change and monsoon variation in the past 2200 years: evidence from laminated stalagmites in Beijing, China. Boreas 32, 304–313.

Hu, C.Y., Henderson, G.M., Huang, J.H., Xie, S., Sun, Y., Johnson, K.R., 2008. Quantification of Holocene Asian monsoon rainfall from spatially separated cave records. Earth and Planetary Science Letters 266, 221–232.

Hu, H., Qian, W., 2007. Identifying the northernmost summer monsoon location in East Asia. Progress in Natural Science 17, 812–820.

Huang, X.Z., 2006. Holocene climate variability of arid central Asia documented by Bosten Lake, Xinjiang, China. In: Ph.D. dissertation, Lanzhou University, Lanzhou (in Chinese with English Abstract).

Huang, X.Z., Chen, F.H., Fan, Y.X., Yang, M.L., 2009. Dry late-glacial and early Holocene climate in arid central Asia indicated by lithological and palynological evidence from Bosten Lake, China. Quaternary International 194, 19–27.

Jiang, T., Zhang, Q., Blender, R., Fraedrich, K., 2005. Yangtze Delta floods and droughts of the last millennium: abrupt changes and long term memory. Theoretical and Applied Climatology 82, 131–141.

Jin, H.L., Xiao, H.L., Zhang, H., Sun, Z., 2005. Evolution and climate changes of the Juyan Lake revealed from grain size and geochemistry element since 1500 a BP. Journal of Glaciology and Geocryology 27, 233–240 (in Chinese with English Abstract).

Jin, L.Y., Li, J., Wang, X., Chen, F.H., 2004. The temporal and spatial distribution of surface dry-wet conditions over northwestern China in recent 50 years. Acta Geographica Sinica 59, 847–854 (in Chinese with English Abstract).

Jin, Z.D., Wang, S.M., 2003. The Medieval warm period and Little Ice Age in the Daihai Area, North China. Chinese Journal of Geochemistry 22, 330–336.

Jones, P.D., Briffa, K.R., Barnett, T.P., Tett, S.F.B., 1998. High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures. Holocene 8, 455–471.

Karpychev, Y.A., 2001. Variations in the Caspian Sea level in the historic epoch. Water Resources 28, 1–14.

Kroonenberg, S.B., Abdurakhmanov, G.M., Badyukova, E.N., Van der Borg, K., Kalashnikov, A., Kasirnov, N.S., Rychagov, G.I., Svitoch, A.A., Vonhof, H.B., Wesselingh, F.P., 2007. Solar-forced 2600 BP and Little Ice Age highstands of the Caspian Sea. Quaternary International 173, 137–143.

Kutzbach, J.E., 1981. Monsoon climate of the early Holocene: climate experiment with the earth's orbital parameters for 9000 years ago. Science 214, 59–61.

Kuzmin, Y.V., Nevesskaya, L.A., Krivonogov, S.K., Burr, G.S., 2007. Apparent ^{14}C ages of the 'pre-bomb' shells and correction values (R, Delta R) for Caspian and Aral Seas (Central Asia). Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 259, 463–466.

Li, J., Zeng, Q., 2002. A unified monsoon index. Geophysical Research Letters 29. doi:10.1029/2001GL013874.

Li, Y., Zhu, L., Li, B., 2002. Environmental changes and Ostracoda in the Chen Co Lake of southern Tibet in recent 1400 years. Acta Geographica Sinica 57, 413–421 (in Chinese with English Abstract).

Li, J., Gou, X., Cook, E.R., Chen, F., 2006. Tree-ring based drought reconstruction for the central Tien Shan area in northwest China. Geophysical Research Letters 33, L07715. doi:10.1029/2006GL025803.

Li, J., Cook, E.R., Chen, F., Gou, X., Zhang, Y., 2007. Drought reconstruction for north central China from tree rings: the value of the Palmer drought severity index. International Journal of Climatology 27, 903–909.

Linderholm, H.W., Braeuning, A., 2006. Comparison of high-resolution climate proxies from the Tibetan plateau and Scandinavia during the last millennium. Quaternary International 154–155, 141–148.

