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The climatic cyclicity in semiarid-arid central Asia over the past 500,000 years

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[1] Central Asia is currently a semiarid-arid region, dominated by the Westerlies. It is important to understand mechanisms of climate and precipitation changes here, as water availability in the region is crucial today and in the future. High-resolution, absolutely-dated oxygen isotope (δ^{18}O) records of stalagmites from Kesang Cave characterize a dynamic precipitation history over most of the past 500,000 years. This record demonstrates, for the first time, that climate change in the region exhibits a processional rhythm with abrupt inceptions of low δ^{18}O speleothem growth at times of high Northern Hemisphere summer insolation followed by gradual δ^{18}O increases that track decreases of insolation. These observations and interpretations contrast with the interpretation of nearby, but higher elevation ice core records. The absolutely-dated cave δ^{18}O shifts can be used to correlate the regional climate variability by providing chronological marks. Combined with other paleoclimate records, the Kesang observations suggest that possible incursions of Asian summer monsoon rainfall or related moisture into the Kesang site and/or adjacent areas during the high insolation times may play an important role in changing orbital-scale hydrology of the region. Based on our record, arid climate will prevail in this region for the next several millennia, providing that anthropogenic effects do not supersede natural processes. **Citation:** Cheng, H., P. Z. Zhang, C. Spötl, R. L. Edwards, Y. J. Cai, D. Z. Zhang, W. C. Sang, M. Tan, and Z. S. An (2012), The climatic cyclicity in semiarid-arid central Asia over the past 500,000 years, *Geophys. Res. Lett.*, *39*, L01705, doi:10.1029/2011GL050202.

1. Introduction

[2] The modern climate in eastern central Asia and in the adjacent northern part of the Tibetan Plateau is dominated by the Westerlies, differing from neighboring regions, which receive Asian Monsoon (AM) precipitation (the Indian Monsoon to the south and the East Asian Monsoon to the southeast) (auxiliary material, Figure S1 in the Auxiliary Material).[1] Many paleoclimate records have been obtained recently from this region. In particular, studies of lake sediments show significant variations in effective moisture during the Holocene [e.g., *Chen et al.*, 2008; *Rudaya et al.*, 2009], ice core records reveal large fluctuations in precipitation oxygen isotope (δ^{18}O) on orbital-scales [e.g., *Thompson et al.*, 1989, 1997], and loess studies illustrate a consistent glacial to interglacial variability [e.g., *Ding et al.*, 2002; *Sun et al.*, 2006]. The human history of the region is rich in accounts of collapses of kingdoms with some of them likely linked to climatic/hydrological change [e.g., *Li*, 1992]. Nevertheless, the climate variability and its relation to low-latitude monsoonal change and high-latitude ice volume variation are poorly documented and hotly debated. This is partially due to a lack of high-resolution and absolutely-dated climate records, leading to difficulties in reliably correlating climatic records in the region to those in adjacent climatic regimes. Such correlations are critical for understanding the interplay among low-latitude monsoonal circulation, the mid-latitude Westerlies, high-latitude ice volume and insolation. Here we present, for the first time, a high-resolution and absolutely-dated speleothem δ^{18}O record from Kesang Cave for this region. This record establishes temporal patterns of regional climate change over most of the past 500 ka (thousand years) from which we infer possible causes and links to climate elsewhere.

2. Cave Location, Samples and Methods

[3] Kesang Cave is located in Tekesi County, western China (42°52′N, 81°45′E, elevation ~2000 m a.s.l.) (Figures S1 and S2 in the Auxiliary Material). The mean cave temperature is ~4.2°C, close to the mean annual temperature in the area (4–5 °C). Precipitation in the area occurs mainly during spring-summer with an annual mean of ~500 mm, 400 mm of which falls between April and September (Figures S3–S5 in the Auxiliary Material). Today, spring-summer moisture may largely be carried by the Westerlies from the Atlantic, Mediterranean and Caspian, with local recycling [*Aizen et al.*, 2006]. Winter moisture is minor, likely due to southward diversion of the Westerlies by the Siberian High [*Carey et al.*, 1997].

