Quaternary Science Reviews 27 (2008) 351–364

Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history

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Received 21 June 2007; received in revised form 14 October 2007; accepted 22 October 2007

Abstract

We synthesize palaeoclimate records from the mid-latitude arid Asian region dominated today by the Westerlies ("arid central Asia" (ACA)) to evaluate spatial and temporal patterns of moisture changes during the Holocene. Sediment records from 11 lakes with reliable chronologies and robust proxies were selected to reconstruct moisture histories based on a five-class ordinal wetness index with assigned scores from the driest to wettest periods at individual sites for 200-year time slices. The proxies used in these records include pollen and diatom assemblages, sediment lithology, lake levels, and geochemistry (mainly isotope) data. The results of our synthesis show that ACA as a whole experienced synchronous and coherent moisture changes during the Holocene, namely a dry early Holocene, a wetter (less dry) early to mid-Holocene, and a moderately wet late Holocene. During the early Holocene most of the lakes experienced very low water levels and even dried out before ca 8 ka (1 ka = 1000 cal a BP). Hence the effective-moisture history in ACA is out-of-phase with that in monsoonal Asia as documented by numerous palaeoclimate records. In monsoonal Asia, a strong summer monsoon and humid climate characterized the early Holocene, and a weakened summer monsoon and drier climate prevailed during the late Holocene, which were mainly controlled by changes in low-latitude summer insolation. In contrast, we propose that the pattern of Holocene effective-moisture evolution in the westerly dominated ACA was mainly determined by North Atlantic sea-surface temperatures (SSTs) and high-latitude air temperatures that affect the availability, amount and transport of water vapor. Also, topography of the Tibetan Plateau and adjacent Asian highlands could have contributed to the intensification of dry climate in ACA during the early Holocene, as a result of strengthening the subsidence of dry air masses, associated with stronger uplift motion on the plateau by intense heating under a stronger summer insolation. Summer insolation might have played a key role in directly controlling moisture conditions in ACA but only after the northern hemisphere ice-sheets had disappeared in the mid- and late Holocene.

1. Introduction

A variety of proxy records has been used to document climate change during the Holocene in many parts of the world. Understanding the spatial and temporal patterns of climate change in a given region may provide insights into

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0277-3791/$ - see front matter
doi:10.1016/j.quascirev.2007.10.017

the underlying climate-forcing mechanisms. In east and south Asia, Asian monsoon variations during the Holocene have been well-documented by precisely dated cave deposits (e.g., Fleitmann et al., 2003; Yuan et al., 2004; Shao et al., 2006). The Indian and East Asian summer monsoons were enhanced shortly after the Younger Dryas (YD) at the onset of the Holocene, was strongest in the early and mid-Holocene, and weakened after the mid-Holocene. This pattern closely follows changes in summer insolation at low latitudes (Kutzbach, 1981). Similar changes in the strength of the Asian monsoons have been documented by other proxy records from peats (Hong et al., 2003), lake sediments (Lister et al., 1991; Gu et al., 1993; Hodell et al., 1999; Xiao et al., 2004; Shen et al., 2005) and marine sediments (Wang et al., 1999; Gupta et al., 2003). However, Holocene climate patterns in arid central Asia (referred to as ACA in this paper) are poorly documented and understood. This lack of understanding is partly due to the complex interplay of competing forcing factors controlling regional climate; these factors include the low-latitude summer monsoonal circulation, the mid-latitude Westerlies, and orographic influences of the Tibetan Plateau. For example, the western part of ACA experienced a wet mid-Holocene and a dry early and late-Holocene, as documented by lake-level changes in the Aral Sea (Boomer et al., 2000), while the eastern part of the region near the monsoon limit showed a variable wetness during the entire Holocene, with some possibly drier intervals in the mid-Holocene (Chen et al., 2003a, b, 2006; Schettler et al., 2006; Zhao et al., 2007).

For expediting the following discussion, we divide the southeastern part of the Eurasian continent into three climatically distinct regions: humid Asia mainly controlled by summer monsoonal circulation; ACA dominated by the Westerlies; and a transitional zone around modern Asian summer monsoon limit in semi-arid northwest China and the southern Mongolian Plateau. In this study we focus only on the westerly dominated ACA for several reasons. First, it is one of the driest regions in the world, and its sparse water resources and fragile ecosystems in a general dry climate would be very sensitive to abrupt changes in rainfall (Qin et al., 2005; Narisma et al., 2007). Second, many lakes in this region, including Aral Sea and Caspian Sea, experienced similar changes during the Holocene (Qin and Yu, 1998). Also, a dramatic decline in lake levels has occurred during the last century at several lakes; such changes have attracted considerable attention because of concerns about shortage of water resources and related ecological problems (Qin and Yu, 1998; Ferronskii et al., 2003). However, a recent lake-level rise and lake expansion in the last 20 years at most lakes in arid west China suggests a possible shift from a warm-dry to a warm-humid climate under global warming (Shi et al., 2007). Several syntheses have been published over the last decade, which provide valuable insights into understanding the Holocene moisture history of the region. However, most of these reviews have focused only on parts of arid central Asia, as previous studies were mostly restricted to China (Shi et al., 1993, 1994; An et al., 2000; Feng et al., 2006). A comprehensive review of Holocene moisture evolution for the entire region is useful to decipher and understand the complex palaeo-moisture evolution under the same atmosphere circulation, namely the Westerlies. In addition, there are potential problems with chronology and proxy interpretations in some of the early published palaeo records (cf. Qin and Yu, 1998; An et al., 2000; Feng et al., 2006). As a result, there remains confusion about the regional climate patterns, and there is an urgent need to standardize and synthesize palaeoclimatic information about ACA mainly based on recent published records. Such an updated synthesis will help not only understand the Holocene moisture history of the region, but also provide information to assess climate simulations using general circulation model (GCM) and regional climate model (RCM, e.g., Sato and Kimura, 2005).

Here we review 11 lake records from the westerlies-dominated region of ACA (Fig. 1). The objectives of this study are (1) to review recently published proxy climate records from lake sediments; (2) to derive a semi-quantitative reconstruction of moisture history during the Holocene; and (3) to understand potential controls and mechanisms of the observed temporal and spatial patterns.

