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RESEARCH ARTICLE

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Key Points:

- A precisely-dated stalagmite $\delta^{18}\text{O}$ record, spanning 8.4–2.7 ka was obtained from Baluk cave, Xinjiang, Northwest China
- Baluk cave $\delta^{18}\text{O}$ record is characterized by abrupt centennial- to multidecadal-scale variations, suggesting dramatic hydroclimatic shifts
- Solar activity-induced northern high-latitude climate variations could be responsible for rapid hydroclimatic changes in arid central Asia

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(continued)

Holocene Solar Activity Imprint on Centennial- to Multidecadal-Scale Hydroclimatic Oscillations in Arid Central Asia

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Abstract Numerous studies have been conducted on the Holocene climatic evolution of arid central Asia (ACA) using various geological proxies. However, the quality of the age control and the temporal resolution of the proxy records used make it difficult to characterize hydroclimatic changes on centennial to multidecadal timescales. Here we present a stalagmite $\delta^{18}\text{O}$ record from Baluk cave in Xinjiang, NW China, in ACA, which has an average 22.8-year resolution and provides a record of inferred hydroclimatic changes from 8.4 to 2.7 ka. Abrupt hydroclimatic shifts are evident during the following intervals: 2.75–2.90, 3.25–3.35, 3.75–3.85, 4.45–4.55, 4.75–4.90, 5.05–5.15, 5.2–5.3, 5.4–5.5, 5.9–6.0, 6.2–6.3, 6.4–6.5, 6.8–6.9, 7.1–7.6, 7.85–7.95, and 8.05–8.25 ka. Notably, an overall in-phase relationship is observed between the hydroclimatic variations and change in solar activity, and the results of spectral analysis suggest the presence of the Eddy (~1,080 years), de Vries (~205 years), and Gleissberg (~88–102 years) cycles. This indicates a linkage between solar activity and hydroclimatic changes in ACA on centennial to multidecadal scales during the Holocene. We suggest that the influence of solar activity on hydroclimatic changes in ACA occurs via its effects on North Atlantic sea surface temperature, North Atlantic Oscillation, northern high-latitude regional temperatures, and via direct heating. The relationship suggests that solar activity may play an important role in determining future hydroclimatic changes in ACA.

1. Introduction

Arid central Asia (ACA) extends across the midlatitudes from the Caspian Sea in the west to western China and the Mongolian Plateau in the east (Figure 1). Climatically, ACA is dominated by the westerly circulation (Chen et al., 2009, 2008). The region comprises extensive areas of dry lands, characterized by an arid/semiarid environment, water resource shortages, and fragile ecosystems (Huang et al., 2015). In the past few decades, the regional hydroclimate has changed significantly under the current global warming trend, which has had a substantial impact on water resources and socioeconomic sustainability (Deng & Chen, 2017; Kouraev et al., 2009; Shi et al., 2007). To evaluate this impact, as well as to predict future hydroclimatic changes in the region, more high-resolution regional Holocene records are needed.

Centennial- to multidecadal-scale climatic events during the Holocene, which are primarily recognized in high-latitude regions (Bond et al., 2001, 1997), have been suggested to be closely associated with the collapse of civilizations (Drysdales et al., 2006; Sandweiss et al., 2001; Staubwasser et al., 2003; Wang et al., 2005). Such climatic events were especially important in influencing man-land relationships in ACA (Yin et al., 1992). The climatic and environmental evolution of ACA has been reconstructed from various geological archives, such as lake sediments (An et al., 2011; Chen et al., 2008; Ding et al., 2002; Mathis et al., 2014; Mischke & Wünnemann, 2006; Rhodes et al., 1996; Ricketts et al., 2001; Rudaya et al., 2009), loess (Chen et al., 2016; Li et al., 2016), peats (Hong et al., 2014), and sand dunes (Long et al., 2017, 2014). Most of these studies have addressed long-term climatic and environmental changes

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(e.g., Chen et al., 2008; Ding et al., 2002), and in addition the proxy records typically have relatively large age uncertainties and low temporal resolution. Thus, it is difficult to use them to address the issue of hydroclimatic changes on centennial to multidecadal scales. By contrast, speleothems, in which absolute U-Th dating and high-resolution proxies can be obtained, are valuable for studying climatic events of short duration (Cheng et al., 2009; Fleitmann et al., 2003; Wang et al., 2005). Speleothems from ACA have been used to reconstruct past climatic changes, and the records have been successfully correlated with global climatic records; notable examples are Kesang cave in NW China (Cai et al., 2017; Cheng et al., 2012) and Tonnel'naya (Ton) cave in Uzbekistan (Cheng et al., 2016). However, these published speleothem records suffer from relatively large dating errors (e.g., Cai et al., 2017), limited numbers of dates (e.g., Cheng et al., 2012), and relatively low sampling resolution during the Holocene (e.g., Cheng et al., 2016). Thus, they do not satisfactorily address the issue of centennial- to multidecadal-scale hydroclimatic oscillations in ACA.