Lioubimtseva, E., Cole, R., Adams, J.M., Kapustin, G., 2005. Impacts of climate and land-cover changes in arid lands of Central Asia. Journal of Arid Environments 62, 285–308.

Litvinsky, B.A., Zhang, G.D., Shabani Samghabadi, A., 1996. History of Civilizations of Central Asia: The Crossroads of Civilization: A.D. 250 to 750. UNESCO Publishing, Paris.
Liu, B., 1976. Climate Change in Southern Tarim Basin. Ancient and Present-Day Bookstore, Tokyo.
Liu, K.B., Yao, Z.J., Thompson, L.G., 1998. A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai–Tibetan plateau. Geology 26, 135–138.
Liu, H., Wang, H., Cui, H., 2003. Climatic changes and timberline responses over the past 2000 years on the Alpine zone of Mt. Taibai. Quaternary Sciences 23, 299–308 (in Chinese with English Abstract).
Liu, J., Zhang, P., Cheng, H., Chen, F., Yang, X., Zhang, D., Zhou, J., Jia, J., An, C., Sang, W., Johnson, K., 2008. Asian summer monsoon precipitation recorded by stalagmite oxygen isotopic composition in the western Loess Plateau during AD1875–2003 and its linkage with ocean-atmosphere system. Chinese Science Bulletin 53, 2041–2049.
Ma, J.Z., Edmunds, W.M., 2006. Groundwater and lake evolution in the Badain Jaran desert ecosystem, Inner Mongolia. Hydrogeology Journal 14, 1231–1243.
Ma, Z., Fu, C., 2006. Some evidence of drying trend over northern China from 1951 to 2004. Chinese Science Bulletin 51, 2913–2925.
Ma, J.Z., Li, D., Zhang, J.W., Edmunds, W.M., Prudhomme, C., 2003. Groundwater recharge and climatic change during the last 1000 years from unsaturated zone of SE Badain Jaran Desert. Chinese Science Bulletin 48, 1469–1474.
Magny, M., Begeot, C., Guiot, J., Peyron, O., 2003. Contrasting patterns of hydrological changes in Europe in response to Holocene climate cooling phases. Quaternary Science Reviews 22, 1589–1596.
Mahpir, J., Tursunov, A.A., 1996. An Introduction to the Hydro-Ecology in the Central Asia. Xinjiang Science, Technology and Hygiene Press, Urumchi (in Chinese).
Mann, M.E., 2004. On smoothing potentially non-stationary climate time series. Geophysical Research Letters 31, 710–713.
Mann, M.E., Jones, P.D., 2003. Global surface temperatures over the past two millennia. Geophysical Research Letters 30, 1820. doi:10.1029/2003gl017814.
Mann, M.E., Bradley, R.S., Hughes, M.K., 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. Geophysical Research Letters 26, 759–762.
Mann, M.E., Zhang, Z., Hughes, M.K., Bradley, R.S., Miller, S.K., Rutherford, S., Ni, F., 2008. Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. Proceedings of the National Academy of Sciences of the United States of America 105, 13252–13257.
Micklin, P.P., 2004. The Aral Sea crisis. In: Nihoul, J.C.J., Zavialov, P.O., Micklin, P.P. (Eds.), Dying and Dead Seas: Climatic Versus Anthropic Causes. Kluwer Academic Publishers, Dordrecht/Boston/London, pp. 99–125.
Mingram, J., Allen, J.R.M., Bruchmann, C., Liu, J., Luo, X., Negendank, J.F.W., Nowaczyk, N., Schettler, G., 2004. Maar-and crater lakes of the Long Gang Volcanic Field (NE China): overview, laminated sediments, and vegetation history of the last 900 years. Quaternary International 123, 135–147.
Moberg, A., Sonechkin, D.M., Holmgren, K., Datsenko, N.M., Karlen, W., 2005. Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433, 613–617.
Narisma, G.T., Foley, J.A., Licker, R., Ramankutty, N., 2007. Abrupt changes in rainfall during the twentieth century. Geophysical Research Letters 34, L06710. doi:10.1029/2006GL028628.