2. Data sources and analyses

In ACA there are abundant climatic records from continental eolian deposits, including loess and dune deposits. However, these records tend to have low temporal resolution and be discontinuous, even in the thick loess deposits on the Chinese loess Plateau that have high accumulation rates (e.g., Lu et al., 2006; Stevens et al., 2006). Therefore, in this study we have selected records from lake sediments based on four criteria: (1) the selected sites should be from extant lakes, so that any potential hard-water effect on radiocarbon ages can be evaluated and corrected. (2) The record length should cover most of the Holocene without documented depositional hiatuses. (3) The proxies derived from the records should be indicative of changes in precipitation or effective moisture (precipitation minus evaporation). (4) The selected records should have a sampling resolution of better than 200 years in most cases. We consider various proxies from different cores at the same lake site in multiple publications as one record. With the exception of the Aral Sea, the core data from individual lakes are considered to be primary data sources. However, secondary data sources from geomorphic evidence, such as shoreline features, lacustrine sediments above the present lake, and historical documents for lake-level change, as is the case in the Aral Sea (Boomer et al., 2000), were taken into consideration in the quantitative wetness reconstruction. Therefore, all the published data from an individual lake were synthetically considered as a record in reconstructing effective-moisture changes during the Holocene. When climatic records from

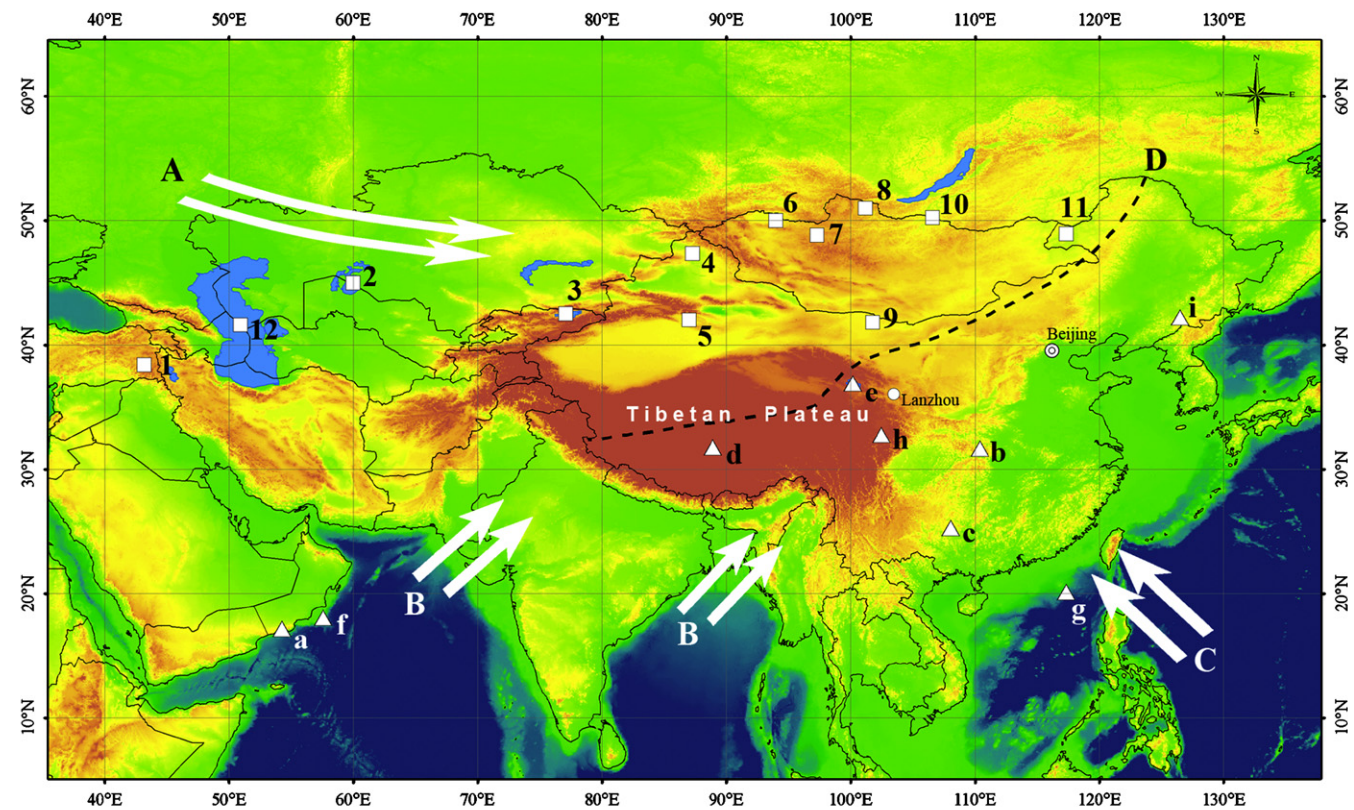


Fig. 1. Overview map showing the palaeoclimatic sites selected in this study from arid central Asia (numbers) and monsoonal Asia (lower case letters), and the dominant circulation systems (arrows with upper case letters) of the Westerlies (A), Indian monsoon (B), and East Asian monsoon (C). The modern Asian summer monsoon limit (dashed line, D, after Gao, 1962) is shown by a dark dashed line. The site numbers in arid central Asia (squares) are the same as those listed in Table 1, except for site number 12 for the Caspian Sea. The sites in monsoonal Asia (triangles) include speleothem records ((a) Qunf Cave, Southern Oman; (b) Shanbao Cave, central China; and (c) Dongge Cave, SW China), lake records ((d) Siling Lake and (e) Qinghai Lake), marine records ((f) Arabian Sea and (g) South China Sea), and peat records ((h) Hongyuan peat bog and (i) Hani peat bog). See Table 1 and the text for references.

a lake are inconsistent in different publications we used the latest publications that also evaluate the previous interpretations. Our site-selection criteria make our review and synthesis different from earlier published reviews (e.g., Li, 1990; Shi et al., 1993; An et al., 2006; Feng et al., 2006; Herzschuh, 2006). Based on these criteria, 11 lake sites were considered suitable for this study (Table 1 and Fig. 1).

At individual sites, all radiocarbon ages were first corrected, if necessary, to remove any possible old-carbon effect using information provided in the original publications. The corrected ^{14}C ages were then calibrated to calibrated ages using the OxCal 3.10 program (Bronk Ramsey, 1995, 2001). Calibrated ages are used in compiling effective-moisture curves throughout the text (expressed as cal a BP or ka, 1 ka = 1000 cal a BP).

Moisture conditions are coded on a five-scale (0–4) wetness index at individual lake sites: the driest (0) indicating the driest interval at that particular site during the Holocene, and the wettest (4) indicating the wettest period at that particular site during the Holocene. The justification for designating an ordinal wetness scale is that each individual lake may not be linearly comparable to other lakes due to different geographic locations, hydrological setting, sedimentary proxies used and as a result of different sensitivity. So the wetness scales are relative, in a semi-quantitative sense, and only applicable to that particular site. Relative wetness was assigned for each 200-year time interval, except for the 500-year intervals at Hovsgol Lake. The effective moisture is based primarily on lithological information and multi-proxy indicators from sediment cores at an individual lake. For example, a high wetness value would be assigned to intervals with varved sediments, fine-grained sediments, low oxygen-isotope values, high *Artemisia*/Chenopodiaceae pollen ratios, or abundant planktonic diatoms. On the other hand, eolian sand, or even fluvial sand would be given the lowest wetness value (0).

