GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45686.1

Manuscript received 8 October 2018
Revised manuscript received 12 December 2018
Manuscript accepted 10 January 2019

Arid Central Asia saw mid-Holocene drought

Hai Xu[1,2]*, Kang'en Zhou[2,3], Jianghu Lan[2], Guilin Zhang[1], and Xinying Zhou[4]
[1]Institute of Surface-Earth System Science, Tianjin University, Tianjin 300072, China
[2]Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710061, China
[3]University of Chinese Academy of Sciences, Beijing 100049, China
[4]Laboratory of Human Evolution and Archeological Science, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China

ABSTRACT

The mid-Holocene hydroclimates and the forcing mechanisms over arid Central Asia (ACA) are hotly debated in the context of global climate change. It is widely assumed that ACA Holocene precipitation broadly followed and/or was out-of-phase with Northern Hemisphere solar insolation. However, here we show a broadly antiphase relationship between Holocene boreal solar insolation and ACA hydroclimatic trend revealed from a well-dated peat core (at the Big Black peatland; BBP) in northwestern China, southern Altai Mountains. Multiple proxies, including peat development rate, pollen assemblages, and peat cellulose isotopic records, show wet conditions during the early and late Holocene, but drought condition during the mid-Holocene. This hydroclimatic pattern is similar to those extracted from other peatlands nearby and those inferred from sedimentary records in lakes in adjacent regions. The trend of $\delta^{18}O$ in BBP peat cellulose is similar to that of a stalagmite in northern Xinjiang, both of which record the Holocene atmospheric precipitation $\delta^{18}O$ trend over ACA areas and possibly suggest a changing proportion of glacier meltwater supply. We speculate that the mid-Holocene drought over ACA could be ascribed to: (1) the northward movement of the westerlies, such that when the westerlies moved northward under warm conditions, less water vapor was transported to ACA, and vice versa, and (2) increased evaporation under mid-Holocene warm conditions. The data from this study and the potential mechanisms suggest that drier conditions are expected over ACA areas under a continuous global warming expectation.

INTRODUCTION

Mid-Holocene climatic changes are crucial to understanding the causes of the recent/modern global warming and to predicting future climate change (e.g., Steig, 1999; Wanner et al., 2008). It is generally deemed that the Holocene hydroclimatic changes over arid Central Asia (ACA) followed boreal solar insolation (Cheng et al., 2012), similar to those over the Asian monsoon areas (Dykoski et al., 2005). Another major viewpoint is that Holocene effective moisture over the ACA is out of phase with that over monsoonal Asia and is out of phase with the boreal solar insolation due to variable amounts and transport of water vapor modulated by North Atlantic sea-surface temperatures and high-latitude air temperatures (Chen et al., 2008). The mid-Holocene temperature increases (driven by high boreal summer insolation) over ACA areas would be larger than those of the global average because arid Asian drylands are expected to be more sensitive in comparison with the global average. For example, the observed surface warming over global drylands (1.2–1.3 °C) over the past century has been 20%–40% higher than that over humid lands (0.8–1.0 °C; Huang et al., 2017). Huang et al. (2017) even estimated that a 2 °C increase in global temperature may lead to an approximate 3.2–4 °C increase over drylands. Potential evaporation over ACA areas is generally several to ten times higher than precipitation (e.g., Ran et al., 2015). It is likely that the mid-Holocene could have been much drier over ACA areas due to the stronger evaporation driven by higher summer temperatures at that time, which would be quite different from the aforementioned hydroclimatic trends. Therefore, additional evidence is necessary to understand the mid-Holocene hydroclimatic changes and their causes over ACA.

In this study, we discuss the hydroclimatic changes and possible forcing mechanisms during the Holocene over ACA based on multiproxy indices extracted from a well-dated peat core collected at the Big Black Peatland (BBP; Fig. 1), in the southern Altai Mountains, northwestern China. We show a broadly antiphase relationship between Holocene ACA hydroclimate and boreal solar insolation and propose that the south/north movement of the westerlies and changes in evaporation could have dominated mid-Holocene hydroclimatic conditions over ACA.