[4] Eight samples from Kesang Cave were used to establish the Kesang δ^{18}O record with three covering the Holocene and five covering the rest of the Pleistocene portion (Figures S6–S8 in the Auxiliary Material). The high degree

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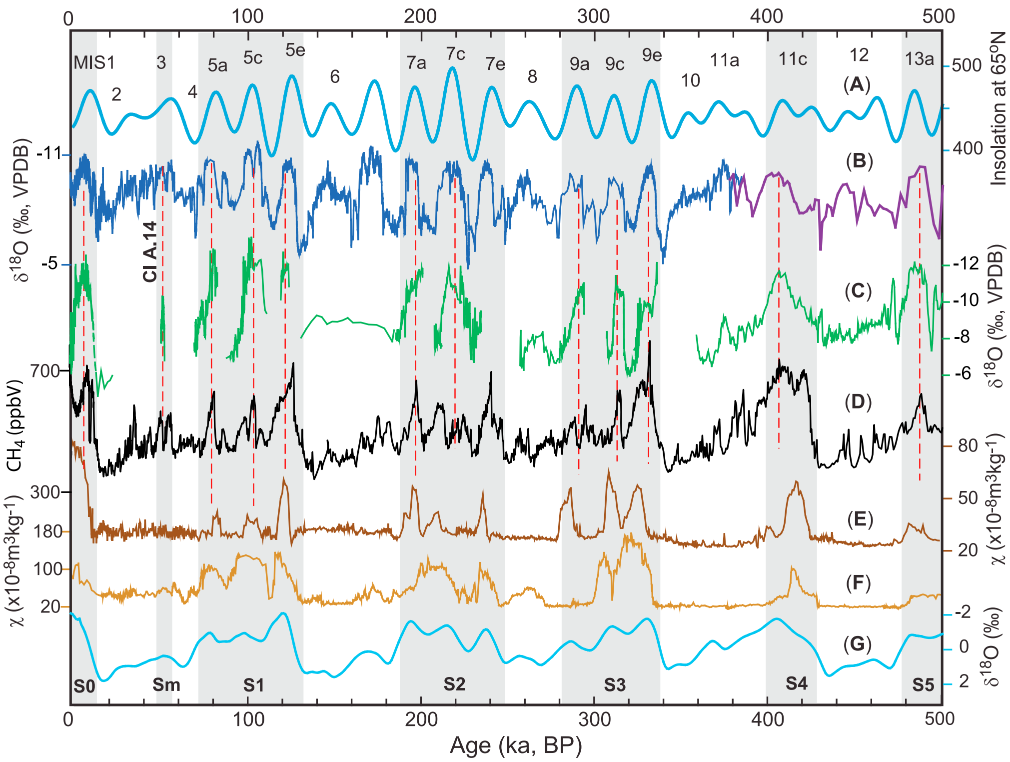

Figure 1. Comparison of the Kesang record with NHSI, AM, ice core, loess and marine records. (A) NHSI (July 21) at 65°N [*Berger*, 1978]. Numbers at the top indicate MISs. (B) AM δ^{18}O records. Blue: Hulu-Sanbao records [*Wang et al.*, 2008; *Cheng et al.*, 2009]; purple: the new Sanbao record (Figure S10 in the Auxiliary Material). (C) The composited Kesang δ^{18}O record (Figure S8 in the Auxiliary Material). (D) EPC CH_4 record [*Loulergue et al.*, 2008]. (E and F) Jingyuan and Chashmanigar loess magnetic susceptibility records from the Chinese Loess Plateau [*Sun et al.*, 2006] and Tajikistan, central Asia [*Ding et al.*, 2002], respectively. (G) The stacked benthic δ^{18}O record [*Imbrie et al.*, 1984]. Vertical grey bars indicate palaeosol units (S0–S5) established in the Chinese Loess Plateau. Red dashed lines illustrate a broad correlation among growth of low δ^{18}O calcite in Kesang Cave, the intensified ASM, peaks of loess magnetic susceptibility and high atmospheric CH_4 values.

