Changes in the Asian monsoon climate during the late last interglacial recorded in oxygen isotopes of a stalagmite from the Yongxing Cave, central China

Article (Accepted Version)

Zhang, Weihong, Zhang, Zhenqiu, Liao, Zebo, Chen, Shitao, Shao, Qingfeng, Wang, Yongjin and Wang, Yi (2019) Changes in the Asian monsoon climate during the late last interglacial recorded in oxygen isotopes of a stalagmite from the Yongxing Cave, central China. *Journal of Asian Earth Sciences*, 179. pp. 211-218. ISSN 1367-9120

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/83824/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Changes in the Asian monsoon climate during the late last interglacial recorded in oxygen isotopes of a stalagmite from the Yongxing Cave, central China

Weihong Zhang^{a,*}, Zhenqiu Zhang^{b,c}, Zebo Liao^c, Shitao Chen^c, Qingfeng Shao^c, Yongjin Wang^c, Yi Wang^{d,e}

^aCollege of Geography and Environmental Sciences, Zhejiang Normal University, Jinhua 321004, China

^bSchool of Life Sciences, Nanjing Normal University, Nanjing 210023, China

^cCollege of Geography Science, Nanjing Normal University, Nanjing 210023, China

d. Department of Geography and School of Global Studies, University of Sussex, Falmer, Brighton BN1 9RH, UK

e. Department of Earth System Science, Institute for Global Change Studies, Tsinghua University, Beijing 100084, China

*Corresponding author. Address: College of Geography and Environmental Sciences, Zhejiang Normal University, 688 Yingbin Road, Jinhua 321004, China
E-mail address: zhangwh@zjnu.cn (W. Zhang).

ABSTRACT: The last interglacial contains information about how climate behaves during a warm period comparable to the current interval. However, there is no consensus on the key signatures and force of the last interglacial climate changes at present. Here we present a high-resolution stalagmite oxygen isotope record from central China, which spans from 123.3 to 116.8 ka. The stalagmite $\delta^{18}\text{O}$ time-series bears a resemblance to changes in Northern Hemisphere summer insolation during the Holocene epoch before the demise of the last interglacial. Superimposed on the long-term $\delta^{18}\text{O}$ record is a pronounced shift to more positive values at

around 121.6 ka, indicating a switch of the Asian monsoon mean state into a weaker condition. This monsoon shift correlates with a decrease in the mean state of the South American Summer Monsoon, and a well-known abrupt mid-Eemian cooling event at high latitudes. These correlations indicate broad-scale features of the climate shift over the warm last interglacial. Another positive $\delta^{18}\text{O}$ shift of up to 3.5 ‰ occurred at around 120 ka, representing the demise of the last interglacial Asian monsoon. By comparing the stalagmite $\delta^{18}\text{O}$ records against changes in ice volume and summer insolation during the last interglacial and recent Holocene, respectively, we conclude that the decreasing Northern Hemisphere summer insolation dominated the rapid demise (termination? weakening?) of the last interglacial Asian monsoon.

Keywords: insolation forcing; Asian monsoon; stalagmite; Eemian; paleoclimatology

1. Introduction

The last interglacial (LIG) has been a focus of long-term research (e.g., [Dansgaard et al., 1993](#); [McManus et al., 1994](#); [Otto-Bliesner et al., 2013](#)), because it contains invaluable information about how the climate behaved during a period similar to the present day. The LIG (130-116 ka) is the most recent interglacial prior to the Holocene, our present interglacial. The LIG is also known as the Eemian in Europe, roughly coeval with

Marine Isotope Stage 5e (MIS 5e; Shackleton et al., 2003; Otvos, 2015). Global mean annual temperatures during the LIG were higher than or similar to those of present day (Turney et al., 2010; McKay et al., 2011; Hoffman et al., 2017), and the mean sea level was about 6-9 m higher than today (Kopp et al., 2009; Dutton et al., 2015).

A number of studies have paid attention to the climate stability during the LIG (e.g., Dansgaard et al., 1993; Mcmanus et al., 1994; Adkins et al., 1997; Galaasen et al., 2014). Abundant evidence points to instabilities (e.g., Oppo et al., 2006; Helmens et al., 2015), for example, the abrupt mid-Eemian cooling event at around 122-120 ka (Karabanov et al., 2000 and references therein; Bauch et al., 2011; Helmens et al., 2015). This event occurred abruptly and lasted about 0.5-1 ka (Helmens et al., 2015). It intersected (interrupted?) with the peak Eemian warmth in the North Atlantic realm (Bauch et al., 2011; Helmens et al., 2015) and the Siberia region (Karabanov et al., 2000). At lower latitudes, such as in middle and southern Europe, high-resolution stalagmite records have ~~depicted~~ (reconstructed?) the detailed climate history of the LIG (Demény et al., 2017). However, these records showed incoherent long-term climatic trends and centennial-scale variations, leading to recognition and correlation of the mid-Eemian cooling event ~~ambiguous~~ (challenging?). This situation stimulates (encourages?) us to study further whether the mid-Eemian cooling event is only limited to the higher

latitudes ([Karabanov et al., 2000](#); [Bauch et al., 2011](#); [Helmens et al., 2015](#)).

Asian monsoon (AM) is dynamically linked to climate at high latitudes. Stalagmite records have shown a good correlation with the centennial-scale Bond events at high latitudes over the Holocene epoch (e.g., [Wang et al., 2005](#); [Cheng et al., 2009a](#); [Liu et al., 2013](#)). During the LIG, some stalagmite records also revealed frequent climate oscillations on the centennial scale ([Kelly et al., 2006](#); [Cai et al., 2010](#); [Jo et al., 2011](#)), with an amplitude similar to that during the Holocene ([Kelly et al., 2006](#)). However, it is unknown about their teleconnection with the North Atlantic climate. Therefore, new high-resolution cave records are needed to further examine the linkage of the AM change to typical climate events at higher latitudes, especially during the mid-Eemian cooling event.