HOLOCENE BBP PEATLAND DEVELOPMENT

A peat core (BBP-13) was collected in an intermountain basin (Item DR1 in the GSA Data Repository[1]) and was dated by ^{14}C dating (Item DR2). Multiproxy indices (Fig. 2), including sedimentation rate, pollen assemblages (Item DR3), and stable oxygen and carbon isotopes (Item DR4), were determined. The ^{14}C ages of peat cellulose indicate that the BBP peat formed at approximately 9500 yr B.P. (Item DR2), and the peat deposition rate remained relatively high from 9500 to 7600 yr B.P. The peat deposition rate began to decrease between 7600 and 6300 yr B.P. and remained very low during the interval of 6300–2800 yr B.P. The BBP peat deposition rate increased after 2800 yr B.P. and remained high during the late Holocene. Peat deposition rates at Chaiwobu (~580 km away from the BBP peatland; Hong et al., 2014) were also high during the early and late Holocene, but very low during the mid-Holocene (see curve j in Fig. 2), similar in pattern to that of the BBP peatland.

HOLOCENE CLIMATIC TRENDS OVER SOUTHERN ALTAI AND NORTHERN XINJIANG

The trends of Holocene climate changes in northern Xinjiang, and even over the wider ACA region, are quite variable between the results of different studies. For example, Chen et al. (2008) proposed an out-of-phase relationship

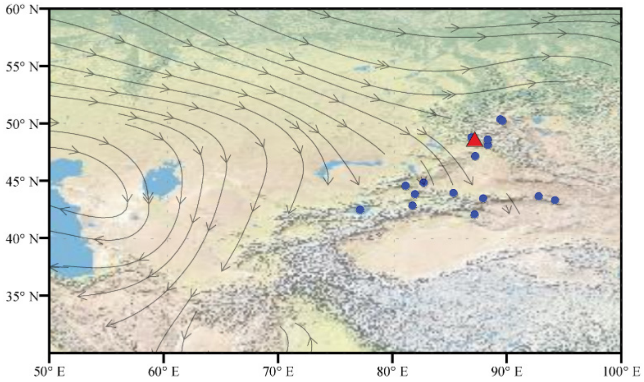
---

*E-mail: xuhai@tju.edu.cn

[1]GSA Data Repository item 2019092, details of modern climates, sampling, dating, analysis, and climatic significance of the multi- proxy indices, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

CITATION: Xu, H., et al., 2019, Arid Central Asia saw mid-Holocene drought: Geology, v. 47, p. 255–258, https://doi.org/10.1130/G45686.1

Figure 1. Location of Big Black peatland (BBP), southern Altai Mountains, northwestern China. BBP peatland (red triangle; also refer to Fig. DR1 [see footnote 1]). Arrow lines show wind stream for June–August (850 hPa; 1968–1996 NCEP/NCAR [National Centers for Environmental Prediction/National Center for Atmospheric Research] reanalysis data; Kalnay et al., 1996). Digital numbers denote sites mentioned in text (see Table DR1 for details).



between ACA effective moisture and the Asian summer monsoon intensity on millennial/centennial scales based on comparison of a set of lake sediment records. However, similar trends between ACA precipitation and Asian monsoon precipitation have been inferred from the $\delta^{18}O$ records of stalagmites. For example, the Holocene long-term precipitation trend inferred from the stalagmite $\delta^{18}O$ record in Keshang Cave, northern Xinjiang, is similar to the Holocene monsoon precipitation trends inferred from stalagmite $\delta^{18}O$ records in the Asian monsoon areas (such as Dongge Cave in southwestern China; Fig. 2). A third view is that ACA precipitation or effective precipitation gradually increased throughout the Holocene. For example, the Holocene precipitation trend in northern Xinjiang indicated by peat $\delta^{13}C$ (Hong et al., 2014) shows a gradual increase. The water level of Wulungu Lake, northern Xinjiang, indicated by sedimentary grain size (Fig. 3; Liu et al., 2008), and that inferred from ostracod assemblages (Mischke and Zhang, 2011) show a broadly increasing trend during the Holocene. Sedimentary pollen records and other proxy indices from this lake also point to an increasing trend of effective moisture (Liu et al., 2008). Broadly increasing trends in effective moisture during the Holocene existed in several other lakes over northern Xinjiang (Fig. 3), like Lake Boston (Mischke and Wünnemann, 2006), Lake Sayram (Jiang et al., 2013), Lake Aibi (Wang and Feng, 2013), Lake Balikun (Tao et al., 2010), and Lake Tuolekule (Ran et al., 2015). The synthesized effective moisture over northern Xinjiang area also shows a broadly increasing trend (Wang and Feng, 2013). The effective moisture inferred from magnetic indicators in several loess profiles also exhibits a broadly increasing trend during the Holocene (Fig. 3; Chen et al., 2016).