of replication of δ^{18}O records of contemporaneous stalagmite growth intervals (Figure S8 in the Auxiliary Material) suggests that the δ^{18}O variability in our records results from changes in the precipitation δ^{18}O and cave temperature without significant kinetic fractionation [*Hendy*, 1971]. The slightly negative correlation between all δ^{13}C and δ^{18}O data for each sample and the broad anti-correlation between δ^{18}O and δ^{13}C on orbital-scales also argue against kinetic fractionation (Figure S9 in the Auxiliary Material). The large range in δ^{18}O (~6 ‰) (Figure 1) cannot be explained by changing cave temperature changing the calcite–water oxygen isotope fractionation, as this process would require unreasonably high changes in cave temperature. Instead, the stalagmite δ^{18}O variations largely reflect changes in the δ^{18}O of meteoric precipitation, particularly the large amplitude changes on the orbital-scale upon which we focus here.

[5] We obtained precise ages (~150 dates), all in stratigraphic order within errors, using a recently developed ^{230}Th dating technique [*Cheng et al.*, 2009] in the University of Minnesota (Table S1 in the Auxiliary Material). In addition, we also extended our Sanbao AM record [*Cheng et al.*, 2009] to ~500 ka BP for comparison (Figure S10 and Table S2 in the Auxiliary Material). Linear interpolation between ^{230}Th dates was used to establish chronologies (Figure S7 in the Auxiliary Material). Oxygen and carbon isotopes were measured on ~3300 sub-samples and sampling techniques and stable isotope measurements are described in the Text S1 of the Auxiliary Material.

3. The Kesang δ^{18}O Record and Comparison

[6] Modern observations show a solid positive correlation between δ^{18}O of precipitation and air temperature on seasonal to decadal timescales in the Westerlies region, including entire central Asia and the northern Tibetan Plateau, suggesting temperature plays a dominant role in controlling variations of precipitation δ^{18}O (Figure S3 in the Auxiliary Material) [e.g., *Thompson et al.*, 1989; *Aizen et al.*, 2006]. This modern relationship to temperature has been extrapolated to explain regional orbital-scale climate variability, such as changes in δ^{18}O of ice core records. The chronology for the Guliya ice core record was established by correlating positive excursions in its δ^{18}O with positive shifts in atmospheric CH_4 [*Thompson et al.*, 1997]. Given this chronology, high δ^{18}O of ice correlates broadly with high Northern Hemisphere summer insolation (NHSI). In the absence of data to the contrary, the idea that Guliya δ^{18}O is a temperature function would be a completely reasonable extrapolation of modern relationships to the past and a reasonable method of establishing a chronology. The Guliya δ^{18}O record has been widely cited in the