Here we use Bosten Lake as an example to illustrate how we assign relative wetness values to proxy records (Fig. 2). During the Lateglacial and early Holocene from 17 to 8.4 ka, all four cores taken from the deepest (>16 m water depth) and shallow parts of the lake consistently show coarse sand deposits with a mean grain size of >0.1 mm (Huang et al., 2007), indicating that the lake had completely dried up (Fig. 2). Thus, this period was driest at Bosten Lake and receives a wetness score of 0. After 8.4 ka, the relative wetness values are assigned for each 200-year interval mainly on the basis of the *Artemisia*-to-Chenopodiaceae (A/C) pollen ratios from core BST04H (Fig. 2; Huang, 2006). A/C ratios have been widely used to represent the relative dominance and production of steppe and desert

Table 1
Palaeomoisture records selected from arid central Asia. Lake sites are listed from west to east as in Fig. 1

Site	Lake	Lat. (°N)	Long. (°E)	Elev. (m a.s.l.)	Lake area (km^2)	Coring site water depth (m)	Max. water depth (m)	Time period (ka)	Sample resolution (a)	Dating method	Number of dating	Proxies used	References
1	Lake Van	38.40	43.20	1648	3522	420	458	0–13	Ca 20	Varve counting	–	$\delta^{18}O$, pollen, SDR[a]	Landmann et al. (1996), Wick et al. (2003)
2	Aral Sea	45.00	60.00	53	17,158	23	40.4	0–12	Ca 200	Conventional ^{14}C	36	Terrace, historical documents, SDR, $CaCO_3$	Boomer et al., (2000), Ferronskii et al. (2003)
3	Issyk-Kul	42.50	77.10	1606	1584	240	668	0–8	Ca 195	AMS-^{14}C	8	$\delta^{18}O$, $CaCO_3$	Rasmussen et al. (2001), Ricketts et al. (2001), Ferronskii et al. (2003)
4	Wulun Lake	47.20	87.29	478.6	927	12	13.9	0–10.3	Ca 90	AMS-^{14}C	6	Pollen, ostracod, ^{13}C, $\delta^{18}O$	Jiang et al. (2007)
5	Bosten Lake	42.00	87.02	1047.5	1100	6.25; 16.10	16.5	0–17	10–80	AMS-^{14}C	17	Pollen, Grain size, $CACO_3$	Wünnemann et al. (2003, 2006), Huang (2006), Huang et al. (2007)
6	Bayan Nuur	50.00	94.02	932	2	N/A[b]	N/A	0–15.6	N/A	Conventional ^{14}C	12	Terraces, pollen	Dorofeyuk and Tarasov (1998), Grunert et al. (2000)
7	Telmen Lake	48.83	97.33	1789	194	24.54	27	0–7	Ca 190	AMS-^{14}C	6	Diatom, pollen, $CaCO_3$	Peck et al. (2002), Fowell et al. (2003)
8	Hovsgol Nuur	51.00	101.20	1645	2760	222; 236	262	0–14.5	200–450	AMS-^{14}C	10	Diatom, pollen, biogenic silica, MS[c]	Tarasov et al. (1996), Dorofeyuk and Tarasov (1998), Karabanov et al. (2004); Nara et al. (2005); Prokopenko et al. (2005)
9	Juyan Lake	41.80	101.80	892	24	N/A	0.63	0–10.7	Ca 160	AMS-^{14}C	5	Pollen	Chen et al. (2003b), Herzschuh et al. (2004)
10	Gun Nuur	50.25	106.60	600	4	5	5	0–9.4	25–100	AMS-^{14}C	9	Diatom, $\delta^{13}C_{org}$, $CaCO_3$, MS	Wang et al. (2004), Feng et al. (2005)
11	Hulun Nuur	48.92	117.38	545	2339	N/A	8	0–12	150–200	Conventional ^{14}C	6	Pollen, MS	Wang and Ji (1995), Yang and Wang (1996)

[a]SDR: sediment deposition rate.
[b]N/A: not available; the moisture proxy from Bayan Nuur (site 6) was based on beaches and there were no information about sample resolution.
[c]MS: magnetic susceptibility.

plants and to infer changes in local effective moisture, with high A/C ratios representing high steppe dominance in a wet climate (El-Moslimany, 1990; Van Campo et al., 1996; Demske and Mischke, 2003; Herzschuh et al., 2004; Zhao et al., 2007). Eleven AMS ^{14}C ages on terrestrial plant remains and bulk organic matter provide the core chronology, after removing a hard-water effect of 1140 years based on dating of surface plant materials and after comparing ages from terrestrial plants remains with those from bulk organic matter of the same sample (Huang, 2006). The chronology of core BST04H was then established using linear interpolation between calibrated radiocarbon ages. Periods with A/C ratios of 0.4–0.6 for the last 8.4 ka receive an average wetness score of 1, A/C ratios of 0.6–0.8 receive a score of 2, A/C ratios of 0.8–1.0 receive a score of 3, and A/C ratios higher than 1.0 receive a score of 4 (Fig. 2).

Once wetness scores for each of 11 lake sites were assigned at 200-year time intervals, a synthesized curve for the entire region of ACA during the Holocene was created by averaging the 11-site scores for each 200-year time slice (Fig. 3). This procedure assumes that each site is equally sensitive to climate change and equally well dated, and that there are no gradients in response across the area. In reality, some records were obviously better dated than others and various proxies from these sites may show different sensitivity to climate change. However, it is not practical for the purpose of this synthesis to assign weights to each individual site, with information available in the publications.

3. Temporal moisture change during the Holocene in arid central Asia

Many lakes, including Bosten Lake (5), Bayan Nuur (6), Juyan Lake (9), Gun Nuur (10) and Hulun Nuur (11), were totally dried up or were very shallow during the early