The BBP accumulation rate and pollen assemblages (Fig. 2; Item DR3) indicate relatively wet climatic conditions during the early Holocene and much wetter conditions during the late Holocene, but drier during the mid-Holocene over northern Xinjiang. BBP peat cellulose $\delta^{13}C$ shows a broadly similar effective moisture trend to that inferred from the *Artemisia* and Chenopodiaceae pollen ratio (A/C ratio; Fig. 2). This hydroclimatic pattern is similar to those over adjacent sites. For example, the Narenxia peat pollen records show wet conditions during ~11,500– 7000 yr B.P., dry conditions during ~7000– 4000 yr B.P., and wet conditions again after 4000 yr B.P. (Fig. 3; Feng et al., 2016). Pollen A/C ratios were much higher during the early Holocene than the mid-Holocene in a profile in Yili valley (Li et al., 2011), also indicating much drier mid-Holocene hydroclimatic conditions. BBP pollen A/C ratios are also similar in trend to those at Lake Aibi (Wang and Feng, 2013); both point to wet conditions during the early and late Holocene but dry conditions during the mid-Holocene. The A/C ratios in Lake Balikun (Tao et al., 2010), Lake Tuolekule (Ran et al., 2015), Lake Akkol, and Lake Grusha (see locations in Fig. 1; see references in Table DR1) indicate much drier mid-Holocene conditions as compared with those during the late Holocene.

WATER VAPOR SOURCES OVER ACA AREAS

The water vapor sources over ACA areas are presently hotly debated. One of the main views is that Holocene water vapor in the North Xinjiang region was mainly transported by the Asian summer monsoon (especially during the Holocene optimum). For example, Harrison et al. (1996) suggested that the Asian summer monsoon in the Holocene optimum might have gone further northwestward than the modern position. Water vapor at Lake Boston, Lake Hoton-Nur, Lake Issyk-Kul, etc. (see locations and references in Figure 1 and Table DR1), has also been suggested to have an Asian summer monsoon source during the early and mid-Holocene. The second major view is that the Asian summer monsoon has not crossed the desert/sandy area southeast of ACA; therefore, the ACA water