Changes in Northern Hemisphere Summer insolation (NHSI) have been considered to initiate the onset and end of the LIG ([Berger and Loutre, 1991](#); [Imbrie J, et al., 1992](#), [Jiang et al., 2017](#)), through a series of feedbacks ([CAPE-Last Interglacial Project Members et al., 2006](#)). Much effort has been devoted to study the onset of the LIG ([Cheng et al., 2009b; 2016](#)), but less attention has been paid to its termination. Investigating the termination of the LIG helps comprehensively understand the relative importance of the NHSI and ice volume in the global climate system. In the AM region, stalagmite records consistently dated the rapid end of the

LIG at about 120 ka, coinciding with the gradual decreasing NHSI (Yuan et al., 2004; Kelly et al., 2006; Cai et al., 2010; Jo et al., 2011, Jiang et al., 2017). In contrast to the abrupt end of the LIG, stalagmite records over the Holocene show a gradual monsoon decreasing after the Holocene optimum, strictly following the gradual NHSI decreasing (Wang et al., 2005; Dong et al., 2010). Thus, a role of the NHSI in the abrupt termination of the LIG AM needs further investigations.

This paper represents a stalagmite oxygen isotope record from the Yongxing Cave, central China. Previously reported stalagmite records from this cave showed a larger $\delta^{18}\text{O}$ amplitude and a strong similarity to the Hulu and NHSI records (Chen et al., 2016). These $\delta^{18}\text{O}$ features indicated a sensitive response to regional climate changes. This study concentrates on a climate shift within the LIG and on causes for rapid demise of the LIG.

2. Materials and Methods

Stalagmite YX266 was obtained from the Yongxing Cave (31°35'N, 111°14'E; 1400 m a.s.l; Fig. 1), about 75 km east of Sanbao Cave (Wang et al., 2008; Cheng et al., 2009b; 2016), near the southern edge of the Chinese Loess Plateau, central China. The sampling site is approximately 105 m behind (from? below?) the entrance of the Yongxing Cave, where temperature and relative humidity are constant (?) at about 14.3 °C and

100%, respectively. Stalagmite YX266 is 283 mm long and 40-60 mm wide, and was already damaged at the time of collection. The speleothem consists of compact calcite (Fig. 2).

For U-Th dating, six subsamples of 50-150 mg were extracted using a 0.9-mm-diameter carbide dental drill. The procedures used for U/Th chemical separation and isotopic measurements are detailed in Shao et al. (2017). The carbonate samples were weighed and dissolved in 7N HNO₃ in a Teflon beaker containing a known quantity of a ²²⁹Th-²³³U-²³⁶U triple spike. U and Th were preconcentrated by coprecipitation with iron hydroxide and then separated from each other and from other cations by passing the sample solution through a U-TEVA resin column. The U/Th fractions were then dried and diluted in a mixture of 0.1N HNO₃ and 0.01N HF for isotopic analysis on a Neptune MC-ICPMS at Nanjing Normal University. U was measured statically by ²³³U, ²³⁵U, ²³⁶U and ²³⁸U on Faraday cups and ²³⁴U simultaneously on a secondary electron multiplier (SEM). Th was analyzed with ²³⁰Th and ²²⁹Th alternately on the SEM and ²³²Th on a Faraday cup, if it is > 3 mV (equivalent to 10¹¹ Ω amplifier). In the case of ²³²Th < 3 mV, the ²³⁰Th, ²²⁹Th and ²³²Th were measured on the SEM by peak jumping. The U isotopic ratios of the HU-1 standard were measured before and after every U and Th isotopic measurement for samples. Mass fractionation was corrected by comparing the measured ²³⁸U/²³⁵U to the natural value of 137.760 for

HU-1 and 137.818 for unknown samples (Hiess et al., 2012). The SEM to Faraday cup yield was assessed by the $\delta^{234}\text{U}$ measured in the HU-1 standard. Hydride interferences, machine abundance sensitivity and amplifier gains were evaluated every day prior to sample measurements. $^{230}\text{Th}/\text{U}$ ages were calculated using half-lives of 75,584 years and 245,620 years for ^{230}Th and ^{234}U , respectively (Cheng et al., 2013). The $^{230}\text{Th}/\text{U}$ age uncertainty was estimated by Monte-Carlo simulations ($n=10^6$). The uranium concentration of YX266 is 0.5-0.7 ppm, the initial thorium content 110-450 ppt, and the resulting age uncertainty 0.5-0.7 ka (Table 1). The dates are in stratigraphic order, with the exception of the date at the bottom of the stalagmite which is slightly younger. A depth-age model (Fig. 2) for stalagmite YX266 was constructed using the StalAge algorithm (Scholz and Hoffmann, 2011). This algorithm automatically detects and accounts for the age inversion.

For stable isotope analysis, a total of 283 calcite powders (about 50-80 μg) were drilled at 1 mm increments along the axis of the sample with a 0.5-mm-diameter carbide dental burr. The $\delta^{18}\text{O}$ values were determined at the Isotope Laboratory of Nanjing Normal University, China, using a Finnigan-MAT-253 mass spectrometer. NBS 19 ($\delta^{18}\text{O} = 2.20\text{‰}$) was used as a reference material and the precision of $\delta^{18}\text{O}$ was 0.06‰. The $\delta^{18}\text{O}$ results are reported in per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard.

3. Results

The chronology indicates that stalagmite YX266 grew from 123.3 to 116.8 ka (Fig. 3), covering the latter part of the LIG and its transition into the last glaciation. The $\delta^{18}\text{O}$ values of YX266 range from -10.4‰ to -6.2‰ , averaging -9.0‰ (Fig. 3). The full $\delta^{18}\text{O}$ amplitude of 4.2‰ indicates a glacial to interglacial transition. The whole $\delta^{18}\text{O}$ record exhibits a long-term increasing trend. A sudden positive isotopic shift of 3.5‰ occurs from 120.0 to 118.6 ka, accounting for 84% of the isotopic range of the whole record. This large-amplitude shift, also seen in other stalagmite records in China (Fig.4; Yuan et al., 2004; Kelly et al., 2006; Wang et al., 2008), denotes the end of the LIG in the AM region. During the LIG, two phases are identified (Fig. 3). Phase 1, from 123.3 to 121.6 ka, is characterized by $\delta^{18}\text{O}$ values ranging from -10.4‰ to -9.1‰ and averaging -9.7‰ ; Phase 2, from 121.6 to 119.8 ka, is characterized by the $\delta^{18}\text{O}$ values ranging from -9.7‰ to -8.5‰ and averaging -9.1‰ . The $\delta^{18}\text{O}$ difference between the two phases is about 0.6‰ , typical of centennial-scale variations of the LIG and Holocene in China (Wang et al., 2005; Kelly et al., 2006).