Here we present a high-resolution $\delta^{18}\text{O}$ record from Baluk cave in Xinjiang Province in ACA, which spans the time interval from the early to late Holocene. Our aims were to derive a high-resolution record of hydroclimatic oscillations in ACA and to explore possible relationship between centennial- to multidecadal-scale climatic variations and solar activity.

Figure 1. (a) Location of Baluk cave (red star) in Northwest China, arid central Asia. Yellow dots indicate the localities of Kesang cave in Northwest China (Cai et al., 2017; Cheng et al., 2016, 2012) and Tonnel'naya (Ton) cave in Uzbekistan, central Asia (Cheng et al., 2016). Blue arrows show the vertically integrated moisture flux during April to July (1981–2010) based on National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996). The red dashed line indicates the modern limit of the Asian summer monsoon (Chen et al., 2009, 2008). The area enclosed by the white dashed line is arid Asia (Feng et al., 2014), and the area enclosed by the yellow dashed line is the core zone of the “westerlies-dominated climatic regime” (Huang et al., 2015). (b) Variations in monthly averaged temperature (MAT), monthly averaged precipitation (MAP), weighted monthly averaged precipitation $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_p$) (Vienna Pee Dee Belemnite, VPDB) at Ürümqi meteorological station (blue square in Figure 1a), ~300 km northeast of Baluk cave. Observational data are available from the Global Network of Isotopes in Precipitation online website.

Figure 2. Polished profiles, U-Th dates, and $\delta^{18}\text{O}$ records of two stalagmites from Baluk cave. Section views along the central growth axes of BLK12A (a, 184 mm in length) and BLK12B (d, 125 mm in length) are shown. The U-Th dates for the two stalagmites (b, e) and the $\delta^{18}\text{O}$ profiles (c, f) are plotted against depth. The age-depth model for BLK12B was calculated using the StalAge algorithm, with the corresponding 95% confidence limits shown in red (e; Scholz & Hoffmann, 2011). ICP-MS = inductively coupled plasma mass spectrometer.

2. Study Site and Analytical Methods

Baluk cave ($84^{\circ}44'\text{E}$, $42^{\circ}26'\text{N}$, 2,752 m a.s.l.) is located about 120 km southeast of Bayanbulak Town, in Xinjiang Province, NW China (Figure 1). The entrance height of the cave is less than 1 m, which substantially reduces air ventilation. Data from nearby Ürümqi meteorological station indicate that mean annual precipitation is 303.6 mm, with about 70% occurring during the warm season (April to September; Figure 1). However, the weighted monthly averaged precipitation $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_p$) from Ürümqi station exhibits relatively high values during summer and low values during winter (Figure 1), and there is a strong positive correlation with monthly averaged temperature ($r = 0.99$, $p < 0.01$) and a weak positive correlation with monthly averaged precipitation ($r = 0.84$, $p < 0.01$; Liu et al., 2015). As shown by the vertically integrated water vapor flux during summer (June to August; Figure 1), the water vapor supplied to the region originates primarily from the west, suggesting the influence of the westerly circulation (Aizen et al., 1996; Chen et al., 2008; Tian et al., 2007; Yao et al., 2013).

In September 2012, two stalagmites (BLK12A and BLK12B) were collected from the central chamber of Baluk cave. Calcite precipitation was continuous in both stalagmites, and clear growth cycles are evident in the polished sections (Figure 2). A total of 29 powder subsamples (14 for BLK12A and 15 for BLK12B) for U-Th dating was obtained using an electrical dental drill in a class-100 laminar flow bench housed in a class-10,000 subsampling room; the weights of the subsamples ranged from 30 to 80 mg. Chemical preparation for U and Th separation was performed in a super cleanroom according to the methods described by Cheng et al. (2000) and Shen et al. (2003). U-Th isotopic compositions and concentrations were determined using a multicollector inductively coupled mass spectrometer, Thermo-Fisher NEPTUNE at the High-Precision Mass Spectrometry, and Environment Change Laboratory of the National Taiwan University during January–April 2013. Instrumental procedures followed the technical improvements of Shen et al. (2012). The U-Th ages of stalagmites BLK12A and BLK12B were calculated based on the decay constants and $^{238}\text{U}/^{235}\text{U}$ ratios reported in Jaffey et al. (1971), Cheng et al. (2013), and Hiess et al. (2012). In addition, an initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of 4.4 ± 2.2 was assumed for age corrections. Uncertainties in the U-Th isotopic

data and ^{230}Th dates (year BP, before 1950 Common Era) are given at the two-sigma (2σ) level or two standard deviations of the mean ($2\sigma_m$) unless otherwise noted.