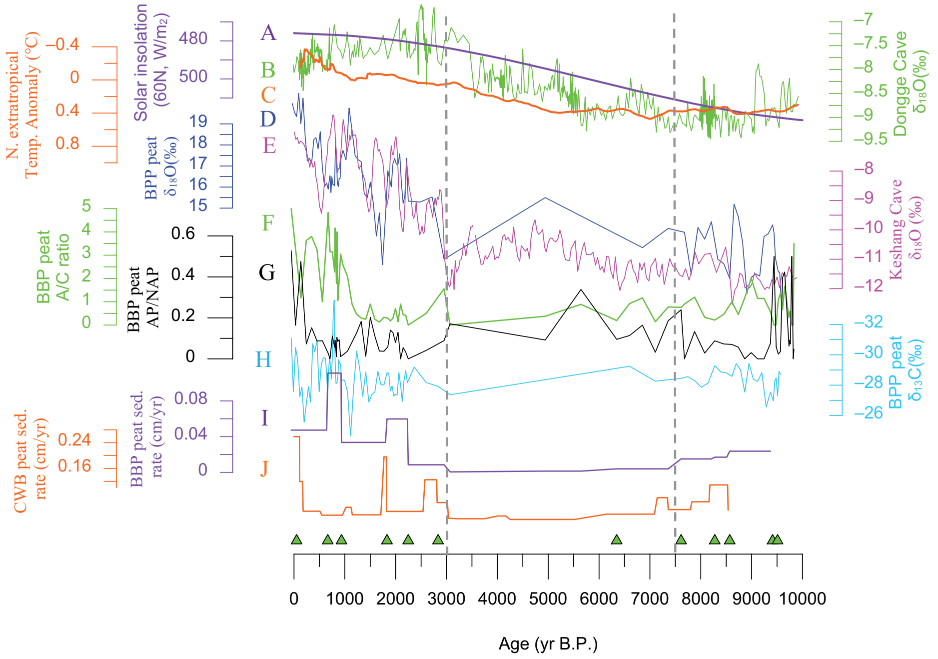


Figure 2. Comparison between Big Black peatland (BBP, southern Altai Mountains, northwestern China) peat records and other proxy indices. A: 60°N June insolation (thick purple; Berger, 1978). B: Dongge Cave stalagmite $\delta^{18}O$ (red; Dykoski et al., 2005). C: Northern Hemisphere extratropical (90°N–30°N) temperature anomalies (orange thick curve; Marcott et al., 2013). D: BBP peat $\delta^{18}O$ (blue). E: Keshang Cave stalagmite $\delta^{18}O$ (pink; Cheng et al., 2012). F: BBP peat A/C (*Artemisia* and Chenopodiaceae pollen) ratio (green). G: BBP peat arboreal/nonarboreal pollen (AP/NAP) ratio (black; see the Data Repository [see text footnote 1]). H: BBP peat $\delta^{13}C$ (sky-blue). I, J: BBP (purple) and Chaiwobu (CWB; orange; Hong et al., 2014) peat accumulation rates. Green filled triangles show ^{14}C dating points. Vertical dashed gray lines show mid-Holocene interval inferred from changes in sedimentation rate and vegetation types of BBP peat.