Isotopic equilibrium during calcite precipitation is a prerequisite in order to interpret the calcite $\delta^{18}\text{O}$ in terms of climate. Dorale and Liu (2009) proposed that replication tests are a more rigorous approach to testing isotopic equilibrium than Hendy tests. The YX266 $\delta^{18}\text{O}$ record

shows a broad similarity to previously published records from Dongge (Yuan et al., 2004; Kelly et al., 2006) and Sanbao (Wang et al., 2008) caves on suborbital to millennial scales (Fig. 4), suggesting an equilibrium condition during calcite precipitation. The minor differences between these records on finer timescales may arise from different regional climate conditions and local cave environments, such as unique flow routings through the epikarst, different CO₂ degassing histories in the cave system (Lachniet, 2009). Overall, kinetic fractionation has little effect on the YX266 isotopic signal and the $\delta^{18}\text{O}$ change is primarily of climatic origin.

4. Discussion

4.1 Stalagmite $\delta^{18}\text{O}$ interpretation

The climatic interpretation of stalagmite $\delta^{18}\text{O}$ records inside China remains a matter of ongoing debate as a result of multiple controls on calcite $\delta^{18}\text{O}$ values (Fairchild et al., 2006; Lachniet, 2009; Zhao et al., 2015b). Based on the Rayleigh fractionation theory, it is proposed that the stalagmite $\delta^{18}\text{O}$ reflects changes in the integrated monsoon precipitation between water vapor sources and cave sites (Yuan et al., 2004; Cheng et al., 2016). Therefore, the calcite $\delta^{18}\text{O}$ measures the mean monsoon rainfall or monsoon intensity along the moisture transport pathway. This interpretation is evidenced by consistent variations in stalagmite $\delta^{18}\text{O}$

records from across many China caves (Yuan et al., 2004; Chen et al., 2016), paralleling with lake level records (Goldsmith et al., 2017) and some model studies (Liu et al., 2014). In addition, covariation of the stalagmite $\delta^{18}\text{O}$ with the corresponding annual calcite layer thickness consolidates the interpretation of the calcite $\delta^{18}\text{O}$ change as a proxy of integrated monsoon rainfall or intensity (Fleitmann et al., 2004; Zhao et al., 2015a). On the other hand, it is argued that Chinese speleothem $\delta^{18}\text{O}$ changes reflect variations in Indian monsoon-sourced $\delta^{18}\text{O}$ values and Indian monsoon rainfall (Pausata et al., 2011; Baker et al., 2015) or a mixed signal of the remote Indian monsoon-sourced and local Pacific-sourced moisture isotope signatures (Maher and Thompson, 2012; Tan, 2014; Beck et al., 2018). Recently, Orland et al. (2015) found that the $\delta^{18}\text{O}$ values in Chinese speleothems record a combination of the regional summer monsoon rainfall and integrated tropical source signals. Regardless, the $\delta^{18}\text{O}$ change inherits the isotopic signature of precipitation and tracks the large-scale monsoon circulation associated with global climate system. The validity of the carbonate $\delta^{18}\text{O}$ variability as a robust palaeoclimatic indicator is supported by its strong correlation with multiple tracers of global climate and environmental changes. For instance, a good correlation is exemplified by its striking similarity to atmospheric ^{14}C (Wang et al., 2005; Steinhilber et al., 2012) and CH_4 concentrations, Greenland temperature (Wang et al., 2001), $\delta^{18}\text{O}$ of

atmospheric O₂ (Wang et al., 2008) and solar insolation (Cheng et al., 2009b; 2016).

4.2 Correlations between AM and NHSI

The increasing trend of the YX266 $\delta^{18}\text{O}$ record is in parallel with the decreasing tendency of the NHSI during the LIG period (Fig. 4). This correspondence suggests that solar forcing should play an important role during the LIG, similar to the condition over the Holocene epoch (Wang et al., 2005).

The solar modulation helps shed light on the debate on AM intensity during the LIG (Rao et al., 2015). The AM intensity was estimated to be unprecedentedly strong in magnetic susceptibility records of Chinese loess (Sun et al., 2006). However, the intensity was inferred to be weaker in the cave records. The Dongge and Sanbao cave records show that the monsoon strength over the LIG is commensurate with that during marine isotope stage (MIS) 5c and 5a (Yuan et al., 2004; Wang et al., 2008). At the Tianmen and Xiaobailong cave sites (Fig.1), however, the AM was indicated to be slightly stronger than the Dongge and Sanbao cave records (Cai et al., 2010; 2015). Despite the paralleling trend between the YX266 and NHSI records during the latter part of MIS5e, a long-lasting, not spliced cave record covering the whole MIS5 interval is needed to check the correlation between the cave and NHSI records.

4.3 Monsoon shifts at the midst of the LIG

YX266 shows a $\delta^{18}\text{O}$ switch of 0.6‰ from lower to higher values at around 121.6 ka (Fig. 3). This change implies a qualitatively different evolution of the monsoon system. In contrast to the YX266 record, the Dongge and Sanbao $\delta^{18}\text{O}$ records do not clearly show such a two-phase picture (Fig. 4). The D3 $\delta^{18}\text{O}$ record of Dongge Cave shows a slightly increasing trend until 122.7 ka and then a negative shift to a stable state (Fig. 4; Kelly et al., 2006). For the Sanbao records, two stalagmite time series (no. SB 23 and 41) consistently exhibit stable monsoon behavior throughout the LIG (Fig. 4; Wang et al., 2008). The difference between these $\delta^{18}\text{O}$ records on the finer scales may result from discrepancies in regional climate conditions and local cave environments as mentioned above.

The intrigue AM switch at about 121.6 ka has counterparts in records far away from the AM regime. It coincided with the mid-Eemian cooling event identified in ice core, land and ocean records (NEEM community members, 2013; Karabanov et al., 2000 and references therein). Greenland temperature maxima occurred immediately after the onset of the LIG (126 ka), followed by a gradual cooling until the slightly rapid cooling at about 120 ka (NEEM community members, 2013; Fig. 5A). At 122 ka, a centennial temperature minimum occurred and coincided with the shift of the monsoon mean state (Fig. 5A). In Europe, a recently

reported stalagmite record displayed a $\delta^{13}\text{C}$ maximum at 122 ka, indicating a dry/cold climate (Fig. 5D; Vansteenberghe et al., 2016). Based on biogenic silica and siliceous microfossil abundance records of Lake Baikal in Siberia, Karabanov et al. (2000) highlighted a close climatic link between the Asia continent and North Atlantic during the LIG. The temperature signal in the North Atlantic may be transported by westerly winds to the AM regime by the acting Siberian High (Porter and An, 1995).