For analysis of stable oxygen isotope composition ($\delta^{18}\text{O}$), 618 powdered subsamples (368 for BLK12A and 250 for BLK12B) were drilled along the growth axis of the stalagmite profiles at a 0.5-mm interval. Measurements were made using a Thermo/Finnigan mass spectrometer (MAT253) equipped with the Kiel Carbonate Device IV at the Key Laboratory of Western China's Environmental Systems (MOE), Lanzhou University. International standards (GBW04405, GBW04406, NBS18, and NBS19) were run separately for every 20 samples to test the accuracy and reproductivity of the measurements. The isotopic values are reported in δ notation, the per mil deviation relative to the Vienna Pee Dee Belemnite standard. The measurement results for stalagmites BLK12A and BLK12B and the standards indicated that the precision of the isotopic analysis was better than 0.05‰ for calcite $\delta^{18}\text{O}$.

3. Results

3.1. Age-Depth Model

As shown in Table 1, all 29 U-Th dates for stalagmites BLK12A and BLK12B are in stratigraphic order, within the error limits. For BLK12A, ^{230}Th dates, with an averaged error of ± 189 years, range from $2,061 \pm 221$ years BP at 2 mm from the top to $9,308 \pm 160$ years BP at 182-mm depth (Figure 2). For BLK12B, the determined age interval is from $2,698 \pm 143$ years BP at 0.5 mm from the top to $8,287 \pm 210$ years BP at 125-mm depth, with an averaged error of ± 176 years (Figure 2 and Table 1). The dating results indicate that the age control for BLK12B is better overall than for BLK12A. The StalAge fitting method, a well-developed approach with a stratigraphic factor (Scholz & Hoffmann, 2011), was applied to build age models for both stalagmites, and the results for BLK12B are shown in Figure 2.

3.2. Baluk Cave $\delta^{18}\text{O}$ Record

Based on the StalAge age-depth models, we calculated $\delta^{18}\text{O}$ time series for stalagmites BLK12A and BLK12B, which cover the time intervals of 9.37–1.90 and 8.36–2.69 ka, respectively. The respective mean time resolution of the two $\delta^{18}\text{O}$ time series is 20.3 years (from 10.2 to 155.4 years) and 22.8 years (from 10.7 to 28.4 years). Stalagmite BLK12B exhibits a more stable growth rate than BLK12A, which suggests that the BLK12B $\delta^{18}\text{O}$ record is likely superior for paleoclimatic reconstruction. Both the $\delta^{18}\text{O}$ time series of BLK12A and BLK12B exhibit similar long-term trends, with the $\delta^{18}\text{O}$ values increasing gradually with time (Figure 2). In addition, both sequences are characterized by large-amplitude shifts (1.0–1.5‰) in $\delta^{18}\text{O}$ values, which suggests that abrupt centennial- to multidecadal-scale hydroclimatic variations are recorded.

Because of its more reliable chronology and stable growth rate, we use the BLK12B $\delta^{18}\text{O}$ record to investigate the occurrence of hydroclimatic events on centennial to multidecadal scales in ACA. The BLK12B $\delta^{18}\text{O}$ record exhibits low values, ranging from -8.5‰ to -6.5‰ during 8.4–5.2 ka, which corresponds to the early to middle Holocene. Subsequently, during 5.1–2.7 ka in the late Holocene, higher $\delta^{18}\text{O}$ values occur, which range from -7.5‰ to -5.5‰ .

A notable feature of the BLK12B $\delta^{18}\text{O}$ record (referenced hereafter as the Baluk cave $\delta^{18}\text{O}$ record) is the abrupt shifts (Figures 2 and 3). The magnitudes of these events are ~ 0.5 – 1.5‰ , accounting for 20–60% of the amplitude of variation of the entire sequence ($\sim 2.5\text{‰}$). In addition, as indicated in Figures 2 and 3, the variations appear to be periodic or quasiperiodic.

4. Discussion

4.1. Advantages of the Baluk Cave $\delta^{18}\text{O}$ Record

To verify the representativeness of the Baluk cave $\delta^{18}\text{O}$ record for the study of centennial- to multidecadal-scale hydroclimatic oscillations, we compared it with several other speleothem records from ACA: nearby Kesang cave in Xinjiang (Cai et al., 2017; Cheng et al., 2012) and Tonnel'naya (Ton) cave in Uzbekistan (Cheng et al., 2016). A similar long-term trend of gradually increasing $\delta^{18}\text{O}$ values is evident in all the records (Figure 3). Notably, the Baluk cave record (this study) is similar to the KS08-1-H/KS06-A-H-I record from Kesang cave (Cheng et al., 2012). This similarity confirms the replicability and climatic origin of speleothem $\delta^{18}\text{O}$ records from ACA, despite the three caves being located hundreds of kilometers from each

Table 1*U and Th Isotopic Composition and ^{230}Th ICP-MS Dates for Stalagmites BLK12A and BLK12B From Baluk Cave, NW China*