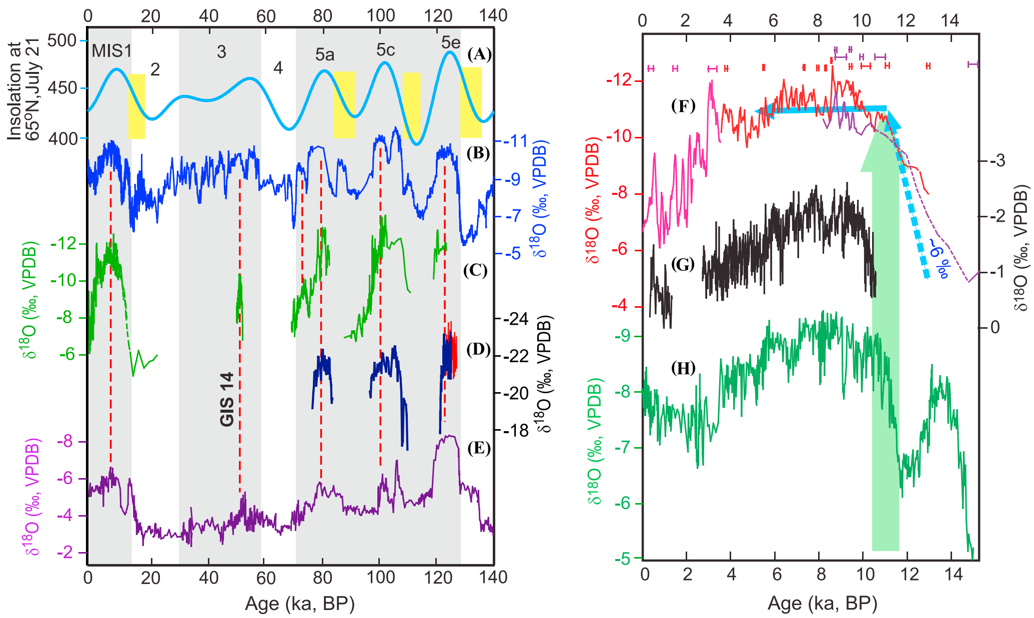

Figure 2. (left) Comparison among the Kesang, AM and Eastern Mediterranean records. (A) July 21 insolation at 65ºN [*Berger*, 1978]. (B) The AM record [*Wang et al.*, 2008]. (C) The Kesang record. (D) The Indian Monsoon record from Tianmen Cave [*Cai et al.*, 2010]. (E) The Eastern Mediterranean record from Soreq Cave [*Bar-Matthews et al.*, 2003]. Vertical dash lines indicate correlations among cave records. Yellow bars at the top indicate hiatuses replicated in multiple samples from Kesang Cave, suggesting drier times during low and waxing phases of insolation on precessional cycles. MISs are shown at the top. (right) Comparison among Holocene cave records. (F) The Kesang record is comprised of three stalagmites (different colors). The ^{230}Th age and 2σ error (on top) are color-coded by stalagmite. Blue arrows indicate the early Holocene jump at $\sim$11 ka, followed by a rather smooth mid-Holocene variance. (G and H) AM records from Qunf [*Fleitmann et al.*, 2003] and Dongge [*Cheng et al.*, 2009] Caves. The green vertical arrow depicts the early Holocene jump in the Kesang record, consistent with AM records.

past two decades as an important chronologic benchmark for correlating and calibrating regional climate variability in the Westerlies region.

[7] In contrast to the inferred relationship in the ice-core records, the fluctuations of precipitation δ^{18}O, as documented by the Kesang record, follow the precessional cycle of NHSI inversely with a similar amplitude to the Guliya record, implying a general anti-correlation between current wet-season (spring-summer) temperature and precipitation δ^{18}O on an orbital-scale (Figure 1). Both the Guliya and Kesang relationships could be valid, with differences related to the different elevations and localities of the sites. Alternately, differences could be reconciled if the low excursions in Guliya δ^{18}O were, instead, correlated to high excursions in CH_4. This would result in a substantial revision in the Guliya chronology and, thus, in numerous previous climate correlations, but would result in similar isotopic shifts at both sites (Figure S11 in the Auxiliary Material). Although we cannot definitively distinguish between these two explanations of the Kesang and Guliya observations, the Soreq record from the Eastern Mediterranean [*Bar-Matthews et al.*, 2003] and the recently reported Tianmen record from the south-central Tibetan Plateau [*Cai et al.*, 2010] all show the same inverse δ^{18}O–NHSI relationship as Kesang (Figure 2), lending some support to the latter possibility.

4. Discussion

[8] Explaining the sense of orbital-scale change in the δ^{18}O of precipitation in the Kesang record based simply on modern observations merely in the Westerlies region is difficult. Indeed, in the modern Westerlies regime, higher (rather than lower) δ^{18}O values of precipitation are currently associated with warm periods and this relationship is rather robust, regardless of geographic locations, seasonal precipitation patterns and moisture sources (Figures S2–S5 in Text S1). Such modern observations cannot be simply analogous to the Kesang orbital variability as the Kesang record displays lower rather than higher precipitation δ^{18}O associated with high NHSI times when wet-season temperatures were higher. Instead, this apparent paradox suggests that a fundamental change in atmospheric circulation is associated with orbital-scale NHSI variations in the region.