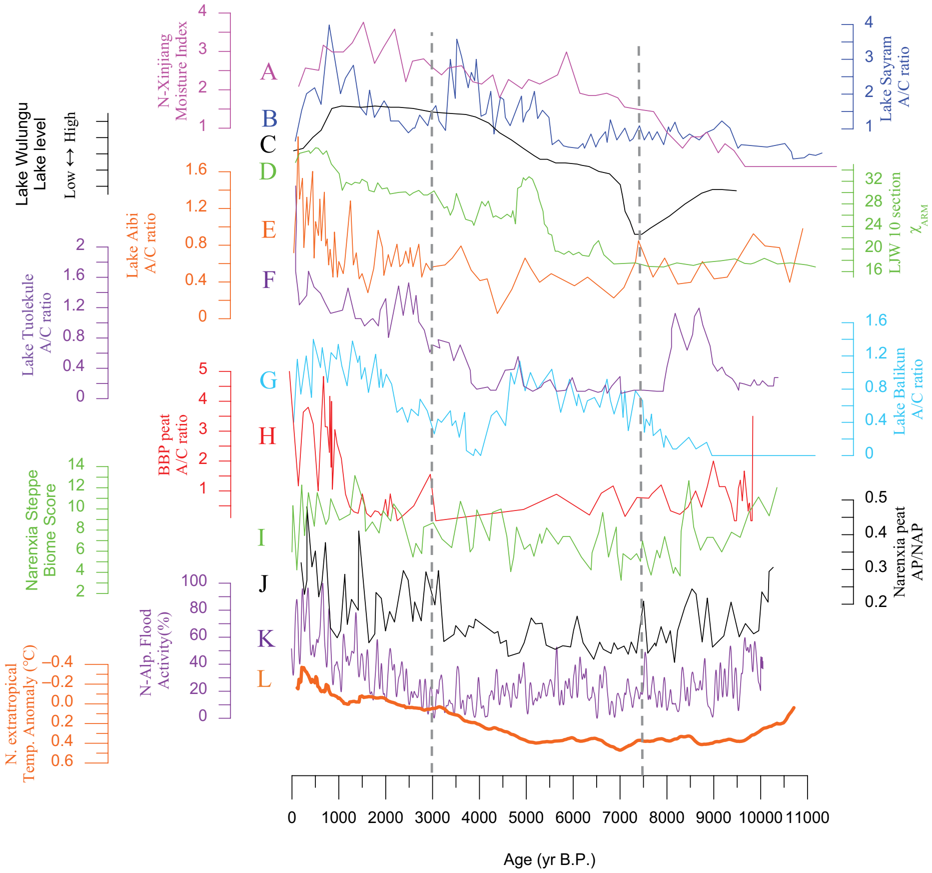


Figure 3. Comparison of Holocene proxy-based effective moisture over northern Xinjiang area, China. A: Synthesized effective moisture over northern Xinjiang (Ran et al., 2015). B: Sedimentary A/C (*Artemisia* and Chenopodiaceae pollen) ratio in Sayram Lake (Jiang et al., 2013). C: Lake levels in Wulungu Lake (Liu et al., 2008). D: Magnetic index in LJW10 loess profile, Yili valley (Chen et al., 2016). ARM—anisotropy of magnetic remanence. E: Lake Aibi A/C ratio (Wang and Feng, 2013). F: Lake Tuolekule A/C ratio (redrawn from Ran et al., 2015). G: Lake Balikun A/C ratio (Tao et al., 2010). H: Big Black peatland (BBP) peat A/C ratio (this study). I, J: Narenxia peat steppe biome score and arboreal/nonarboreal pollen (AP/NAP) ratio, respectively (Feng et al., 2016). K: Flood frequency over northern Alps mountains (Wirth et al., 2013). L: Northern Hemisphere extratropical (90°N–30°N) temperature anomalies (Marcott et al., 2013). Vertical dashed gray lines are same as those in Figure 2.

vapor could have been transported by westerlies from the North Atlantic, Mediterranean Sea, etc., and could have been partly supplied by the recycling of Asian inland water (Aizen et al., 2006; Liu et al., 2008; Chen et al., 2008). In particular, when reaching the Altai Mountain areas in northern Xinjiang, the water vapor is largely precipitated due to the influence of topography, leading to high annual precipitation around the Altai Mountains as compared with that in surrounding areas.

Precipitation at Tianshan Mountain reconstructed from tree-ring records is significantly correlated with the North Atlantic oscillation index (Zhang et al., 2015), which implies that precipitation in the northern Xinjiang area may be transported by the westerlies. The modern rainfall δ^{18}O observations also suggest water vapor transported by westerlies but not by Asian summer monsoon (Item DR4). In addition, the hydroclimatic pattern in northern Xinjiang reconstructed in this study is similar to that in the Alps mountain region in Europe (Fig. 3; Wirth et al., 2013), implying that even on longer time scales, the westerlies may regulate the hydroclimatic features in the regions along its route.

In northern Xinjiang, snowfall occurs mainly in winter and early spring, and the snow δ^{18}O value (about –20‰ to ~–30‰) is much lower than rainfall δ^{18}O values in summer (e.g., Wang et al., 2016). The water vapor recycling recharged by snowmelt in warm seasons may lead to negative δ^{18}O values in rainfall water. The ratio of recycling water in Urumqi, Xinjiang, is ~16%, as simulated by Wang et al. (2016). Aizen et al. (2006) suggested that the local water vapor recycling might account for a larger proportion of the regional precipitation. It is likely that on long-term time scales (e.g., multidecadal, centennial, and millennial scales), the ratio of snowmelt recycling supplied by the glaciers could be larger during warm intervals, and the regional precipitation δ^{18}O could be more negative; alternatively, during the cold periods, the ratio of snowmelt recycling could be smaller, and the regional precipitation δ^{18}O values would be larger (less negative). Therefore, we propose that the negative atmospheric precipitation δ^{18}O values during the early to mid-Holocene over ACA areas, as inferred from both the BBP peat cellulose δ^{18}O values and the Keshang Cave stalagmite δ^{18}O values (Fig. 2), may be related to the relatively higher proportion of glacier meltwater recycling during this period. During the late Holocene, both the BBP peat cellulose δ^{18}O and the Keshang Cave stalagmite δ^{18}O values gradually increased (Fig. 2), implying that the proportion of glacier meltwater involved in the recycling gradually decreased, which is consistent with the observed shrinking of the glacier cover in the ACA region.