Sample ID	Depth (mm)	^{238}U (ppb) ^a	^{232}Th (ppt)	$\delta^{234}\text{U}$ (measured) ^a	$^{230}\text{Th}/^{238}\text{U}$ (activity) ^b	$^{230}\text{Th}/^{232}\text{Th}$ (ppm) ^c	^{230}Th age (year; uncorrected)	^{230}Th age (year BP; corrected) ^{b,d}	$\delta^{234}\text{U}_{\text{Initial}}$ (corrected) ^e
BLK12A									
A7	2.0	666.6 ± 0.5	16,757.6 ± 49.0	261.0 ± 1.3	0.02925 ± 0.00046	23.4 ± 0.4	2,124 ± 221	2,061 ± 221	262.6 ± 1.4
A8	14.0	610.7 ± 0.7	41,654.3 ± 304.8	241.9 ± 2.0	0.05258 ± 0.00108	12.7 ± 0.3	3,252 ± 741	3,189 ± 741	244.2 ± 2.0
A9	14.0	685.1 ± 0.7	7,923.2 ± 26.3	249.8 ± 1.4	0.04075 ± 0.00052	58.1 ± 0.8	3,366 ± 131	3,303 ± 131	252.2 ± 1.4
A10	39.0	916.7 ± 1.0	16,867.1 ± 62.5	236.0 ± 1.6	0.05095 ± 0.00071	45.7 ± 0.7	4,191 ± 208	4,128 ± 208	238.8 ± 1.6
A11	54.0	923.9 ± 1.3	4,891.5 ± 16.4	235.4 ± 1.9	0.05401 ± 0.00037	168.2 ± 1.3	4,755 ± 67	4,692 ± 67	238.6 ± 1.9
A12	65.0	931.2 ± 1.1	4,085.3 ± 9.5	236.7 ± 1.6	0.05751 ± 0.00035	216.2 ± 1.4	5,092 ± 57	5,029 ± 57	240.2 ± 1.6
A13	84.0	995.7 ± 1.1	2,664.0 ± 7.0	244.2 ± 1.7	0.06412 ± 0.00029	395.1 ± 2.0	5,703 ± 40	5,640 ± 40	248.1 ± 1.8
A14	93.5	1,054.0 ± 1.4	7,537.4 ± 29.4	254.4 ± 2.2	0.06984 ± 0.00056	161.0 ± 1.4	6,085 ± 92	6,022 ± 92	258.8 ± 2.2
A15	111.0	1,267.0 ± 1.7	23,421.5 ± 148.8	237.2 ± 1.7	0.08136 ± 0.00099	72.6 ± 1.0	7,008 ± 218	6,945 ± 218	241.9 ± 1.7
A16	119.0	1,055.2 ± 1.3	10,961.3 ± 29.5	222.5 ± 1.7	0.08108 ± 0.00056	128.7 ± 0.9	7,244 ± 125	7,181 ± 125	227.0 ± 1.8
A17	138.0	532.3 ± 0.7	7,346.9 ± 34.0	242.6 ± 1.6	0.08818 ± 0.00085	105.3 ± 1.1	7,715 ± 167	7,652 ± 167	248.0 ± 1.6
A18	155.0	1,191.1 ± 1.4	7,150.8 ± 18.9	267.3 ± 1.7	0.09219 ± 0.00054	253.2 ± 1.6	8,090 ± 81	8,027 ± 81	273.5 ± 1.7
A19	172.0	1,381.2 ± 1.7	45,196.6 ± 310.5	337.3 ± 2.3	0.11108 ± 0.00130	56.0 ± 0.8	8,778 ± 343	8,715 ± 343	345.8 ± 2.4
A20	182.0	1,106.0 ± 1.2	15,302.6 ± 55.7	347.2 ± 1.6	0.11440 ± 0.00098	136.3 ± 1.3	9,371 ± 160	9,308 ± 160	356.5 ± 1.6
BLK12B									
B1	0.5	770.1 ± 1.6	10,284.2 ± 42.3	293.5 ± 2.6	0.03552 ± 0.00047	43.9 ± 0.6	3,033 ± 44	2,698 ± 143	295.8 ± 2.6
B2	1.5	681.4 ± 1.2	27,987.8 ± 123.8	290.9 ± 2.6	0.04268 ± 0.00079	17.1 ± 0.3	3,662 ± 69	2,755 ± 429	293.2 ± 2.6
B3	10.0	863.6 ± 1.3	4,017.3 ± 11.0	300.1 ± 2.2	0.03812 ± 0.00027	135.1 ± 1.0	3,242 ± 24	3,084 ± 53	302.7 ± 2.2
B4	14.0	947.7 ± 1.5	4,780.9 ± 12.5	307.7 ± 2.3	0.04122 ± 0.00028	134.7 ± 1.0	3,488 ± 25	3,323 ± 57	310.6 ± 2.3
B5	21.0	993.6 ± 1.7	6,136.1 ± 17.9	300.4 ± 2.5	0.04469 ± 0.00032	119.3 ± 1.0	3,808 ± 29	3,620 ± 69	303.6 ± 2.5
B6	29.5	1,162.0 ± 2.2	18,376.8 ± 65.7	301.7 ± 2.4	0.05108 ± 0.00058	53.3 ± 0.6	4,359 ± 51	3,975 ± 169	305.1 ± 2.5
B7	40.5	1,292.8 ± 2.3	13,473.9 ± 39.7	309.1 ± 2.3	0.05621 ± 0.00046	88.9 ± 0.8	4,778 ± 40	4,505 ± 113	313.1 ± 2.4
B8	54.0	1,294.8 ± 2.2	31,328.7 ± 120.8	296.9 ± 2.5	0.06288 ± 0.00069	42.9 ± 0.5	5,410 ± 62	4,854 ± 255	301.0 ± 2.5
B9	63.5	1,339.1 ± 2.4	14,030.6 ± 51.0	290.8 ± 2.2	0.06263 ± 0.00047	98.6 ± 0.8	5,414 ± 43	5,137 ± 115	295.1 ± 2.3
B10	73.0	1,234.3 ± 2.2	33,183.8 ± 134.9	332.5 ± 2.6	0.07522 ± 0.00083	46.1 ± 0.5	6,322 ± 73	5,726 ± 277	337.9 ± 2.6
B11	83.0	1,174.1 ± 2.0	18,188.2 ± 57.0	317.7 ± 2.6	0.07594 ± 0.00063	80.8 ± 0.7	6,458 ± 56	6,085 ± 165	323.3 ± 2.7
B12	91.5	1,118.9 ± 1.5	10,262.0 ± 40.2	296.8 ± 2.1	0.07939 ± 0.00064	142.7 ± 1.3	6,873 ± 59	6,624 ± 110	302.5 ± 2.1
B13	99.0	1,303.0 ± 2.1	14,268.0 ± 39.0	329.2 ± 2.5	0.08672 ± 0.00059	130.6 ± 0.9	7,337 ± 53	7,057 ± 121	335.9 ± 2.5
B14	111.0	1,380.4 ± 2.4	47,112.1 ± 243.0	338.8 ± 2.5	0.10112 ± 0.00117	48.9 ± 0.6	8,537 ± 103	7,802 ± 353	346.3 ± 2.5
B15	125.0	1,322.9 ± 1.4	24,982.5 ± 127.3	356.6 ± 1.5	0.10456 ± 0.00118	91.3 ± 1.1	8,717 ± 103	8,287 ± 210	365.1 ± 1.6