In the Southern Hemisphere, a climate response is found in a speleothem record from the Peruvian Andes (Burns et al., 2015). This stalagmite record measures intensity of South American Summer Monsoon (SASM). At 122.6 ka, a remarkable SASM shift towards the weaker intensity occurred in synchrony with the AM shift (Fig. 5C), considering the date uncertainty. Unlike the irreversible decreasing trend of the AM and SASM after 121.6 ka, Siberia and Europe climate returned to mild (?) conditions similar to the early-Eemian optimum after the mid-Eemian cooling (Tzedakis et al., 1994; Karabanov et al., 2000; Vansteenberghe et al., 2016). The consistent shift in the AM and SASM intensity could not be explained by the bipolar seesaw mechanism (Broecker, 1998), although some studies have pointed out the existence of the mechanism based on anti-phased temperature variations between the two hemispheres during the LIG (NEEM community members, 2013;

Hoffman et al., 2017). If the bipolar seesaw mechanism had operated at the time of the mid-Eemian cooling event, the AM and SASM would have changed in the opposite direction. Orbitally driven insolation changes, together with influences of the reduced temperature at high latitudes, may push the AM system into a different mode of operation at about (after?) 121.6 ka. Previous studies indicated that the positive moisture-advection feedback from the ocean to land could qualitatively change the development of the monsoon system (Levermann et al., 2009; Schewe et al., 2012). At 121.6 ka, the decreases in the insolation output and global temperature probably reduced the monsoonal moisture-advection feedback to a threshold, and caused the occurrence of the rapid monsoon shift.

4.4 Rapid demise of the LIG

The substantial and rapid $\delta^{18}\text{O}$ shift of 3.5‰ at about 120 ka marks the end of the LIG AM (Fig. 6C). This isotopic change is supported by the nearby Dongge and Sanbao cave $\delta^{18}\text{O}$ records (Yuan et al., 2004; Kelly et al., 2006; Wang et al., 2008; Fig.4), which shows similar timing and amplitude to our record. Similar climate signature is also indicated in the stalagmite $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ records in Daeya Cave, South Korea (Jo et al., 2011). The coherence between the cave records across East Asia collectively points to a rapid and pronounced decrease (weakening?) in

the AM circulation at the end of the LIG.

This monsoon decline (weakening?) at ~120 ka is correlated with climate events globally. For example, a stalagmite $\delta^{18}\text{O}$ shift towards more positive values in Belgium occurred abruptly at 120 ka (Vansteenberghe et al., 2016; Fig. 6B). This shift indicated changes in oceanic moisture $\delta^{18}\text{O}$ signal associated with an increase in the global ice volume at the end of the LIG. At the same time, stalagmite $\delta^{18}\text{O}$ records from Israel and Peru indicated some significant rainfall decrease (Bar-Matthews et al., 2003; Burns et al., 2015; Fig. 6D and E). All the high-resolution stalagmite records from China, Belgium, Israel, and Peru depicted a rapid termination of the LIG at the low and middle latitudes. By contrast, a gradual termination was registered in the bipolar regions (high latitudes). Ice core isotope records in Greenland (NEEM community members, 2013) and Antarctica (Jouzel et al., 2007) consistently documented a relatively gradual temperature decrease at approximately 120 ka (Fig. 6A and G). At this time, a decrease in Atlantic meridional overturning circulation (AMOC) occurred, estimated by the $^{143}\text{Nd}/^{144}\text{Nd}$ record from the Bermuda Rise (Böhm et al., 2015; Fig. 6F). If the decrease in AMOC were responsible for the termination of the LIG, the temperatures in both polar regions would not have changed in the same direction contradicting the bipolar seesaw mechanism (Broecker, 1998; EPICA Community Members, 2006). The reduction in the

monsoon circulation, polar temperature and AMOC at about 120 ka may represent the complicated response of different components within the Earth system towards the decreasing NHSI and increasing global ice volume.

The rapid termination of the LIG in the AM region was possibly linked, to a large extent, the decreasing NHSI. The AM circulation was modulated by a combination of NHSI and the North Atlantic climate (Wang et al., 2001, 2005, 2008; Cheng et al., 2009b, 2016). During the Holocene optimum (9.5-6.0 ka) and the early Holocene (11.5-9.5 ka), the AM changed in concert (agreement?) with the Greenland temperature on the multimillennial scale (Dong et al., 2010; Fig. 7B). However, the two climate systems began to decouple immediately since the end of the Holocene maximum humid period (at 6.0 ka), in which the AM closely followed the decreasing NHSI, while the Greenland temperature tracked the stabilized global sea level (Dong et al., 2010; Fig. 7B). At 6.0 ka, the benthic foraminiferal $\delta^{18}\text{O}$ value, representing the global ice volume, was 3.33‰ (Lisiecki and Stern, 2016) and the NHSI at 65° N was 458 W/m² (Berger and Loutre, 1991). Similarly, the AM and Greenland temperature varied in concert (agreement?) before the rapid termination of the LIG, after that they began to decouple (Fig. 7A). At ~120 ka, the benthic foraminiferal $\delta^{18}\text{O}$ value was 3.40‰ (Lisiecki and Stern, 2016), nearly

identical to the value at 6.0 ka (3.33 ‰), but the NHSI at 65° N was 439 W/m² (Berger and Loutre, 1991), much lower than the value at 6.0 ka (458 W/m²). This comparison indicates that the lower NHSI may be largely responsible for the rapid termination of the LIG AM. The influence of the decreasing NHSI on the AM shift may operate through lowering tropical sea surface temperatures (Tierney et al., 2016), further lowering land-sea temperature contrasts (Kutzbach et al., 2008), and thus limiting moisture–advection feedbacks from the ocean to land (Webster et al., 1998). Response to the decreasing NHSI, the continuously increasing ice volumes since 120 ka likely contributed to the rapid termination of the LIG as well (Fig. 7A). This is because large ice sheets in the north can induce a southward migration of the ITCZ (Chiang and Bitz, 2005; Broccoli et al., 2006), which can reduce the AM intensity (Fleitmann et al., 2007; Wang et al., 2017).