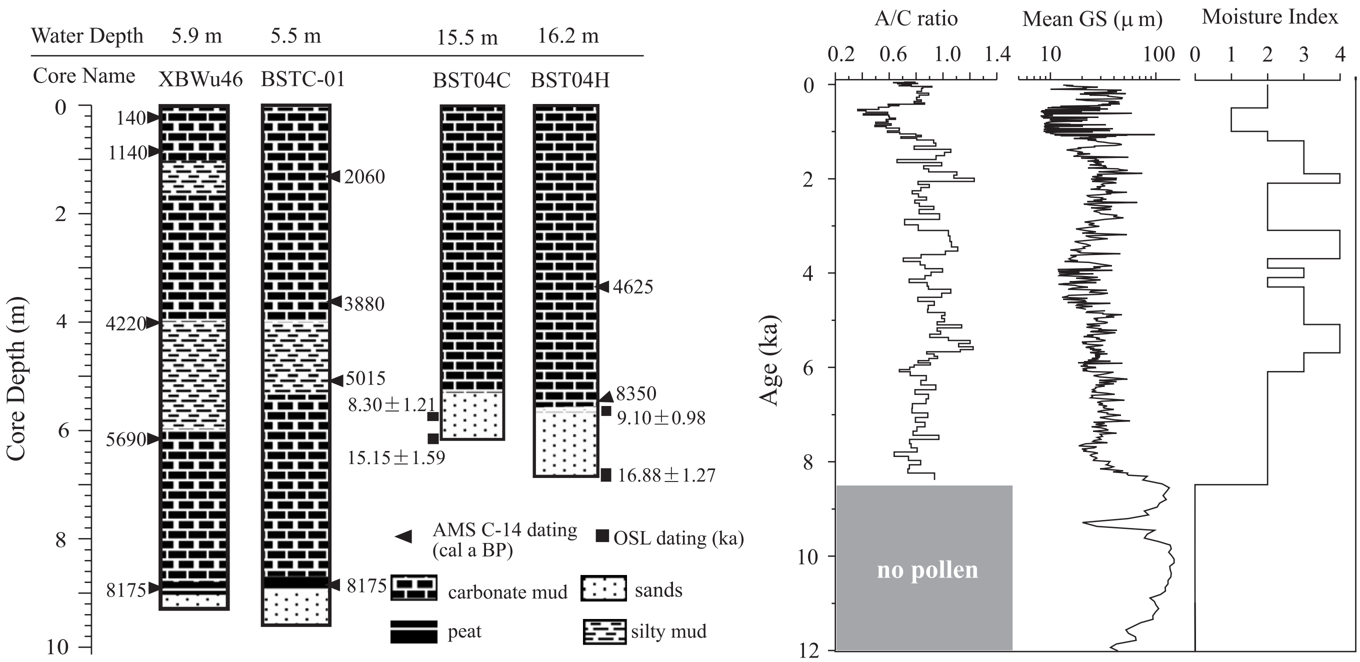


Fig. 2. Holocene moisture records from Bosten Lake, Xinjiang, NW China as an example showing how to convert sedimentary proxy records into a relative moisture index. Sediment core XBWu46 is from Wünnemann et al. (2003, 2006) and other cores from Huang (2006). Calibrated ages shown with the cores are based on radiocarbon ages on terrestrial plant remains and OSL dating on quartz. The *Artemisia*-to-Chenopodiaceae (A/C) pollen ratio and mean grain size analysis are from core BST04H (Huang, 2006).

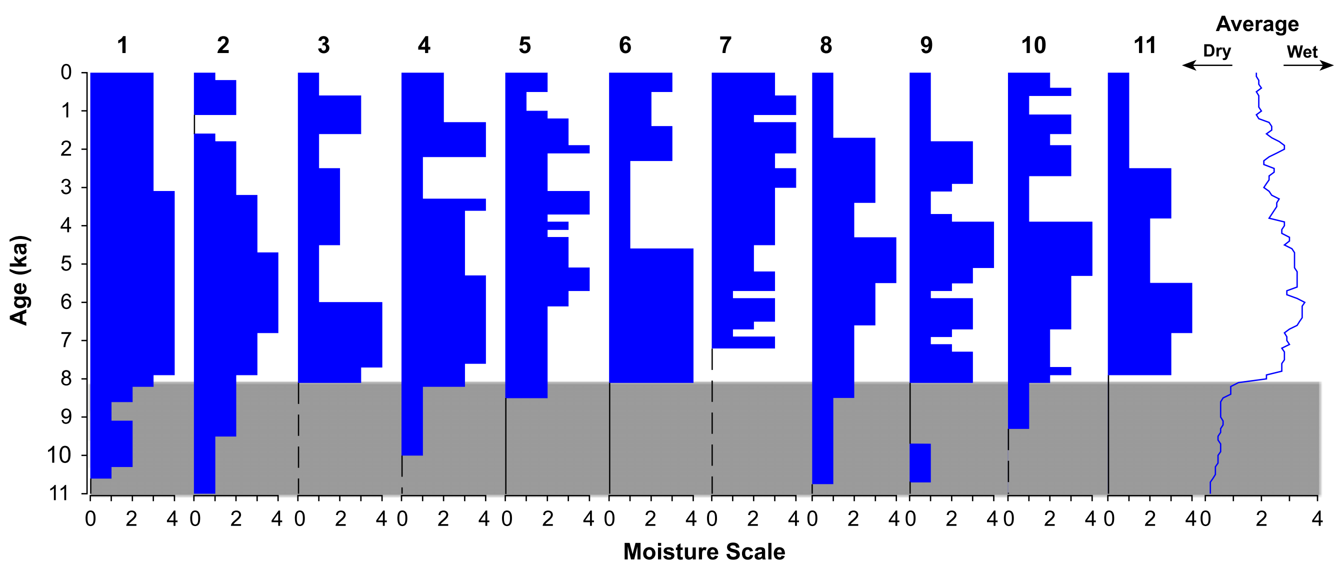


Fig. 3. Temporal moisture changes at each site (site numbers are the same as in Table 1) and the average moisture index (far right curve) for ACA as a whole during the Holocene. The vertical dotted line at sites 3, 4, 7 and 10 indicate that the shown sediment cores did not penetrate the entire Holocene sediment. Shading indicates widespread dry lake beds or low lake-levels in arid central Asia.

Holocene before 8 ka (Fig. 3). Large deep lakes, such as the Aral Sea, Issyk-Kul and Lake Van, were still present, but at low lake levels. The Caspian Sea also reportedly had a lower water level before 8 ka than at present (Kazanci et al., 2004), though this site is not included in this synthesis because of its low sampling resolution. These records suggest that the climate was extremely dry during the early Holocene. After ca 8 ka, a return to moist conditions in the study region is indicated by the appearance of most shallow lakes and by rising lake levels of deep lakes. The timing for lake appearance is different among lake records. Gun Nuur started to be filled by water as early as ca 9 ka (Wang et al., 2004; Feng et al., 2005), although lake level further increased at ca 7 ka (Fig. 3). Lake Telmen started to appear at ca 7 ka (Fowell et al., 2003). This absence of synchronicity in the appearance of lakes (and thus a humid climate) may result either from local differences in individual lakes' geological and hydrological settings, such as groundwater influences, lake area-to-volume ratio (basin morphology) and mean residence time, or from regional differences in climate responses. Dating problems in the original records may also result in the absence of synchronicity. Pollen data supported the general humid climate in mid-Holocene at 6 ka in the Mongolian Plateau (Tarasov et al., 1999).

Most lakes experienced maximum effective moisture between 8 and 4 ka in the mid-Holocene (Fig. 3). After this moisture increase, a coherent decrease in moisture continued to the present, with a return to a slightly wet climate around 2 ka (Fig. 3). The duration and extent of this late-Holocene climate amelioration was relatively short and less extensive in comparison to the previous moisture maxima.

The synthesized Holocene effective moisture in ACA can be summarized as follows: (1) a drier than present climate prevailed in the early Holocene before ca 8 ka; (2) maximum moisture conditions with the highest lake levels or densest vegetation cover are in the mid-Holocene around 8–4 ka at most sites; and (3) a decreasing moisture trend (but still wetter than the early Holocene) lasted until ca 1.5 ka. Most sites showed decreasing moisture during the last 2000 years.

4. Spatial patterns of Holocene moisture evolution in arid central Asia and monsoonal Asia

We divide the Holocene into four periods to investigate the regional patterns of Holocene moisture change in ACA and compared them with those in monsoonal Asia: early Holocene (ca 11–8 ka), mid-Holocene (8–5 ka), late Holocene (5–2 ka), and the last 2 ka. The Holocene moisture histories show distinct spatial patterns between ACA and monsoonal Asia (Fig. 4). Climate was clearly dry in the westerly dominated ACA during the early Holocene but it was humid during the mid-Holocene (Fig. 4). A moderately humid climate prevailed in ACA during the late Holocene and the last 2 ka, although there are large regional variations, with a less spatially coherent pattern compared to the early or mid-Holocene (Fig. 4). Some lake sites (e.g., Lake Telmen) show a continuous moisture increase until the late Holocene. A low-resolution lake-level curve of the Caspian Sea reconstructed from coastal terraces also shows low levels in the early Holocene and high levels in the mid-Holocene around 6 ka (Fig. 4; Overeem et al., 2003; Kazanci et al., 2004).