Note. Chemical analysis was performed from 25 to 30 January 30 in 2013 (Shen et al., 2002, 2003) and MC-ICP-MS analysis from 6 to 25 February 2013 (Shen et al., 2012). Analytical errors are 2 sigma of the mean. Decay constants are $9.1705 \times 10^{-6} \text{ year}^{-1}$ for ^{230}Th , $2.8221 \times 10^{-6} \text{ year}^{-1}$ for ^{234}U (Cheng et al., 2013), and $1.55125 \times 10^{-10} \text{ year}^{-1}$ for ^{238}U (Jaffey et al., 1971). The values shown are for a material at secular equilibrium, with the crustal $^{232}\text{Th}/^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%. ICP-MS = inductively coupled plasma mass spectrometer.

^a $[\text{U}] = [\text{U}] \times 137.818 (\pm 0.65\%)$; Hiess et al., 2012). $\delta^{234}\text{U} = ([^{234}\text{U}/^{238}\text{U}]_{\text{activity}} - 1) \times 1,000$. ^b $[^{230}\text{Th}/^{238}\text{U}]_{\text{activity}} = 1 - e^{-\lambda^{230}\text{Th}T} + (\delta^{234}\text{U}_{\text{measured}}/1,000) [^{230}\text{Th}/^{238}\text{U}]_{\text{activity}} (1 - e^{-(\lambda^{230}\text{Th} - \lambda^{234}\text{U})T})$, where T is the age. BP means before present, where present is 1950 Common Era. ^cThe degree of detrital ^{230}Th contamination is indicated by the $[^{230}\text{Th}/^{232}\text{Th}]$ atomic ratio instead of the activity ratio. ^dAge corrections for samples were calculated using an estimated atomic $^{230}\text{Th}/^{232}\text{Th}$ ratio of 4 ± 2 ppm. ^e $\delta^{234}\text{U}_{\text{Initial}}$ initial corrected was calculated based on the ^{230}Th age (T), that is, $\delta^{234}\text{U}_{\text{Initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{(\lambda^{234}\text{U} - \lambda^{230}\text{Th})T}$, and T is corrected age. The use of bold emphasis makes the corrected ^{230}Th dates clearly, which is the common form of U-Th dating results presentation.