ACA HYDROCLIMATIC CHANGES AND THE WESTERLIES

During the winter and early spring, the study area is ice-covered, and precipitation (including snow) would be stored in the catchment because evaporation is very low (Item DR1) due to the low temperature and high snow/ice albedo. When temperature increases in the mid-late spring, snow cover and the lakes/wetlands melt around the study area, and at the same time evaporation increases sharply (Item DR1). Annual evaporation is much higher than precipitation (E >> P) over the ACA areas (Item DR1); the precipitation during the cold seasons is lower than the evaporation of the next spring seasons. Therefore, precipitation during the cold seasons could have no or minor influence on the summer hydroclimatic conditions over the study areas. What mainly influences the summer hydroclimatic conditions are summer water vapor transportation, glacier meltwater (if there are any glaciers in a specific catchment), and evaporation.

The variations of water vapor transport in ACA are related to both the intensity of the westerlies and the location of the westerly belt. Generally, the intensity of westerly wind is relatively strong in winter, and the westerly belt is shifted southward in winter compared to that in summer (Folland et al., 2009). This suggests that during longer cold periods, the westerly intensity may be increased, and the westerly zone could move south, resulting in more water vapor transported from the North Atlantic, Mediterranean, Caspian Sea, etc., to the ACA region. On the contrary, the flux of water vapor to the ACA region would decrease during the relatively warm periods. Solar activity/insolation, as an external heat source for Earth, may directly or indirectly affect the regional temperature and the location of the westerlies. Stronger (weaker) solar activity/insolation corresponds to higher (lower) surface temperature, and northward (southward) movement of the westerlies, resulting in less (more) water supply to ACA regions.

Therefore, the hydroclimate over ACA areas is expected to act in a "warm/dry–cold/wet" pattern, which is also supported by a large number of paleoclimate records. For example, recent work shows that it was much wetter during the cold periods over the eastern ACA areas during the past 4000 yr (Lan et al., 2018). Therefore, we propose that the dry and wet changes in ACA may be partly ascribed to the variation of water vapor supply due to the north-south movement of the westerly belt, where the high mid-Holocene boreal summer insolation (Berger, 1978) may have led to high boreal summer temperatures and northward migration of the westerly belt, and eventually led to a decrease in the water vapor flux to the ACA region.

The high mid-Holocene boreal summer temperature (Fig. 3) may also have led to increases in summer surface evaporation. Although the low boreal mid-Holocene winter insolation (Berger, 1978) may have resulted in low winter temperatures, this would not have significantly influenced the annual evaporation because the winter evaporation is very small compared with the annual value (Item DR1). Since annual evaporation is much higher than annual precipitation over ACA areas, the increases in evaporation (ΔE) could also be much higher than changes in annual precipitation (ΔP), which may also partly contribute to the observed mid-Holocene drought over ACA areas.

CONCLUSIONS AND IMPLICATIONS

Our multiproxy records show wetter early and late Holocene and drier mid-Holocene conditions in the Altai area of northern Xinjiang, which is similar in pattern to those recorded in adjacent peatlands, lakes, and loess profiles. We contend that the mid-Holocene drought in the northern Xinjiang region, and even in ACA, could be ascribed to the northward advance of the westerly belt and the increased evaporation caused by higher summer temperatures during this period. Providing these mechanisms stand, the ACA areas are expected to be even drier under a continuous global warming scenario.

ACKNOWLEDGMENTS

We thank the editor and anonymous reviewers for valuable comments and suggestions. This work was funded by National Natural Science Foundation of China (NSFC) research programs no. 41761144070 and no. 41672169, and by the External Cooperation Program of the Bureau of International Cooperation, Chinese Academy of Sciences (no. 132B61KYSB20130003).