Herzschuh (2006) provided a detailed review of Holocene effective-moisture changes in monsoonal Asia, including the

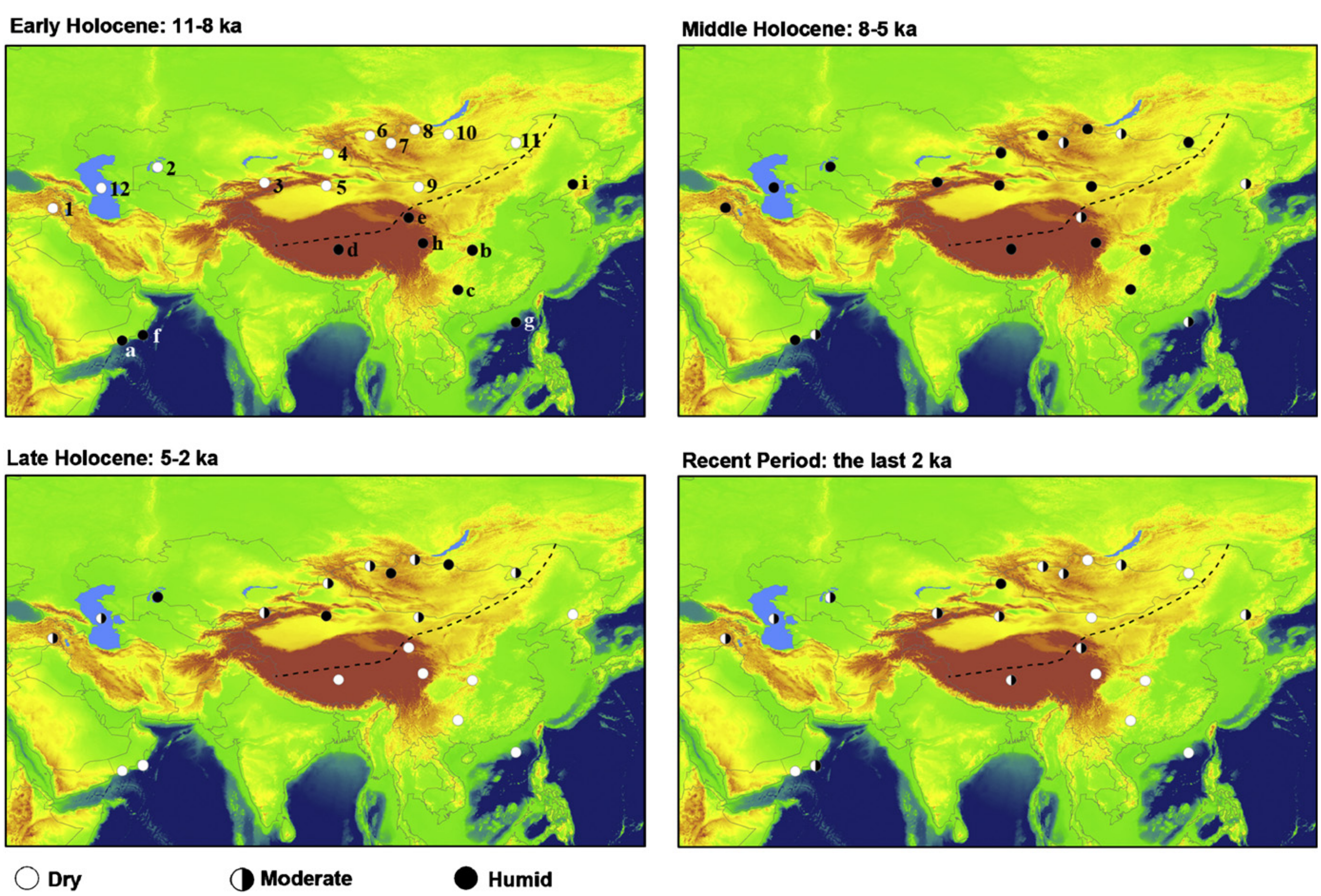


Fig. 4. Spatial patterns of effective-moisture change from arid central Asia and monsoonal Asia for four different periods of the Holocene (sites are the same as in Fig. 1). The Caspian Sea is from Overeem et al. (2003). The modern boundary between the Asian monsoon dominant region and the Westerlies dominant region is shown by a heavy dashed line on the map. Three summarized moisture scales: dry (wetness score 0–1.5), moderate (score 1.5–2.5), and wet (score 2.5–4.0).

East Asian and Indian monsoon regions of Asia, based on published data. She showed that the Holocene climate optimum with high precipitation occurred during the early Holocene in the Indian monsoon region, but possibly occurred during the mid-Holocene in the East Asian monsoon region. Here in our synthesis we have only selected palaeoclimate records with a reliable chronologies and robust climate proxies to evaluate the Holocene monsoon or moisture history and to compare with our synthesis in ACA. We used four published speleothem records from monsoonal Asia covering most of the Holocene, namely Dongge Cave (Yuan et al., 2004; Wang et al., 2005a) in southwest China whose climate is dominantly influenced by the Indian monsoon, Shanbao Cave (Shao et al., 2006) in central China that is climatically controlled by the East Asian monsoon, and Hoti Cave (Fleitmann et al., 2007) and Qunf Cave (Fleitmann et al., 2003) in the Oman that is dominated by the Indian monsoon. We also evaluate two peat-core records from northeast China (Hong et al., 2005) and from the eastern Tibetan Plateau (Hong et al., 2003), and two marine records from the Arabian Sea (Staubwasser et al., 2002; Gupta et al., 2003) and from the South China Sea (Wang et al., 1999), respectively. We also selected two lake records documented by carbonate oxygen isotopes, Siling Lake (Gu et al., 1993) in the southern Tibetan Plateau where climate is controlled by the Indian monsoon and Qinghai Lake (Lister et al., 1991; Liu et al., 2007) in the northeast Tibetan Plateau that is dominated by the East Asian Monsoon. All these well-dated monsoon records show a strong monsoon (high precipitation) in the early and mid-Holocene, and a weak monsoon (low precipitation and dry climate) during the late Holocene (see Fig. 5 for most records mentioned above). However, some speleothem records appear to show a trend of increasing summer monsoon over the last millennium (Fig. 5; Fleitmann et al., 2003, 2007; Yuan et al., 2004; Wang et al., 2005a; Shao et al., 2006). We found that the Indian and East Asian summer monsoons show similar and consistent changes at orbital time scales during the Holocene.