other. However, we suggest that the Baluk cave record has advantages for documenting short-timescale hydroclimate changes compared with the previous cave records. First, the 15 U-Th dates of stalagmite BLK12B are relatively dense and evenly distributed, while those of the Kesang and Ton cave records are sparse (five to six dates during the study period; Figure 3). Second, the mean temporal resolution of the Baluk $\delta^{18}\text{O}$ record (~ 22.8 years) is higher than those of Kesang (~ 34.4 years) and Ton (~ 37.0 years) caves (Cheng et al., 2016, 2012). This relatively high temporal resolution is important for studying hydroclimatic changes on the centennial to multidecadal timescales. For instance, in the Baluk cave record there are substantial increases in $\delta^{18}\text{O}$ centered at 8.2, 5.1, and 2.9 ka; however, a shift of similarly high amplitude is only evident in stalagmite KS06-A-H-A from Kesang cave, which is centered at 2.9 ka (Cheng et al., 2012; Figure 3). The mismatch of the record of abrupt events between stalagmites CNKS-7 and CNKS-9 records from Kesang cave is likely caused mainly by their large dating errors (Cai et al., 2017), whereas in the case of Ton cave it is likely due to the low stalagmite growth rate and hence the inherently low temporal resolution (Cheng et al., 2016). Third, stalagmite BLK12B is 125 mm long and clearly exhibits continuous growth cycles (Figure 2d), whereas the Holocene intervals of the stalagmites from Kesang and Ton caves

Figure 3. Comparison of speleothem $\delta^{18}\text{O}$ time series from ACA. (a) Baluk cave (this study). (b) Kesang cave (Cheng et al., 2012). (c) Kesang cave (Cai et al., 2017); the black and gray lines represent stalagmites CNKS-9 and CNKS-7, respectively. (d) Ton cave (Cheng et al., 2016); the gray and red lines represent stalagmites TON-1 and TON-2, respectively. The U-Th dates for Baluk, Kesang, and Ton caves are indicated by the black error bars. Note that the errors of two dates for stalagmite CNKS-7 from Kesang cave (Cai et al., 2017) are too large to be included in the figure (2.523 ± 1.079 ka, 3.772 ± 3.58 ka), and instead, error bars are replaced by dashed lines.

are no more than ~ 50 mm. The growth rate of stalagmite BLK12B ranges from 15.0 to 46.7 mm/kyr, with a mean of 22.9 mm/kyr. There are, however, substantial variations in growth rates in the Kesang and Ton cave stalagmites: from ~ 0.2 to ~ 6 mm/kyr (with a mean of 3.2 mm/kyr; Cheng et al., 2012), from 1.8 to 37.8 mm/kyr (with a mean of 18.3 mm/kyr; Cai et al., 2017), and from 1.2 to 10 mm/kyr (with a mean of 3.9 mm/kyr; Cheng et al., 2016). Thus, stalagmite BLK12B grew at a faster rate and has the potential to provide a higher-resolution paleoclimatic record than the stalagmites from the other caves. In summary, the Baluk cave $\delta^{18}\text{O}$ record has the advantages of a faster growth rate, higher temporal resolution, and more accurate age control; hence, it is more suitable for reconstructing centennial- to multidecadal-scale hydroclimatic variations in ACA during the Holocene, compared to the previously published cave records.

4.2. Relationship Between the Baluk Cave $\delta^{18}\text{O}$ Record and Solar Activity

Speleothem $\delta^{18}\text{O}$ records from Xinjiang and central Asia and their paleoclimatic significance have attracted substantial research interest in recent years (Cai et al., 2017; Cheng et al., 2016, 2012). For example, Cai et al. (2017) suggested that upwind moisture transported by the westerlies, and the related precipitation, was responsible for the low speleothem $\delta^{18}\text{O}$ values during the early Holocene. This confirms that the

Figure 4. Comparison of the hydroclimatic record from Baluk cave with records of solar activity. (a) Baluk $\delta^{18}\text{O}$ (this study), (b) atmospheric residual $\Delta^{14}\text{C}$ (Stuiver et al., 1998), (c) TSI (Steinhilber et al., 2009), and (d) cosmic radiation production rate (PC; Steinhilber et al., 2012). The long-term linear trends of the four records were removed using PAST3.0 (Hammer et al., 2001). Correlations among the records are individually illustrated with light blue and yellow shading; note that the yellow-shaded zones exhibit minor lags or leads. The identified hydroclimatic events are numbered from 1–15.

hydroclimatic conditions of the study area were dominated by westerlies-transported water vapor. Reanalysis data and model simulation results also suggest that the low speleothem $\delta^{18}\text{O}$ values during the early Holocene were caused by long-distance water vapor transport from the North Atlantic region, while moisture from the tropical Indian Ocean, South Asia, and the Middle East, transported a short distance and with high precipitation $\delta^{18}\text{O}$ values, increased during the late Holocene (Liu et al., 2015; Zhang & Jin, 2016; Zhang et al., 2017). This also supports the hydroclimatic significance of speleothem $\delta^{18}\text{O}$ records. In addition, Cheng et al. (2016) considered that speleothem $\delta^{18}\text{O}$ records from westerlies-dominated central Asia reflected a supraregional pattern of climate variability, implying a relationship between hydroclimatic conditions in ACA and the oxygen isotopic record of speleothems from the region. In summary, despite the differences in their detailed interpretation, there is a consensus that speleothem $\delta^{18}\text{O}$ records from ACA contain a regional signal of hydroclimatic variability.