REFERENCES CITED

Aizen, V.B., Aizen, E.M., Joswiak, D.R., Fujita, K., Takeuchi, N., and Nikitin, S.A., 2006, Climatic and atmospheric circulation pattern variability from ice-core isotope/geochemistry records (Altai, Tien Shan and Tibet): Annals of Glaciology, v. 43, p. 49–60, https://doi.org/10.3189/172756406781812078.

Berger, A.L., 1978, Long-term variations of daily insolation and Quaternary climatic changes: Journal of the Atmospheric Sciences, v. 35, p. 2362–2367, https://doi.org/10.1175/1520-0469(1978)035<2362:LTVODI>2.0.CO;2.

Chen, F., Yu, Z., Yang, M., Ito, E., Wang, S., Madsen, D.B., Huang, X., Zhao, Y., Sato, T., and Birks, H.J.B., 2008, Holocene moisture evolution in arid Central Asia and its out-of-phase relationship with Asian monsoon history: Quaternary Science Reviews, v. 27, p. 351–364, https://doi.org/10.1016/j.quascirev.2007.10.017.

Chen, F., Jia, J., Chen, J., Li, G., Zhang, X., Xie, H., Xia, D., Huang, W., and An, C., 2016, A persistent Holocene wetting trend in arid Central Asia, with wettest conditions in the late Holocene, revealed by multi-proxy analyses of loess-paleosol sequences in Xinjiang, China: Quaternary Science Reviews, v. 146, p. 134–146, https://doi.org/10.1016/j.quascirev.2016.06.002.

Cheng, H., Zhang, P.Z., Spötl, C., Edwards, R.L., Cai, Y.J., Zhang, D.Z., Sang, W.C., Tan, M., and An, Z.S., 2012, The climatic cyclicity in semiarid-arid Central Asia over the past 500,000 years: Geophysical Research Letters, v. 39, L01705, https://doi.org/10.1029/2011GL050202.

Dykoski, C.A., Edwards, R.L., Cheng, H., Yuan, D., Cai, Y., Zhang, M., Lin, Y., Qing, J., An, Z., and Revenaugh, J., 2005, A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China: Earth and Planetary Science Letters, v. 233, p. 71–86, https://doi.org/10.1016/j.epsl.2005.01.036.

Feng, Z., Sun, A., Abdusalih, N., Ran, M., Kurban, A., Lan, B., Zhang, D., and Yang, Y., 2016, Vegetation changes and associated climatic changes in the southern Altai Mountains within China during the Holocene: The Holocene, v. 27, p. 1–11.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., and Hurrell, J.W., 2009, The summer North Atlantic Oscillation: Past, present, and future: Journal of Climate, v. 22, p. 1082–1103, https://doi.org/10.1175/2008JCLI2459.1.

Harrison, S.P., Ge, Y., and Tarasov, P.E., 1996, Late Quaternary lake-level record from northern Eurasia: Quaternary Research, v. 45, p. 138–159, https://doi.org/10.1006/qres.1996.0016.

Hong, B., Gasse, F., Uchida, M., Hong, Y., Leng, X., Shibata, Y., An, N., Zhu, Y., and Wang, Y., 2014, Increasing summer rainfall in arid eastern-Central Asia over the past 8500 years: Scientific Reports, v. 4, p. 5279, https://doi.org/10.1038/srep05279.

Huang, J.P., Yu, H.P., Dai, A.G., Wei, Y., and Kang, L.T., 2017, Drylands face potential threat under 2 °C global warming target: Nature Climate Change, v. 7, p. 417–422, https://doi.org/10.1038/nclimate3275.

Jiang, Q.F., Ji, J.F., Shen, J., Matsumoto, R., Tong, G.B., Qian, P., Ren, X.M., and Yan, D.Z., 2013, Holocene vegetational and climatic variation in westerly-dominated areas of Central Asia inferred from Sayram Lake in northern Xinjiang, China: Science China, ser. D, Earth Sciences, v. 56, p. 339–353, https://doi.org/10.1007/s11430-012-4550-9.