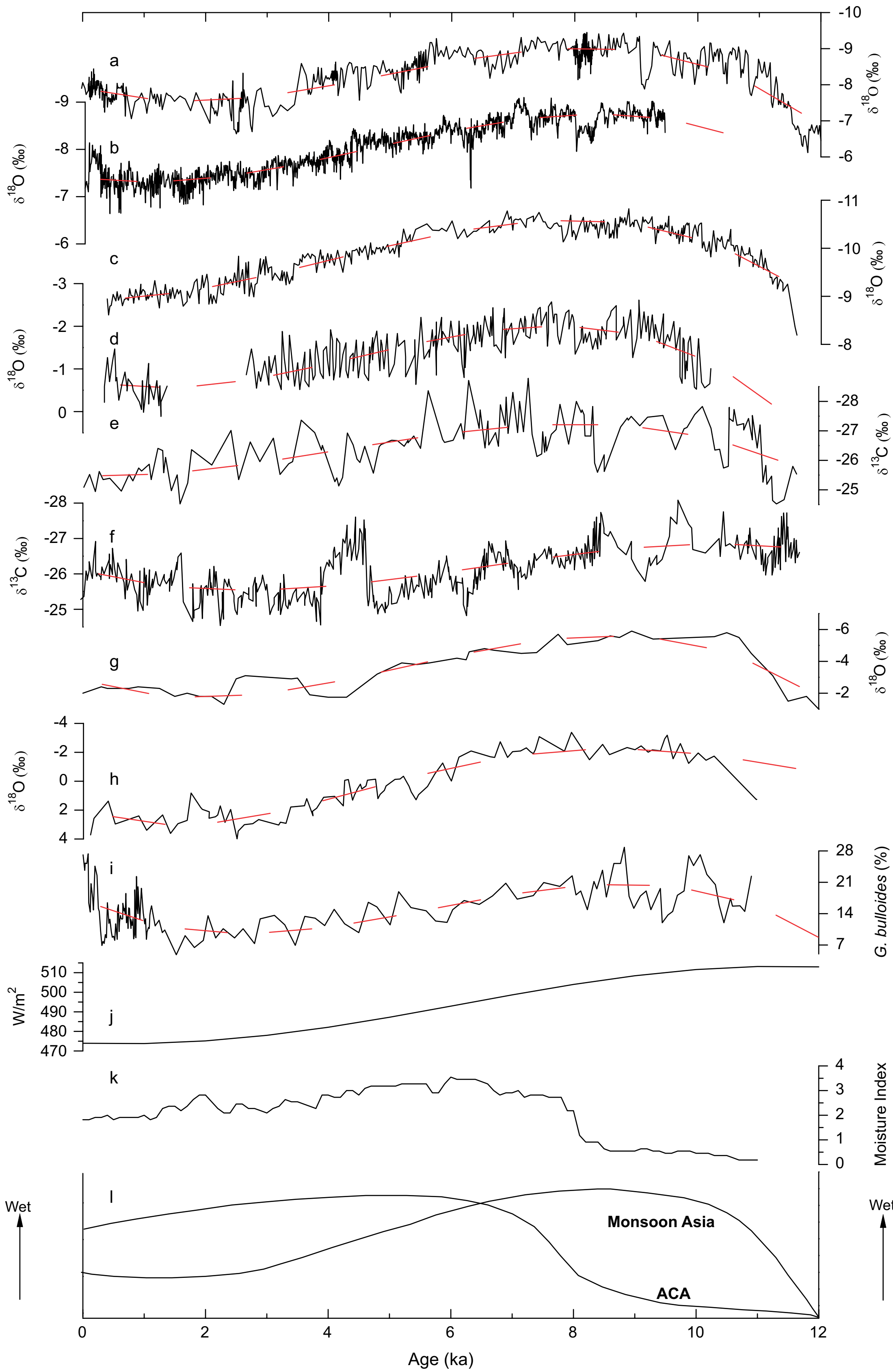
5. Contrasting patterns of Holocene moisture histories between arid central Asia and monsoonal Asia

Various proxy data from speleothem, lake sediments, peat cores and marine sediments as discussed above show similar patterns in effective moisture and precipitation change during the Holocene in monsoonal Asia. In their review, An et al. (2000) proposed that the Holocene optimum of the East Asian monsoon was asynchronous among different regions. However, evidence from recently well-dated records does not appear to support this hypothesis (Feng et al., 2006). Also, our synthesis shows that the East Asian and Indian monsoons have been synchronous during the Holocene, which is different from the conclusion in a recent synthesis by Herzschuh (2006). The different conclusions from these syntheses are partly due to the fact that An et al. (2000) and Herzschuh (2006) used some coarse-resolution and poorly dated records, especially in the case of An et al. (2000). The general trend of Holocene Asian monsoon history has been related to changes in summer insolation at low latitudes (Kutzbach, 1981; COHMAP Members, 1988; Wang et al., 2005a). Strong summer insolation in the Northern Hemisphere during the early Holocene (Berger and Loutre, 1991) induced strong land–ocean pressure and temperature gradients and increased onshore moist air flow in the summer, causing an enhanced Asian summer monsoon (COHMAP Members, 1988). The gradual weakening of the Asian summer monsoon since the mid-Holocene was in response to the orbitally induced decrease in summer insolation (e.g., Gupta et al., 2003), enhanced by the feedbacks from changes in vegetation cover and soil moisture as was the case in North Africa (Kutzbach et al., 1996; Ganopolski et al., 1998). A time delay of 2000 years of the strongest summer monsoon following the maximum summer insolation was apparently modulated by the waning ice-sheets in the Northern Hemisphere (Fleitmann et al., 2007).

In contrast to the moisture history of the region dominated by the Asian summer monsoon, the effective moisture in ACA was lowest in the early Holocene and highest in the mid-Holocene. The effective moisture in the late Holocene was lower than during the mid-Holocene but higher than during the early Holocene. As a result, the Holocene moisture history in the westerlies-dominated ACA was out-of-phase with that in the Asian monsoonal-dominated region. That is, a wet monsoon Asia corresponds to a dry ACA during the early Holocene, and a decreased monsoon and wet ACA during the mid- and late Holocene. This out-of-phase pattern of Holocene moisture histories between monsoonal Asia and ACA is summarized in Fig. 5k.

6. Possible forcing mechanisms for Holocene moisture evolution in arid central Asia

The Holocene ACA moisture history appears to be similar to the pattern of the Holocene sea-surface temperatures (SSTs) in the North Atlantic (e.g., Kaplan and Wolfe, 2006) and in the Norwegian Sea (Koç et al., 1993; Birks and Koç, 2002; Figs. 6c and d), as well as the air temperatures recorded in the GRIP ice-core (Dahl-Jensen et al., 1998; Fig. 6e) and in the European pollen records (Davis et al., 2003). The North Atlantic was warmest in the mid-Holocene between ca 9–8 ka and 5 ka after the rapid temperature increase in the early Holocene (Fig. 6c). Recent alkenone-derived SST reconstructions in the North Atlantic show similar patterns (e.g., Kim et al., 2007). Air temperature in Greenland and Europe also reached its maximum during the mid-Holocene. Relative sea level from Barbados, as an indicator of global ice volume, increased following the early Holocene and reached near present sea-level at ca 8 ka (Fig. 6f; Peltier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Moisture Index
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ACA
Age (ka)

and Fairbanks, 2006), corresponding to the final collapse of ice-sheets in the Northern Hemisphere (Lowe and Walker, 1997). All this evidence supports possible linkages between Holocene ACA moisture changes and temperature changes around the North Atlantic Ocean. Influences of SST in the Atlantic and Pacific oceans on continental droughts in North America have been increasingly documented from instrumental record (e.g., McCabe et al., 2004) and proxy data (Li et al., 2007). So oceanic controls over effective moisture in the interior of Eurasian continent are a plausible mechanism, through the so-called circumglobal teleconnection along a mid-latitude wave train where both the North Atlantic and central Asia have been identified as prominent ''centers of action'' (Ding and Wang, 2005).