The Baluk cave $\delta^{18}\text{O}$ record documents the occurrence of abrupt centennial- to multidecadal-scale hydroclimatic shifts during 8.4–2.7 ka. As indicated in Figure 4a, these events (numbered from 1–15 in Figure 4a) are most clearly registered during 2.75–2.90, 3.25–3.35, 3.75–3.85, 4.45–4.55, 4.75–4.90, 5.05–5.15, 5.2–5.3, 5.4–5.5, 5.9–6.0, 6.2–6.3, 6.4–6.5, 6.8–6.9, 7.1–7.6, 7.85–7.95, and 8.05–8.25 ka. Their timing is coincident with changes in solar activity (Figures 4b–4d). The rapid hydroclimatic shifts recorded in Baluk cave are

correlative with changes in the residual atmospheric $\Delta^{14}\text{C}$ concentration reconstructed from tree ring records (Stuiver et al., 1998), where $\Delta^{14}\text{C}$ peaks correspond to weakened solar activity (Figure 4b) and vice versa, with the record of total solar irradiance (TSI) based on cosmogenic radionuclide ^{10}Be values from polar ice cores (Steinhilber et al., 2009), with minima corresponding to decreased solar activity (Figure 4c), and with ^{10}Be records of cosmic ray intensity obtained from Greenland and Antarctic ice cores (Steinhilber et al., 2012; Figure 4d). For example, a ~500-year positive shift in the $\delta^{18}\text{O}$ record from Baluk cave occurred during 7.1–7.6 ka, which is consistent with a reduction in solar activity indicated by high residual atmospheric $\Delta^{14}\text{C}$ concentrations (Figure 4b), low TSI (Figure 4c), and a high cosmic radiation production rate (Figure 4d). Similarly, the shift in the Baluk cave record at 6.2–6.3 ka coincides with abrupt changes in residual atmospheric $\Delta^{14}\text{C}$, TSI, and cosmic ray intensity (Figure 4). During 4.75–4.90 ka the variation of the Baluk cave $\delta^{18}\text{O}$ record is coherent with rapid changes in residual atmospheric $\Delta^{14}\text{C}$ concentration, TSI, and cosmic ray intensity, and during 3.75–3.85 ka it is coherent with the records of atmospheric $\Delta^{14}\text{C}$ and cosmic ray intensity. Therefore, an overall coherent pattern of variability is evident between hydroclimatic changes in ACA and the three proxy records of solar activity. The cross-correlation coefficients between the Baluk cave $\delta^{18}\text{O}$ and residual atmospheric $\Delta^{14}\text{C}$, TSI, and cosmic ray intensity are 0.31, -0.24 , and 0.32 ($n = 250$, $p < 0.01$), respectively. This strongly suggests a linkage between hydroclimatic variability in ACA and solar activity records on centennial to multidecadal scales.

Power spectrum analysis of the Baluk $\delta^{18}\text{O}$ time series revealed the presence of periodicities of 1,080, 540, 216, 199–204, 168–180, 148–151, and 102 years (Figure 5a). Some of them are correlative with cycles of solar activity (Figures 5b–5d), such as the de Vries cycle (~205 years; Wagner et al., 2001), Gleissberg cycle (~88–102 years; Peristykh & Damon, 2003; Usoskin & Mursula, 2003), and Eddy cycle (~1,000 years; Abreu et al., 2010). A quasi-200-year cycle is dominant in the Baluk $\delta^{18}\text{O}$ record (above 99% significance level), and it has also been detected in tree ring and lake sediment records from ACA spanning the last two millennia (Raspopov et al., 2008; Song et al., 2015). Because of its importance in both the Baluk cave and TSI records (Figures 5a and 5c), we used band-pass filtering to extract a specific component (centered on ~200 years) which facilitates comparison of the two records (Figures 5e and 5f). The results indicate an overall in-phase relationship between the two filtered records, particularly during the intervals of 7.5–6.9, 5.9–5.1, and 4.4–2.7 ka (gray shading in Figures 5e and 5f). The similarity between the two records further supports a linkage between hydroclimatic changes in ACA and solar activity on centennial to multidecadal scales during the Holocene.