Nihoul, J.C.J., Zavialov, P.O., Micklin, P.P., 2004. Dying and Dead Seas: Climatic Versus Anthropic Causes. Kluwer Academic Publishers, Dordrecht/Boston/London.
Nourgaliev, D.K., Heller, F., Borisov, A.S., Hajdas, I., Bonani, G., Iassonov, P.G., Oberhansli, H., 2003. Very high resolution paleosecular variation record for the last ~1200 years from the Aral Sea. Geophysical Research Letters 30, 1914. doi:10.1029/2003GL018145.
Oerlemans, J., 2005. Extracting a climate signal from 169 glacier records. Science 308, 675–677.
Palmer, W.C., 1965. Meteorological Drought. Research Paper No. 45. U.S. Weather Bureau, Washington D.C.
Qin, B., Shi, Y., 1992. Changes of inland lakes of Asia since Holocene. In: Shi, Y. (Ed.), Advances on Studies of Climate in China and Sea Level Variation. China Ocean Press, Beijing, pp. 134–135 (in Chinese).
Qin, B., Yu, G., 1998. Implications of lake level variations at 6 ka and 18 ka in mainland Asia. Global and Planetary Change 18, 59–72.
Raible, C.C., Yoshimori, M., Stocker, T.F., Casty, C., 2007. Extreme midlatitude cyclones and their implications for precipitation and wind speed extremes in simulations of the Maunder minimum versus present day conditions. Climate Dynamics 28, 409–423.
Ren, G.Y., 1998. Pollen evidence for increased summer rainfall in the Medieval warm period at Maili, Northeast China. Geophysical Research Letters 25, 1931–1934.
Sato, T., Tsujimura, M., Yamanaka, T., Iwasaki, H., Sugimoto, A., Sugita, M., Kimura, F., Davaa, G., Oyunbaatar, D., 2007. Water sources in semiarid northeast Asia as revealed by field observations and isotope transport model. Journal of Geophysical Research 112, D17112. doi:10.1029/2006JD008321.
Shao, X.M., Huang, L., Liu, H.B., Liang, E.Y., Fang, X.Q., Wang, L.L., 2005. Reconstruction of precipitation variation from tree rings in recent 1000 years in Delingha, Qinghai. Science in China, Series D 48, 939–949.
Shen, C., Wang, W.C., Peng, Y., Xu, Y., Zheng, J., 2009. Variability of summer precipitation over Eastern China during the last millennium. Climate of the Past 5, 129–141.
Sheppard, P.R., Tarasov, P.E., Graumlich, L.J., Heussner, K.U., Wagner, M., Osterle, H., Thompson, L.G., 2004. Annual precipitation since 515 BC reconstructed from living and fossil juniper growth of northeastern Qinghai Province, China. Climate Dynamics 23, 869–881.
Shi, Y., Shen, Y., Kang, E., Li, D., Ding, Y., Zhang, G., Hu, R., 2007. Recent and future climate change in Northwest China. Climatic Change 80, 379–393.
Small, E.E., Giorgi, F., Sloan, L.C., Hostetler, S., 2001. The effects of desiccation and climatic change on the hydrology of the Aral Sea. Journal of Climate 14, 300–322.
Solomina, O., Alverson, K., 2004. High latitude Eurasian paleoenvironments: introduction and synthesis. Palaeogeography Palaeoclimatology Palaeoecology 209, 1–18.
Sontakke, N.A., Pant, G.B., Singh, N., 1993. Construction of all-India summer monsoon rainfall series for the period 1844–1991. Journal of Climate 6, 1807–1811.
Sorrel, P., Popescu, S.M., Head, M.J., Suc, J.P., Klotz, S., Oberhansli, H., 2006. Hydrographic development of the Aral Sea during the last 2000 years based on a quantitative analysis of dinoflagellate cysts. Palaeogeography Palaeoclimatology Palaeoecology 234, 304–327.
Soucek, S., 2000. A History of Inner Asia. Cambridge University Press, Cambridge.
Tang, X., Qian, W.H., Liang, P., 2006. Climatic features of boundary belt for East Asian summer monsoon. Plateau Meteorology 25, 375–381 (in Chinese with English Abstract).
Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Lin, P.E., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K.B., 1995. A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability. Annals of Glaciology 21, 175–181.
Thompson, L.G., Yao, T., Davis, M.E., Mosley-Thompson, E., Mashiotta, T.A., Lin, P., Mikhalenko, V.N., Zagorodnov, V.S., 2006. Holocene climate variability archived in the Puruogangri ice cap on the central Tibetan Plateau. Annals of Glaciology 43, 61–69.
Tian, W.C., 1993. Bohu County Annals. Xinjiang University Press, Urumchi (in Chinese).
Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bulletin of the American Meteorological Society 84, 1205–1217.
Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent positive North Atlantic Oscillation mode dominated the Medieval Climate Anomaly. Science 324, 78–80.
Van Campo, E., Gasse, F., 1993. Pollen- and diatom-inferred climatic and hydrological changes in Sumxi Co basin (Western Tibet) since 13,000 yr B.P. Quaternary Research 39, 300–313.
Van Campo, E., Cour, P., Hang, S.X., 1996. Holocene environmental changes in Bangong Co basin (Western Tibet). Part 2: the pollen record. Palaeogeography Palaeoclimatology Palaeoecology 120, 49–63.
Wang, P.X., 2009. Global monsoon in a geological perspective. Chinese Science Bulletin 54, 1–24.
Wang, S., Dong, G., 2002. Environmental Characteristics and Changes in Western China. Science Press, Beijing (in Chinese).
Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.C., Dorale, J.A., 2001a. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu cave, China. Science 294, 2345–2348.
Wang, S.W., Gong, D.Y., Zhu, J.H., 2001b. Twentieth-century climatic warming in China in the context of the Holocene. Holocene 11, 313–321.
Wang, S.M., Liu, J., Zhou, J., 2003. The climate of Little Ice Age maximum in China. Journal of Lake Sciences 15, 369–376 (in Chinese with English Abstract).
Wang, Y.J., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, C.A., Li, X.D., 2005a. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. Science 308, 854–857.
Wang, P., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z., Kershaw, P., Sarnthein, M., 2005b. Evolution and variability of the Asian monsoon system: state of the art and outstanding issues. Quaternary Science Reviews 24, 595–629.
Wang, K.L., Jiang, H., Zhao, H.Y., 2005c. Atmospheric water vapor transport from westerly and monsoon over the Northwest China. Advances in Water Science 16, 432–438 (in Chinese with English Abstract).
Wang, K.L., Jiang, H., Zhao, H.Y., 2006. Advection and convergence of water vapor transport over the northwest China. Advances in Water Science 17, 164–169 (in Chinese with English Abstract).
Wang, N.L., Jiang, X., Thompson, L.G., Davis, M.E., 2007. Accumulation rates over the past 500 years recorded in ice cores from the Northern and Southern Tibetan Plateau, China. Arctic, Antarctic, and Alpine Research 39, 671–677.
Wu, J.L., Liu, J.J., Wang, S.M., 2004. Climatic change record from stable isotopes in Lake Aibi, Xinjiang during the past 1500 years. Quaternary Sciences 24, 585–590 (in Chinese with English Abstract).
Wünnemann, B., Mischke, S., Chen, F.H., 2006. A Holocene sedimentary record from Bosten Lake, China. Palaeogeography Palaeoclimatology Palaeoecology 234, 223–238.
Yang, B., Braeuning, A., Johnson, K.R., Shi, Y.F., 2002a. General characteristics of temperature variation in China during the last two millennia. Geophysical Research Letters 29 doi:10.1029/2001gl014485.
Yang, X.P., Zhu, Z.D., Jaekel, D., Owen, L.A., Han, J.M., 2002b. Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions. Quaternary International 97–98, 155–166.