Precipitation in the ACA region depends mainly on the amount of water vapor transported by the mid-latitude Westerlies from the North Atlantic Ocean and from inland seas and lakes along the westerly cyclonic storm paths (Böhner, 2006). We hypothesize that both North Atlantic SST and air temperature may have controlled the ACA precipitation changes during the Holocene. During the last deglaciation and early Holocene, the ice-sheets at high latitudes were still large compared with the mid- and late Holocene, modulating and reducing air temperature even though summer insolation was higher. Large meltwater discharges from the ice-sheets also reduced the ocean-surface temperature in the North Atlantic Ocean. Both low air temperature and SST are well-documented by proxies from various archives (Koç et al., 1993; Dahl-Jensen et al., 1998; Johnsen et al., 2001; Birks and Koç, 2002; Kaplan and Wolfe, 2006; see Fig. 6). During the early Holocene, the maximum summer insolation enhanced the Asian summer monsoon (Staubwasser et al., 2002; Wang et al., 2005b) and increased the latitudinal temperature gradient (high temperature in low latitudes) on land, due to the cooling effect of ice-sheets at high latitudes. The higher temperature in low latitudes during the early Holocene is documented in the Guliya ice core from the Tibetan Plateau (Thompson et al., 1997; Thompson et al., 2006). This large meridional temperature gradient during the early Holocene would have enhanced the mid-latitude westerlies air-stream and also would have shifted the westerlies jet stream southward. The cold ocean surface would have reduced water evaporation from the North Atlantic Ocean, while cold inland continental conditions in the ACA region would result in weak cyclonic activity at middle latitudes, and a strong but southward westerlies jet stream would influence ACA with strong winds throughout the whole year. All of these would result in less precipitation and a dry climate in ACA during the early Holocene. Eolian data and model simulations indicate that the influence of the Atlantic Westerlies could penetrate markedly eastward, even to the western Chinese Loess Plateau (Vandenberghe et al., 2006). During the mid- and late Holocene, when Northern Hemisphere ice-sheets were reduced or eliminated, both the North Atlantic SST and high-altitude air temperature increased (Fig. 6). The high SST in the North Atlantic region would induce more vapor from the Atlantic and high continental temperatures would induce high humidity available for recycled local moisture over the Eurasian continent (Numaguti, 1999), both of which would lead to more precipitation in arid central Asia. In addition, high air temperatures in ACA during the mid-Holocene would be expected to increase cyclonic activity and synoptic disturbances along the Westerlies, resulting in more convective precipitation. The increasing precipitation in ACA shown by instrumental data over the last 50 years (Jin et al., 2005) and an increase in effective moisture as documented by tree-ring records in the Tianshan Mountains (Li et al., 2006) support a warm and wet association in the Westerly dominated central Asia. Therefore, a warm North Atlantic would lead to higher evaporation from the North Atlantic, and higher air temperatures would enhance the westerlies disturbance and increased cyclonic activity (precipitation). Both factors would result in convective precipitation enhancing the moisture supply to central Asia. The decreasing effective moisture after the mid-Holocene in ACA matches a temperature decrease related to the reducing summer insolation. Therefore, we suggest that summer insolation of the Northern Hemisphere played a key role in ACA moisture changes only when the ice-sheets had disappeared.

The Tibetan Plateau and adjacent highlands in Asia may also play important roles in causing out-of-phase moisture changes during the Holocene. Strong insolation in summer at low latitudes causes a strong uplift motion of air mass over the high Asia (including the Tibetan Plateau). The resultant low pressure in the low troposphere near the land surface leads to a large-scale convergence and enhancement of the Asia summer monsoon (Ye and Gao, 1979). On the other hand, strong summer insolation and convective heating in southeast Asia during summer will consequently result in the intensified subsidence of air masses to the north of High Asia (Tibetan Plateau), which inevitably causes a dry climate in ACA (Broccoli and Manabe, 1992; Rodwell and Hoskins, 1996). Therefore, a strong summer monsoon would be correlated to a dry climate in arid central Asia. We propose that the stronger summer insolation in the early Holocene would have intensified

Fig. 5. Comparison of synthesized Holocene effective-moisture evolution in arid central Asia (k) with other selected proxy records from monsoonal Asia: (a) Dongge Cave D4, China (after Yuan et al., 2004); (b) Dongge Cave DA, China (after Wang et al., 2005a); (c) Shanbao Cave SB10-26, China (after Shao et al., 2006); (d) Qunf Cave, Oman (after Fleitmann et al., 2003); (e) Hongyuan Peat, and (f) Hani peat, China (after Hong et al., 2003, 2005); (g) Siling Lake, China (after Gu et al., 1993); (h) Qinghai lake (after Liu et al., 2007); and (i) Arabian Sea (after Gupta et al., 2003). All curves in panels (a)–(i) show the same direction of moisture change with increasing moisture upward. The long-term trend for each proxy curve is showed by smooth dashed line. Summer insolation at 30°N ((j) after Berger and Loutre, 1991) is also shown. The out-of-phase relationship of Holocene moisture evolution between monsoon Asia and ACA is illustrated in (l).