4.3. Possible Origin of the Link Between Solar Activity and Hydroclimatic Oscillations in ACA During the Holocene

Numerous studies have suggested that Holocene hydroclimatic changes in ACA are associated with variations in the high-latitude Northern Hemisphere climate system (e.g., Chen et al., 2016, 2010, 2015, 2008; Huang et al., 2014; Li et al., 2013; Mathis et al., 2014; Tarasov et al., 2007). For example, Chen et al. (2008) proposed that precipitation in ACA during the Holocene was controlled by North Atlantic sea surface temperature (SST) and high-latitude air temperature, modulated by ice sheets. On the centennial scale, North Atlantic Oscillation (NAO) was considered a secondary factor in driving hydroclimatic changes in ACA (Chen et al., 2010, 2015; Chu et al., 2008).

Several studies have demonstrated the persistent influence of solar forcing on North Atlantic climate during the Holocene, including of SST and the NAO (e.g., Bond et al., 2001; Morley et al., 2011; Weber et al., 2004). Therefore, we infer that the observed correlations between solar variability and the Baluk $\delta^{18}\text{O}$ record are largely due to the mediation of northern high-latitude climate change on centennial- to multidecadal-scale hydroclimatic variations in ACA during the Holocene. It is possible that minima in solar activity (Steinhilber et al., 2012, 2009; Stuiver et al., 1998; Figure 4) would have induced the cooling of the troposphere and high-latitude North Atlantic SST, which was also related to changes in the NAO. This would in turn have reduced surface water evaporation, hence water vapor production and its transport to midlatitude ACA via the westerlies (Chen et al., 2008). The reduction of water vapor production in the North Atlantic would have resulted in its decreased contribution as a long-distance moisture source to precipitation in the study area and hence to the increases in the Baluk $\delta^{18}\text{O}$ values. In addition, changes in solar activity could also directly affect regional moisture variations via the effect of direct heating on air temperature (Camp & Tung, 2007; Usoskin et al., 2005; van Geel et al., 1999) and/or cosmic ray-cloud effects (Carslaw et al., 2002).

Figure 5. Results of cyclicity analysis of the Baluk cave record and solar activity records. (a) Baluk cave $\delta^{18}\text{O}$ (this study), (b) atmospheric $\Delta^{14}\text{C}$ residual (Stuiver et al., 1998), (c) TSI (Steinhilber et al., 2009), and (d) cosmic radiation PC (Steinhilber et al., 2012). The analyses were conducted using PAST3.0-REDFIT (Hammer et al., 2001). The Eddy cycle (~1,080 years), de Vries cycle (~205 years), and Gleissberg cycle (~88–102 years) are shown above the 90% confidence line in the four records. Also shown are the results of band-pass filter analysis (width of 200–205 years) of the Baluk $\delta^{18}\text{O}$ (e) and reconstructed TSI (f). Gray shading indicates time intervals of 2.7–4.4, 5.1–5.9, and 6.9–7.5 ka.

5. Conclusions

We have obtained a well-dated high-resolution stalagmite $\delta^{18}\text{O}$ record from Baluk cave in Xinjiang Province, NW China, in ACA, which provides a record of regional hydroclimatic changes from 8.4 to 2.7 ka. We draw the following principal conclusions:

1. Compared to the stalagmite records from elsewhere in the region, such as from Kesang and Ton caves, the Baluk cave stalagmite record has a faster growth rate with more evenly distributed age control points. These attributes make the $\delta^{18}\text{O}$ record from Baluk cave more suitable for characterizing centennial- to multidecadal-scale hydroclimatic changes.
2. A series of abrupt hydroclimatic shifts are evident in the Baluk cave $\delta^{18}\text{O}$ record, especially during the following time intervals: 2.75–2.90 ka, 3.25–3.35, 3.75–3.85, 4.45–4.55, 4.75–4.90, 5.05–5.15, 5.2–5.3, 5.4–5.5, 5.9–6.0, 6.2–6.3, 6.4–6.5, 6.8–6.9, 7.1–7.6, 7.85–7.95, and 8.05–8.25 ka. The hydroclimatic shifts are correlative with episodes of weakened solar activity indicated by increased residual atmospheric

$\Delta^{14}\text{C}$, decreased TSI, and intensified cosmic ray intensity. Solar cycles, such as the Eddy cycle (~1080 years), de Vries cycle (~205 years), and Gleissberg cycle (~88–102 years), are clearly evident in the Baluk cave record. All of these lines of evidence point to a dynamic linkage between hydroclimatic conditions in ACA and solar activity on centennial to multidecadal scales during the Holocene.

3. We suggest that variations in North Atlantic climate, namely, SST, the NAO, and northern high-latitude regional temperature, as well local changes in temperature and humidity induced by changes in solar activity, are a plausible cause of centennial- to multidecadal-scale hydroclimatic shifts in ACA during the Holocene.

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