Kalnay, E., et al., 1996, The NCEP/NCAR 40-year reanalysis project: Bulletin of the American Meteorological Society, v. 77, p. 437–471, https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Lan, J.H., et al., 2018, Late Holocene hydroclimatic variations and possible forcing mechanisms over the eastern Central Asia: China Earth Sciences, v. 61, https://doi.org/10.1007/s11430-018-9240-x.

Li, X., Zhao, K., Dodson, J., and Zhou, X., 2011, Moisture dynamics in Central Asia for the last 15kyr: New evidence from Yili Valley, Xinjiang, NW China: Quaternary Science Reviews, v. 30, p. 3457–3466, https://doi.org/10.1016/j.quascirev.2011.09.010.

Liu, X., Ulrike, H., Ji, S., Jiang, Q., and Xiao, X., 2008, Holocene environmental and climatic changes inferred from Wulungu Lake in northern Xinjiang, China: Quaternary Research, v. 70, p. 412–425, https://doi.org/10.1016/j.yqres.2008.06.005.

Marcott, S.A., Shakun, J.D., Clark, P.U., and Mix, A.C., 2013, A reconstruction of regional and global temperature for the past 11,300 years: Science, v. 339, p. 1198–1201, https://doi.org/10.1126/science.1228026.

Mischke, S., and Wünnemann, B., 2006, The Holocene salinity history of Bosten Lake (Xinjiang, China) inferred from ostracod species assemblages and shell chemistry: Possible palaeoclimatic implications: Quaternary International, v. 154–155, p. 100–112, https://doi.org/10.1016/j.quaint.2006.02.014.

Mischke, S., and Zhang, C., 2011, Ostracod distribution in Ulungur Lake (Xinjiang, China) and a reassessed Holocene record: Ecological Research, v. 26, p. 133–145, https://doi.org/10.1007/s11284-010-0768-1.

Ran, M., Zhang, C., and Feng, Z., 2015, Climatic and hydrological variations during the past 8000 years in northern Xinjiang of China and the associated mechanisms: Quaternary International, v. 358, p. 21–34, https://doi.org/10.1016/j.quaint.2014.07.056.

Steig, E.J., 1999, Mid-Holocene climate change: Science, v. 286, p. 1485–1487, https://doi.org/10.1126/science.286.5444.1485.

Tao, S.C., An, C.B., Chen, F.H., Tang, L.Y., Wang, Z.L., Lü, Y.B., Li, Z.F., Zheng, T.M., and Zhao, J.J., 2010, Pollen-inferred vegetation and environmental changes since 16.7 ka BP at Balikun Lake, Xinjiang: Chinese Science Bulletin, v. 55, p. 2449–2457, https://doi.org/10.1007/s11434-010-3174-8.

Wang, S., Zhang, M., Che, Y., Chen, F., and Qiang, F., 2016, Contribution of recycled moisture to precipitation in oases of arid Central Asia: A stable isotope approach: Water Resources Research, v. 52, p. 3246–3257, https://doi.org/10.1002/2015WR018135.

Wang, W., and Feng, Z., 2013, Holocene moisture evolution across the Mongolian Plateau and its surrounding areas: A synthesis of climatic records: Earth-Science Reviews, v. 122, p. 38–57, https://doi.org/10.1016/j.earscirev.2013.03.005.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T.J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., and Kaplan, J.O., 2008, Mid- to late Holocene climate change: An overview: Quaternary Science Reviews, v. 27, p. 1791–1828, https://doi.org/10.1016/j.quascirev.2008.06.013.

Wirth, S.B., Glur, L., Gilli, A., and Anselmetti, F.S., 2013, Holocene flood frequency across the central Alps—Solar forcing and evidence for variations in North Atlantic atmospheric circulation: Quaternary Science Reviews, v. 80, p. 112–128, https://doi.org/10.1016/j.quascirev.2013.09.002.

Zhang, T., Zhang, R., Yuan, Y., Gao, Y., Wei, W., Diushen, M., He, Q., Shang, H., and Wang, J., 2015, Reconstructed precipitation on a centennial timescale from tree rings in the western Tien Shan Mountains, Central Asia: Quaternary International, v. 358, p. 58–67, https://doi.org/10.1016/j.quaint.2014.10.054.

Printed in USA