5. Conclusions

The LIG represents the most recent interval when the global climate was remarkably similar to the present, and thus it provides us a compelling opportunity for understanding climate changes during a warm period. Here a high-resolution stalagmite record is provided to characterize the key changes in the AM strength during the LIG. Our stalagmite $\delta^{18}\text{O}$ record covers a period of 123.3–116.8 ka, the latter part of

the LIG. The $\delta^{18}\text{O}$ record shows a long-term trend in parallel with ~~Northern Hemisphere summer insolation~~ (NHSI?) changes, with the negative $\delta^{18}\text{O}$ values corresponding to the higher insolation. A pronounced shift in the AM mean-state is identified based on changes in stalagmite $\delta^{18}\text{O}$ at 121.6 ka. The AM shift correlates with abrupt changes of South American Summer Monsoon. The simultaneous shifts in monsoon mean-state in both hemispheres indicate a qualitatively different (??) evolution of the monsoon systems since 121.6 ka. Besides, the shift of the AM coincides with the mid-Eemian cooling event, extensively studied (?) at higher latitudes. This correlation points to a teleconnection between the climate at high latitudes and AM during the LIG. Another AM shift occurred at 120 ka. This shift has an intensity similar to the amplitude of glacial-interglacial cycles and is coincided with the decreasing NHSI. This shift, consolidated by other cave records, represents the end of the LIG AM. Based on comparisons of stalagmite records against the NHSI and ice volumes during the LIG and Holocene, we draw the conclusion that the NHSI change exerted a dominant influence on the rapid demise of the LIG AM.

Acknowledgments

We are grateful to Prof. Tingyong Li and an anonymous reviewer for their

constructive suggestions and comments on an early version of the manuscript. This work was supported by the National Natural Science Foundation of China (grant numbers 41602350, 41571102 and 41572340).

References

- Adkins, J.F., Boyle, E.A., Keigwin, L., Cortijo, E., 1997. Variability of the North Atlantic thermohaline circulation during the last interglacial period. *Nature* 390 (6656), 154-156.
- Andersen, K.K., Svensson, A., Johnsen, S.J., Rasmussen, S.O., Matthias, B., Rothlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Steffensen, J.P., Dahl-Jensen, D., Vinther, B.M., Clausen, H.B., 2006. The Greenland ice core chronology 2005, 15–42 ka. Part 1: constructing the time scale. *Quat. Sci. Rev.* 25 (23-24), 3246-3257.
- Baker, A.J., Sodemann, H., Baldini, J.U., Breitenbach, S.F., Johnson, K.R., Hunen, J.V., Zhang, P.Z., 2015. Seasonality of westerly moisture transport in the East Asian summer monsoon and its implications for interpreting precipitation $\delta^{18}\text{O}$. *J. Geophys. Res.* 120 (12), 5850-5862.
- Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., Hawkesworth C.J., 2003. Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the Eastern Mediterranean region and their implication for paleorainfall during interglacial intervals. *Geochim. Cosmochim. Acta* 67 (17), 3181-3199.
- Bauch, H.A., Kandiano, E.S., Helmke, J., Anderson, N., Rosell-Mele, A., 2011. Climatic bisection of the last interglacial warm period in the Polar North Atlantic. *Quat. Sci. Rev.* 30 (15-16), 1813-1818.
- Bazin, L., Landais, A., Lemieux-Dudon, B., Kele, H.T.M., Veres, D., 2013. An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka. *Clim. Past* 9 (4), 1715-1731.
- Beck, J.W., Zhou, W., Li, C., Wu, Z.K., White, L., Xian, F., Kong, X.H., An, Z.S., 2018. A 550,000-year record of East Asian monsoon rainfall from ^{10}Be in loess. *Science* 360 (6391), 877-881.
- Berger, A., Loutre, M., 1991. Insolation values for the climate of the last 10 million years. *Quat. Sci. Rev.* 10 (4), 297-317.
- Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Anderson, M.B., Deininger, M., 2015. Strong and deep Atlantic meridional overturning circulation during the last glacial cycle. *Nature* 517 (7532), 73-76.
- Broccoli, A.J., Dahl, K.A., Stouffer, R.J., 2006. Response of the ITCZ to Northern Hemisphere cooling. *Geophys. Res. Lett.* 33 (1), L01702.
- Broecker, W.S., 1998. Paleoocean circulation during the Last Deglaciation: A bipolar seesaw? *Paleoceanography* 13 (2), 119-121.
- Burns, S., Kanner, L.C., Cheng, H., Edwards, R.L., 2015. A tropical speleothem record of glacial

inception, the South American Summer Monsoon from 125 to 115 ka. *Clim. Past* 11 (6), 931-938.

Cai, Y.J., Cheng, H., An, Z.S., Edwards, R.L., Wang, X.F., Tan, L.C., Wang, J., 2010. Large variations of oxygen isotopes in precipitation over south-central Tibet during Marine Isotope Stage 5. *Geology* 38 (3), 243-246.

Cai, Y.J., Fung, I.Y., Edwards, R.L., An, Z., Cheng, H., Lee, J., Tan, L.C., Shen, C.C., Wang, X.F., Day, J.A., Zhou, W.J., Kelly, M.J., Chiang, J.C.H., 2015. Variability of stalagmite-inferred Indian monsoon precipitation over the past 252,000 y. *PNAS* 112 (10), 2954-2959.

CAPE-Last Interglacial Project Members., 2006. Last Interglacial Arctic warmth confirms polar amplification of climate change. *Quat. Sci. Rev.* 25 (13-14), 1383-1400.

Chen, S.T., Wang, Y.J., Cheng, H., Edwards, R.L., Wang, X.F., Kong, X.G., Liu, D.B., 2016. Strong coupling of Asian Monsoon and Antarctic climates on sub-orbital timescales. *Sci. Rep.* 6, 32995.

Cheng, H., Edwards, R.L., Broecker, W.S., Denton, G.H., Kong, X.G., Wang, Y., Zhang, R., Wang, X.F., 2009b. Ice age terminations. *Science* 326 (5950), 248-252.

Cheng, H., Edwards, R.L., Shen, C.C., Polyak, V.J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y.J., Kong, X.G., Spötl, C., Wang, X.F., Alexander-Jr, E.C., 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth Planet. Sci. Lett.* 371-372, 82-91.

Cheng, H., Edwards, R.L., Sinha, A., Spötl, C., Yi, L., Chen, S.T., Kelly, M., Kathayat, G., Wang, X.F., Li, X., Kong, X.G., Wang, Y.J., Ning, Y.F., Zhang, H.W., 2016. The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* 534 (7609), 640-646.