[9] What then, is the key factor that could result in much lower δ^{18}O of the precipitation during times of high NHSI? Neither source/amount effects in the current Westerlies regime may explain the Kesang observation, because they appear to be largely independent from the temperature effect (Figure S3 in the Auxiliary Material). For instance, both Inylchek in Tianshan and Belucha in Altai Mountains have similar temperature – δ^{18}O correlations despite their different moisture sources [*Aizen et al.*, 2006]. If one broadens the discussion to include moisture sources beyond the current Westerlies regime, one candidate would be moisture derived from the adjacent Asian summer monsoon (ASM). The ASM is characterized by anomalously low δ^{18}O and by high rainfall amounts during warm periods, thus satisfying the basic Kesang observation. We consider it to be a reasonable explanation, given that ASM precipitation or related moisture could plausibly reach Kesang when the ASM was

strong and that Kesang record correlates broadly with AM records in the adjacent regions (Figures 1 and 2).

[10] A recent isotope study of the Inylchek ice core in the Tianshan [*Aizen et al.*, 2006] and analyses of modern meteorological data [e.g., *Tang and Miao*, 2009; *Conroy and Overpeck*, 2011] indicate that some moisture in western China originates from the Indian Ocean or AM regions. Given the fact that the ASM currently is weaker than the average intensity, when viewed on orbital-scales [*Cheng et al.*, 2009], it is likely that more moisture could originate in the same regions during times when the ASM was much stronger and extended farther inland. Actually, the modern ASM is extremely dynamic, sweeping thousands of kilometers inland from the Indian Ocean with its seasonal onset in Sri Lanka, crossing all of India and extending into Kashmir and northern Pakistan and in the east, from the South China Sea across all of eastern China, as far as eastern Siberia. Similarly, the AM changes temporally in phase with NHSI on orbital-scale [e.g., *Cheng et al.*, 2009] and could vary considerably in spatial extent on the same timescale as well. It seems reasonable that ASM rainfall or related moisture could have penetrated farther inland when NHSI was much higher than today. This moisture could have reached the Kesang area directly or indirectly through regional river systems and/or recycling from lakes. Similar scenarios have been revealed for the currently arid Arabian Peninsula [*Fleitmann et al.*, 2011] and southern Israel [*Waldmann et al.*, 2010] where many past wet periods inferred by speleothem growth were linked to strong Indian and North African summer monsoons at high NHSI times.

[11] On the basis of regional pollen, molluscs, lake level, paleosol and archaeological data, *Winkler and Wang* [1993] showed that the fringe of the ASM was far northwest of its current position during the mid-Holocene, with Kesang Cave included within the region affected by the ASM at the time (Figure S1 in the Auxiliary Material). This conclusion is supported by recent studies of Holocene lakes and vegetation [e.g., *Tarasov et al.*, 2000; *Rudaya et al.*, 2009]. Thus, it is plausible that the ASM influence reached the Kesang Cave site during high NHSI times when the ASM were as strong as or stronger than in the mid-Holocene. This would readily explain the observed anti-correlation between the Kesang δ^{18}O and NHSI, because the ASM rainfall is characterized by the same correlation with NHSI and we would expect more precipitation with lower δ^{18}O values in western China.

[12] Loess is abundant in central Asia and China, providing an important archive of paleoclimate. Magnetic susceptibility records of loess from both central Asia and China consistently indicate wetter-warmer interstadial or interglacial conditions in the region [e.g., *Ding et al.*, 2002; *Sun et al.*, 2006], consistent with the Kesang record (Figure 1). Moreover, similar to loess records, Kesang speleothem growth rates slowed dramatically (or locally came to a halt) and speleothem δ^{18}O values were typically high during glacial periods (i.e., Marine Isotope Stages (MIS) 2, 4, 6, 8, 10 and 12) when ice-sheet volume was relatively large and NHSI was generally low (Figure 1).

[13] Many lake and pollen studies in central Asia and the Tibetan Plateau have focused on climate change during the Holocene. The reconstructed climate history proves a "mid-Holocene Optimum" (wet and warm), broadly consistent with the Kesang observation. Of note are many multi-stage paleo-megalakes in today's deserts of western China [e.g., *Huang and Han*, 2007] and multiple alluvial sequences developed in Tianshan area [e.g., *Lu et al.*, 2010]. These quite likely are related to the orbital-scale hydrological rhythm that we observe at Kesang, but imprecise dating renders precise correlations difficult. Also notable is a sharp δ^{18}O jump at ~3 ka BP followed by large amplitude fluctuations on centennial-decadal timescales superimposed on an increasing δ^{18}O trend over the past 3 ka (Figure 2). These large oscillations could relate to the cultural history of the area, as some 36 kingdoms collapsed over this time interval, perhaps, in some cases, related to climate [*Li*, 1992].