Yang, B., Braeuning, A., Shi, Y., Chen, F., 2004. Evidence for a late Holocene warm and humid climate period and environmental characteristics in the arid zones of northwest China during 2.2 ~ 1.8 kyr BP. Journal of Geophysical Research 109 doi:10.1029/2003JD003787.

Yang, B., Wang, J., Braeuning, A., Dong, Z., Esper, J., 2009. Late Holocene climatic and environmental changes in arid central Asia. Quaternary International 194, 68–78.

Yao, T.D., Xie, Z.C., Yang, Q.Z., Thompson, L.G., 1991. Temperature and precipitation fluctuations since 1600 A.D. provided by the Dunde Ice Cap, China. IAHS Publication No. 208. In: Kotlyakov, V.M., Ushakov, A., Glazovsky, A. (Eds.), Glaciers-Ocean-Atmosphere Interactions. International Association of Hydrological Sciences, Wallingford, pp. 61–70.

Yao, T.D., Thompson, L.G., Qin, D.H., Tian, L.D., Jiao, K.Q., Yang, Z.H., Xie, C., 1996. Variations in temperature and precipitation in the past 2000a on the Xizang (Tibet) Plateau-Guliya ice core record. Science in China, Series D 39, 425–433.

Yao, T.D., Jiao, K.Q., Yang, M.X., 2000. Precipitation variations recorded in Guliya ice core in the past 400 years. Progress in Natural Science 10, 288–293.

Yin, Z.Y., Shao, X.M., Qin, N.S., Liang, E., 2008. Reconstruction of a 1436-year soil moisture and vegetation water use history based on tree-ring widths from Qilian junipers in northeastern Qaidam Basin, northwestern China. International Journal of Climatology 28, 37–53.

Zhang, D.E., 1991. The Little Ice Age climate in China and its correlations with global change. Quaternary Sciences, 104–112 (in Chinese with English Abstract).

Zhang, D.E., Liu, C.Z., Jiang, J.M., 1997. Reconstruction of six regional dry/wet series and their abrupt changes during the last 1000 years in East China. Quaternary Sciences, 1–11 (in Chinese with English Abstract).

Zhang, Z., Wang, S., Wu, R., Wu, Y., Qu, W., 1998. Environmental changes recorded by lake sediments from east Juyanhai Lake in inner Mongolia during the past 2600 years. Journal of Lake Sciences 10, 44–51 (in Chinese with English Abstract).

Zhang, Q.B., Cheng, G.D., Yao, T.D., Kang, X.C., Huang, J.G., 2003. A 2326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau. Geophysical Research Letters 30, 1739. doi:10.1029/2003gl017425.

Zhang, H., Jin, H.L., Xiao, H.L., Chen, Y.H., 2004. Soluble salt sediments of east Juyan Lake and its indicating palaeoclimate environment changes. Journal of Desert Research 24, 409–415 (in Chinese with English Abstract).

Zhang, P., Cheng, H., Edwards, R.L., Chen, F., Wang, Y., Yang, X., Liu, J., Tan, M., Wang, X., Liu, J., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, J., Jin, L., Johnson, K.R., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. Science 322, 940–942.

Zheng, J.Y., Wang, W.C., Ge, Q.S., Man, Z.M., Zhang, P.Y., 2006. Precipitation variability and extreme events in eastern China during the past 1500 years. Terrestrial Atmospheric and Oceanic Sciences 17, 579–592.

Zhong, W., Xiong, H.G., 1999. Paleo-climatic and environmental development since about 4 ka B.P. and the relation with abandonments of ancient cities in southern Xinjiang. Journal of Desert Research 19, 343–347 (in Chinese with English Abstract).

Zhou, A.F., 2007. Varve chronology and late Holocene environmental changes in Sugan Lake, northern Qaidam Basin. In: Ph.D. dissertation, Lanzhou University, Lanzhou (in Chinese with English Abstract).

Zhou, A.F., Chen, F.H., Qiang, M.R., Yang, M.L., Zhang, J.W., 2007. The discovery of annually laminated sediments (varves) from shallow Sugan Lake in inland arid China and their paleoclimatic significance. Science in China, Series D 50, 1218–1224.

Zou, X., Zhai, P., Zhang, Q., 2005. Variations in droughts over China: 1951–2003. Geophysical Research Letters 32, L04707. doi:10.1029/2004GL021853.