Cheng, H., Fleitmann, D., Edwards, R.L., Wang, X.F., Cruz, F.W., Auler, A.S., Mangin, A., Wang, Y.J., Kong, X.G., Burns, S.J., Matter, A., 2009a. Timing and structure of the 8.2 kyr B.P. event inferred from $\delta^{18}\text{O}$ records of stalagmites from China, Oman, and Brazil. *Geology*, 37 (11), 1007-1010.

Chiang, J.C., Bitz, C.M., 2005. Influence of high latitude ice cover on the marine Intertropical Convergence Zone. *Clim. Dyn.* 25 (5), 477-496.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S. Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364 (6434), 218-220.

Demény, A., Kern, Z., Czuppon, G., Németh, A., Leél-Össy, S., Siklósy, Z., Lin, K., Hu, H.M., Shen, C.C., Vennemann, T.W., Haszpra, L., 2017. Stable isotope compositions of speleothems from the last interglacial–Spatial patterns of climate fluctuations in Europe. *Quat. Sci. Rev.* 161, 68-80.

Dong, J.G., Wang, Y.J., Cheng, H., Hardt, B., Edwards, R.L., Kong, X.G., Wu, J.Y., Chen, S.T., Liu, D.B., Jiang, X.Y., Zhao, K., 2010. A high-resolution stalagmite record of the Holocene East Asian monsoon from Mt Shennongjia, central China. *The Holocene* 20 (2), 257-264.

Dorale, J.A., Liu, Z.H., 2009. Limitations of Hendy test criteria in judging the paleoclimate suitability of speleothems and the need for replication. *J. Cave Karst Stud.* 71 (1), 73-80.

Dutton, A., Carlson, A.E., Long, A.J., Milne, G.A., Clark, P.U., DeConto, R., Horton, B.P., Rahmstorf, S., Raymo, M.E., 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* 349 (6244), aaa4019.

EPICA Community Members., 2006. One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature* 444 (7116), 195-198.

Fairchild, I.J., Smith, C.L., Baker, A., Fuller, L., Spötl, C., Matthey, D., McDermott, F., E.I.M.F.,

473 2006. Modification and preservation of environmental signals in speleothems. *Earth Sci. Rev.* 75
 474 (1-4), 105-153.
 475 Fleitmann, D., Burns, S.J., Mangini, A., Mudelsee, M., Kramers, J., Villa, I., Neff, U., Al-Subbary,
 476 A.A., Buettner, A., Hippler, D., Matter, A., 2007. Holocene ITCZ and Indian monsoon dynamics
 477 recorded in stalagmites from Oman and Yemen (Socotra). *Quat. Sci. Rev.* 26 (1-2), 170-188.
 478 Fleitmann, D., Burns, S.J., Neff, U., Mudelsee, M., Mangini, A., Matter, A., 2004. Palaeoclimatic
 479 interpretation of high-resolution oxygen isotope profiles derived from annually laminated
 480 speleothems from Southern Oman. *Quat. Sci. Rev.* 23 (7-8), 935-945.
 481 Galaasen, E.V., Ninemann, U.S., Irvani, N., Kleiven, H.F., Rosenthal, Y., Kissel, C., Hodell, D.A.,
 482 2014. Rapid reductions in North Atlantic deep water during the peak of the last interglacial period.
 483 *Science* 343 (6175), 1129-1132.
 484 Goldsmith, Y., Broecker, W.S., Xu, H., Polissar, P.J., DeMenocal, P.B., Porat, N., Lan, J.H., Cheng,
 485 P., Zhou, W.J., An, Z.S., 2017. Northward extent of East Asian monsoon covaries with intensity on
 486 orbital and millennial timescales. *PNAS* 114 (8), 1817-1821.
 487 Helmens, K.F., Salonen, J.S., Pliikk, A., Engels, S., Väiliranta, M., Kylander, M., Brendryen, J.,
 488 Renssen, H., 2015. Major cooling intersecting peak Eemian Interglacial warmth in northern
 489 Europe. *Quat. Sci. Rev.* 122, 293-299.
 490 Hiess, J., Condon, D.J., Mclean, N., Noble, S.R., 2012. $^{238}\text{U}/^{235}\text{U}$ Systematics in terrestrial
 491 uranium-bearing minerals. *Science* 335 (6076), 1610-1614.
 492 Hoffman, J.S., Clark, P.U., Parnell, A.C., He, F., 2017. Regional and global sea-surface
 493 temperatures during the last interglaciation. *Science* 355 (6322), 276-279.
 494 Imbrie, J., Boyle, E.A., Clemens, S.C., Duffy, A., Howard, W.R., Kukla, G., Kutzbach, J.,
 495 Martinson, D.G., McIntyre, A., Mix, A.C., Molino, B., Morley, L.L., Peterson, L.C., Pisias, N.G.,
 496 Prell, W.L., Raymo, M.E., Shackleton, N.J., Toggweiler, J.R., 1992. On the Structure and Origin
 497 of Major Glaciation Cycles 1. Linear Responses to Milankovitch Forcing. *Paleoceanography* 7 (6),
 498 701-738.
 499 Jiang, X.Y., He, Y.Q., Wang, X.Y., Sun, X.S., Hong, H., Liu, J., Yu, T.L., Li, Z.Z., Shen, C.C., 2017.
 500 The Preboreal-like Asian monsoon climate in the early Last Interglacial period recorded from the
 501 Dark Cave, Southwest China. *J. Asian Earth Sci.* 143, 39-44.
 502 Jo, K.N., Woo, K.S., Lim, H.S., Cheng, H., Edwards, R.L., Wang, Y.J., Jiang, X.Y., Kim, R., Lee,
 503 J.I., Yoon, H.I., Yoo, K.C., 2011. Holocene and Eemian climatic optima in the Korean Peninsula
 504 based on textural and carbon isotopic records from the stalagmite of the Daeya Cave, South Korea.
 505 *Quat. Sci. Rev.* 30 (9-10), 1218-1231.
 506 Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B.,
 507 Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M.,
 508 Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A.,
 509 Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B.,
 510 Stocker, T.F., Tison, J.L., Werner, M., Wolff, E.W., 2007. Orbital and millennial Antarctic climate
 511 variability over the past 800,000 Years. *Science* 317 (5839), 793-796.
 512 Karabanov, E.B., Prosenko, A.A., Williams, D.F., Khursevich, G.K., 2000. Evidence for
 513 mid-Eemian cooling in continental climatic record from Lake Baikal. *J. Paleolimnol.* 23 (4),
 514 365-371.
 515 Kelly, M.J., Edwards, R.L., Cheng, H., Yuan, D.X., Cai, Y.J., Zhang, M.L., Lin, Y.S., An, Z.S.,
 516 2006. High resolution characterization of the Asian Monsoon between 146,000 and 99,000 years
 517 B.P. from Dongge Cave, China and global correlation of events surrounding Termination II.