[14] Alternatively, another conceivable hypothesis, which does not directly involve the ASM, would be one that invokes changes in the precipitation seasonality. Although the positive correlation between temperature and precipitation δ^{18}O is persistent throughout the Westerlies region, the seasonality does change spatially from winter precipitation in the Eastern Mediterranean and the main part of central Asia to spring-summer precipitation in eastern central Asia. Kesang site is close to the fringes of the seasonality change and thus could be subject to temporal changes in seasonality. If the wet season at Kesang changed from spring-summer to winter at times of high NHSI, one would expect a shift in precipitation δ^{18}O to lower values as observed. This hypothesis has been discussed in the context of intensification of winter precipitation in the Eastern Mediterranean [e.g., *Tzedakis*, 2007] explaining low δ^{18}O excursions [*Bar-Matthews et al.*, 2003]. However, the Eastern Mediterranean type of climate appears to be drier (wetter) during interglacial (glacial) periods, as inferred directly from the lake level history of the Dead Sea basin [e.g., *Waldmann et al.*, 2010] and thus is clearly out of phase with the Kesang and other proxy records from both loess and paleolakes that suggest wetter (drier) interglacial (glacial) periods. In addition, when NHSI is high, winter insolation is generally low. The latter may strengthen the Siberian High during winter, which, in turn, could divert the Westerlies southwestward, reducing winter moisture transport from the west [*Carey et al.*, 1997] (Figures S1 and S2 in the Auxiliary Material).

[15] Whether or not the ASM hypothesis is valid, another Kesang observation demands explanation. Kesang speleothem growths resumed almost exclusively at times of high NHSI with low calcite δ^{18}O values. This threshold scenario is particularly clear during MIS 5 and the Holocene when dating errors are small (Figure 2). Furthermore, whereas the peaks in NHSI are broadly symmetric in time, the correlative lows in δ^{18}O are not, with rapid shifts to low δ^{18}O and more gradual shifts back to high values (Figure 2). The rapid onsets of speleothem growth could reflect a rapid shift of ASM rainfall/moisture into the region in response to AM jump. The gradual ending may result from a buffering effect of local water sources. During the peak of an ASM incursion, many basins (e.g., the Aral Sea basin) in the region would fill with low δ^{18}O water (directly from the ASM or indirectly by rivers, e.g., the Amu Darya). As the ASM retreats from the region, water in the basins would progressively evaporate, reducing water availability progressively in the region. This process would gradually concentrate ^{18}O in the water basins, providing progressively higher δ^{18}O to recycled moisture. This asymmetric feature of the Kesang record also provides an additional constraint to the Kesang story (Figure S12 in the Auxiliary Material).

At present, the region is arid and $\delta^{18}O$ of Kesang calcite is already high. NHSI will continue its downward-upward trend over the next several millennia [*Berger*, 1978]. Thus, providing that anthropogenic effects do not supersede natural rhythms, the future hydrological projection for the area for next several millennia would be a persistent arid condition, analogous on the orbital-scale to times when Kesang cave calcite growth was very low or zero (Figure 2).

5. Conclusions

[16] Over precessional cycles, the $\delta^{18}O$ of rainfall in eastern central Asia is broadly anti-correlated with NHSI, likely resulting from shifts in the summertime boundary between the Westerlies and the ASM. This scenario bears remarkable similarities to the hydrological changes revealed by cave records from the currently arid Arabian Peninsula and southern Israel. These records show clear evidence of former wet periods likely caused by incursions of Indian [*Fleitmann et al.*, 2011] and North African [*Waldmann et al.*, 2010] summer monsoon rainfall. Further simulation and speleothem studies in the region are critical to provide further tests on the ASM hypothesis that appears to be the most plausible explanation of the observations. The absolutely-dated $\delta^{18}O$ shifts ($\sim$6 ‰) in the Kesang record will also provide chronological benchmarks for correlating and calibrating the regional climate records, such as the ice core records in the Westerlies regime.

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