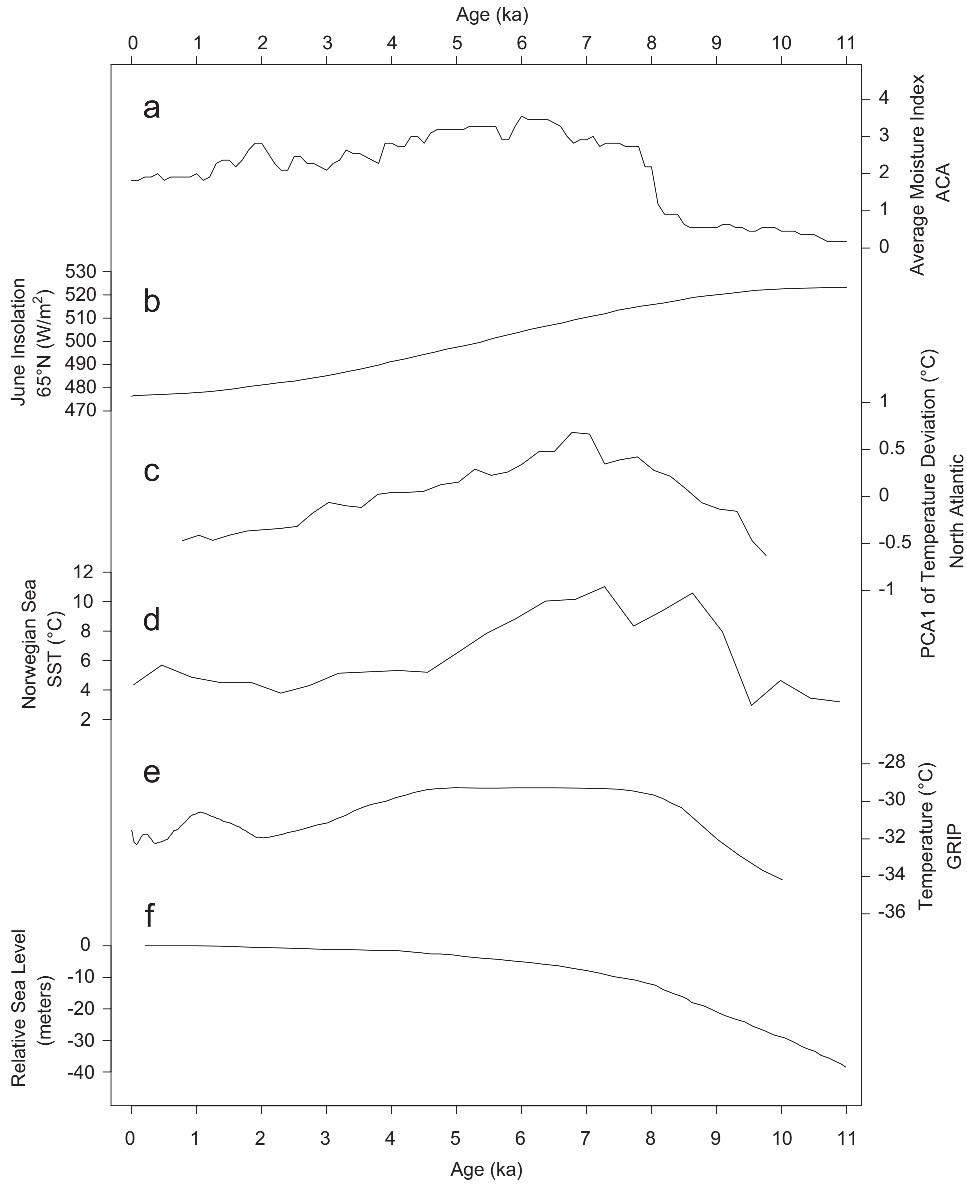

Fig. 6. (a) Synthesized Holocene mean moisture index in ACA; (b) correlation with Northern Hemisphere summer insolation (Berger and Loutre, 1991); (c) sea-surface temperature (SST) of the North Atlantic region (Kaplan and Wolxfe, 2006); (d) SST of the Norwegian Sea (Koç et al., 1993); (e) air temperature from GRIP ice-core (Dahl-Jensen et al., 1998); and (f) relative sea-level change from Barbados (Peltier and Fairbanks, 2006).

the Asian summer monsoon, inducing a wet climate in monsoon-dominated region, and at the same time strengthened the subsidence of air masses to central Asia north of the Tibetan Plateau, causing a drier climate in ACA (e.g., Sato and Kimura, 2005; Zhao et al., 2007).

In summary, we hypothesize that the out-of-phase pattern of Holocene moisture (precipitation) evolution in ACA with the Asian summer monsoon was mainly controlled by North Atlantic SST and high-latitude air temperature as modulated by waning ice-sheets. The remaining ice-sheets led to low SST in the North Atlantic Ocean and low air-temperatures at high latitudes in the early Holocene, resulting in low vapor transport by the Westerlies, while both high SST and air-temperature might increase westerlies moisture transport and cyclonic activity leading to high precipitation during the mid- and late Holocene in ACA. Intense heating of the Tibetan Plateau by high summer insolation may have partially enhanced a drier climate during the early Holocene in ACA. The Northern Hemisphere summer insolation played key roles only when Northern Hemisphere ice-sheets vanished in the mid- and late Holocene, explaining the slightly decreasing moisture after the mid-Holocene in ACA.

7. Conclusions

On the basis of palaeoclimatic records from 11 selected lakes in westerly dominated ACA, we find an out-of-phase relationship in Holocene moisture histories between ACA and the Asian monsoon-controlled region. In contrast to monsoonal Asia where maximum moisture occurred during the early to mid-Holocene, maximum moisture (precipitation) occurred during the mid-Holocene in ACA. We suggest that the out-of-phase pattern results from different controlling factors of moisture change in both regions. In monsoonal Asia, summer insolation at low latitudes has been the main driving force for changing intensities of Asian summer monsoon and precipitation. However, the climate in ACA has been mostly influenced by North Atlantic Ocean SST and high-latitude air-temperature as modulated by the waning ice-sheets in the Northern Hemisphere during the early Holocene. Persistently high SST in the North Atlantic Ocean, high air-temperatures in mid-latitudes, and still high summer insolation during the mid-Holocene all played major roles in causing peak effective moisture in ACA, through enhanced moisture transport from the North Atlantic and increased cyclonic activities.

We suggest that further studies are needed to document and fully understand the spatial and temporal patterns of Holocene moisture (precipitation) changes in ACA during the Holocene. Additional sites should be used to further test our out-of-phase hypothesis of Holocene moisture changes derived from the limited number of sites reviewed here. Due to the limitations of currently available climate records from the region, we do not discuss potential abrupt changes during the Holocene, such as the well-documented 8.2 ka event and 4.2 ka dry events. Newly collected high-resolution records should be able to evaluate their presence and potential North Atlantic connections. In addition, climate simulations using GCM and RCM would be useful in testing the relative importance of competing forcing factors under different boundary conditions in and around arid central Asia. In particular, potential influences of ocean conditions on continental aridity should be explored in the Eurasian continent based on analyses of instrumental and proxy data. Also, role of Arctic Oscillation (AO) should be taken into account when discussing large-scale climate connections, as AO is closely connected with the Rossby wave pattern. This study will hopefully help to improve our understanding of wet–dry climate changes and desertification processes in ACA and enhance our ability to project the regional moisture responses to future global warming.

Acknowledgements

This synthesis results from discussions at the INQUA RACHAD 2006 Workshop held on 25–27 July 2006 in Lanzhou, China. We thank Zhaodong Feng (Lanzhou University, China), Hilary Birks (University of Bergen, Norway), Georg Schettler (Geoforschungszentrum Potsdam, Germany), Xunlin Yang (Lanzhou University, China) and other workshop participants for their valuable contributions and discussion. We also thank two anonymous reviewers for their constructive comments and suggestions. This research was supported by Chinese NSF Grants (#90502008 and #40421101). The RACHAD Workshop was partly supported by the 111 Program (#B06026) of Chinese Ministry of Science and Technology. Yu and Ito were partially supported by US National Science Foundation for their work in northwest China.

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