Palaeogeogr. Palaeoclimatol. Palaeoecol. 236 (1-2), 20-38.
 Kopp, R.E., Simons, F.J., Mitrovica, J.X., Maloof, A.C., Oppenheimer, M., 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462 (7275), 863-867.
 Kutzbach, J.E., Liu, X.D., Liu, Z.Y., Chen, G.S., 2008. Simulation of the evolutionary response of global summer monsoons to orbital forcing over the past 280,000 years. *Clim. Dyn.* 30 (6), 567-579.
 Lachniet, M.S., 2009. Climatic and environmental controls on speleothem oxygen-isotope values. *Quat. Sci. Rev.* 28 (5-6), 412-432.
 Levermann, A., Schewe, J., Petoukhov, V., Held, H., 2009. Basic mechanism for abrupt monsoon transitions. *PNAS* 106 (49), 20572-20577.
 Lisiecki, E., Stern, J.V., 2016. Regional and global benthic $\delta^{18}\text{O}$ stacks for the last glacial cycle. *Paleoceanography* 31 (10), 1368-1394.
 Liu, Y.H., Henderson, G.M., Hu, C.Y., Mason, A.J., Charnley, N., Johnson, K.R., Xie, S.C., 2013. Links between the East Asian monsoon and North Atlantic climate during the 8,200 year event. *Nat. Geosci.* 6 (2), 117-120.
 Liu, Z.Y., Wen, X.Y., Brady, E.C., Otto-Bliesner, B., Yu, G., Lu, H.Y., Cheng, H., Wang, Y.J., Zheng, W.P., Ding, Y.H., Edwards, R.L., Cheng, J., Liu, W., Yang, H., 2014. Chinese cave records and the East Asia Summer Monsoon. *Quat. Sci. Rev.* 83, 115-128.
 Maher, B.A., Thompson, R., 2012. Oxygen isotopes from Chinese caves: records not of monsoon rainfall but of circulation regime. *J. Quaternary Sci.* 27 (6), 615-624.
 McKay, N.P., Overpeck, J.T., Otto-Bliesner, B.L., 2011. The role of ocean thermal expansion in Last Interglacial sea level rise. *Geophys. Res. Lett.* 38 (14), L14605.
 McManus, J.F., Bond, G.C., Broecker, W.S., Johnson, S., Labeyrie, L., Higgins, S., 1994. High-resolution climate records from the North Atlantic during the last interglacial. *Nature* 371 (6495), 326-329.
 NEEM community members., 2013. Eemian interglacial reconstructed from a Greenland folded ice core. *Nature* 493 (7433), 489-494.
 Oppo, D.W., McManus, J.F., Cullen, J.L., 2006. Evolution and demise of the Last Interglacial warmth in the subpolar North Atlantic. *Quat. Sci. Rev.* 25 (23-24), 3268-3277.
 Orland, I.J., Edwards, R.L., Cheng, H., Kozdon, R., Cross, M., Valley, J.W., 2015. Direct measurements of deglacial monsoon strength in a Chinese stalagmite. *Geology* 43 (6), 555-558.
 Otto-Bliesner, B.L., Rosenbloom, N.A., Stone, E.J., McKay, N.P., Lunt, D.J., Brady, E.C., Overpeck, J.T., 2013. How warm was the last interglacial? New model-data comparisons. *Philos. Trans. R. Soc. London, Ser. A* 371, 20130097.
 Otvos, E.G., 2015. The last interglacial stage: definitions and marine highstand, North America and Eurasia. *Quat. Int.* 383, 158-173.
 Pausata, F.S., Battisti, D.S., Nisancioglu, K.H., Bitz, C.M., 2011. Chinese stalagmite $\delta^{18}\text{O}$ controlled by changes in the Indian monsoon during a simulated Heinrich event. *Nat. Geosci.* 4 (7), 474-480.
 Porter, S.C., An, Z.S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation. *Nature* 375 (6529), 305-308.
 Rao, Z.G., Liu, X.K., Hua, H., Gao, Y.L., Chen, F.H., 2015. Evolving history of the East Asian summer monsoon intensity during the MIS5: inconsistent records from Chinese stalagmites and loess deposits. *Environ. Earth Sci.* 73 (7), 3937-3950.

Schewe, J., Levermann, A., Cheng, H., 2012. A critical humidity threshold for monsoon transitions. *Clim. Past* 8 (2), 535-544.

Scholz, D., Hoffmann, D.L., 2011. StalAge-An algorithm designed for construction of speleothem age models. *Quat. Geochronol.* 6 (3-4), 369-382.

Shackleton, N.J., Sánchez-Goni, M.F., Pailler, D., Lancelot, Y., 2003. Marine Isotope Substage 5e and the Eemian Interglacial. *Global Planet. Change* 36 (3), 151-155.

Shao, Q.F., Pons-Branchu, E., Zhu, Q.P., Wang, W., Valladas, H., Fontugne, M., 2017. High precision U/Th dating of the rock paintings at Mt. Huashan, Guangxi, southern China. *Quat. Res.* 88 (1), 1-13.

Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., Wilhelms, F., 2012. 9,400 years of cosmic radiation and solar activity from ice cores and tree rings. *PNAS* 109 (16), 5967-5971.

Sun, Y.B., Clemens, S.C., An, Z.S., Yu, Z.W., 2006. Astronomical timescale and palaeoclimatic implication of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau. *Quat. Sci. Rev.* 25 (1-2), 33-48.

Tan, M., 2014. Circulation effect: response of precipitation $\delta^{18}\text{O}$ to the ENSO cycle in monsoon regions of China. *Clim. Dyn.* 42 (3-4), 1067-1077.

Tierney, J.E., Pausata, F.S.R., Demenocal, P., 2016. Deglacial Indian monsoon failure and North Atlantic stadials linked by Indian Ocean surface cooling. *Nat. Geosci.* 9 (1), 46-50.

Turney, C.S., Jones, R.T., 2010. Does the Agulhas Current amplify global temperatures during super-interglacials? *J. Quaternary Sci.* 25 (6), 839-843.

Tzedakis, P.C., Bennett, K.D., Magri, D., 1994. Climate and the pollen record. *Nature* 370 (6490), 513-513.

Vansteenberghe, S., Verheyden, S., Cheng, H., Edwards, R.L., Keppens, E., Claeys, P., 2016. Paleoclimate in continental northwestern Europe during the Eemian and early Weichselian (125-97 ka): Insights from a Belgian speleothem. *Clim. Past* 12 (7), 1445-1458.

Wang, X.F., Edwards, R.L., Auler, A.S., Cheng, H., Kong, X.G., Wang, Y.J., Cruz, F.W., Dorale, J.A., Chiang, H.W., 2017. Hydroclimate changes across the Amazon lowlands over the past 45,000 years. *Nature* 541 (7636), 204-207.

Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.C., Dorale, J.A., 2001. A High-Resolution Absolute-Dated Late Pleistocene Monsoon Record from Hulu Cave, China. *Science* 294 (5550), 2345-2348.

Wang, Y.J., Cheng, H., Edwards, R.L., Kong, X.G., Shao, X.H., Chen, S.T., Wu, J.Y., Jiang, X.Y., Wang, X.F., An, Z.S., 2008. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. *Nature* 451 (7182), 1090-1093.

Wang, Y.J., Cheng, H., Edwards, R.L., He, Y.Q., Kong, X.G., An, Z.S., Wu, J.Y., Kelly, M.J., Dykoski, C.A., Li, X.D., 2005. The Holocene Asian Monsoon: Links to Solar Changes and North Atlantic Climate. *Science* 308 (5723), 854-857.

Webster, P.J., Magana, V., Palmer, T.N., Shukla, J., Tomas, R.A., Yanai, M., Yasunari, T., 1998. Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.* 103 (C7), 14451-14510.

Yuan, D.X., Cheng, H., Edwards, R.L., Dykoski, C.A., Kelly, M.J., Zhang, M.L., Qing, J.M., Lin, Y.S., Wang, Y.J., Wu, J.Y., Dorale, J.A., An, Z.S., Cai, Y.J., 2004. Timing, duration, and transitions of the last interglacial Asian monsoon. *Science* 304 (5670), 575-578.

Zhao, K., Wang, Y.J., Edwards, R.L., Cheng, H., Liu, D.B., Kong, X.G., 2015a. A high-resolved record of the Asian Summer Monsoon from Dongge Cave, China for the past 1200 years. *Quat.*

Sci. Rev. 122, 250-257.
 Zhao, M., Li, H.C., Liu, Z.H., Mii, H.S., Sun, H.L., Shen, C.C., Kang, S.C., 2015b. Changes in climate and vegetation of central Guizhou in southwest China since the last glacial reflected by stalagmite records from Yelang Cave. *J. Asian Earth Sci.* 114 (3), 549-561.

Table and Figure Captions

Table 1 ^{230}Th ages for stalagmite YX266 in the Yongxing Cave, China

Fig. 1 Map showing locations of the Yongxing Cave and other caves mentioned in the paper.

Fig. 2 Paragraph of stalagmite YX266 and its age model. Black dots represent ^{230}Th dates. The age model is established using the StalAge algorithm, with the corresponding 95 %-confidence limits shown in red (Scholz and Hoffmann, 2011).

Fig. 3 Two phases and rapid demise of the last interglacial Asian monsoon. The horizontal gray lines denote $\delta^{18}\text{O}$ average values for phase 1 and phase 2, which are -9.7‰ and -9.1‰, respectively. The two phases are bordered by the $\delta^{18}\text{O}$ increase of 0.6‰ at 121.6 ka. Another positive $\delta^{18}\text{O}$ shift of 3.5‰ denotes the demise of the last interglacial Asian monsoon.

Fig. 4 Comparison of the YX266 record with summer insolation and other cave records. The YX266 record closely tracks the Northern Hemisphere summer insolation, with the stronger monsoon corresponding to the higher summer insolation during the LIG (Berger and Loutre, 1991). The Dongge (Kelly et al., 2006) and Sanbao (Wang et al., 2008) records show a generally stable monsoon during the LIG. Dates with errors are indicated with color-coded error bars for each record.

Fig. 5 Correlations of the abrupt monsoon shift with other climate changes. (A) Greenland temperature (NEEM community members, 2013); (B) Asian monsoon (this study); (C) South American Summer Monsoon (Burns et al., 2015). The stalagmite record was shifted toward younger ages by 1 ka for visual comparison; (D) Continent

climate in northwestern Europe (Vansteenberg et al., 2016). The temperature minimum over Greenland occurred in concert with the abrupt shifts of the Asian monsoon and the South American Summer Monsoon, and with the dry/cold maximum in northwestern Europe. The vertical dashed line indicates the correlation between these climate changes.

Fig. 6 Rapid positive shift in the YX266 $\delta^{18}\text{O}$ record at 120 ka compared to other paleoclimate records. (A) Greenland temperature change (NEEM community members, 2013); (B) Stalagmite Han-9 $\delta^{18}\text{O}$ record from Belgium (Vansteenberg et al., 2016); (C) Stalagmite YX266 $\delta^{18}\text{O}$ record in China (this study); (D) Stalagmite P10-H1 $\delta^{18}\text{O}$ record in Peru (Burns et al., 2015); (E) Soreq cave $\delta^{18}\text{O}$ record in Israel (Bar-Matthews et al., 2003); (F) Marine sediment $^{143}\text{Nd}/^{144}\text{Nd}$ ratio (expressed as ϵ_{Nd}) record in Bermuda Rise (Böhm et al., 2015); (G) Antarctic ice core EDC $\delta^{18}\text{O}$ record (Jouzel et al., 2007) plotted on the AICC2012 timescale (Bazin et al., 2013). The vertical bar indicates the rapid demise of the last interglacial Asian monsoon at about 120 ka.

Fig.7 Comparison of stalagmite $\delta^{18}\text{O}$ records to insolation and ice volume data during the last interglacial and Holocene. Panel A and B represent conditions during the last interglacial and Holocene, respectively. Orange lines represent stalagmite records: the YX266 record (this study) and Sanbao cave record in the Holocene (Dong et al., 2010). Black lines indicate Greenland temperature changes. The Holocene record is from ice core NGRIP (Anderson et al., 2006); the record for the last interglacial is from ice core NEEM (NEEM community members, 2013). Green lines denote benthic foraminiferal $\delta^{18}\text{O}$ records (Lisiecki and Stern, 2016). Purple curves are 21 July insolation summer insolation at 65°N (Berger and Loutre, 1991). Vertical bars mark the decoupling between the Asian monsoon and Greenland temperature changes.