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Multicentennial to millennial-scale changes in East Asian Summer Monsoon the during Greenland interstadial 25

Jinguo Dong[a*], Chuan-Chou Shen[b,c*], Yi Wang [d], Hsun-Ming Hu[b,c], Yogaraj Banerjee[b,c], Wei Huang[e]

[a] College of Geosciences, Nantong University, Nantong 226007, PRC

[b] High-Precision Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC

[c] Research Center for Future Earth, National Taiwan University, Taipei 10617, Taiwan, ROC

[d] Department of Geography, School of Global Studies, University of Sussex, Brighton, UK BN1 9QJ

[e] Department of Geographical Science, Yichun University, Yichun 336000, PRC

*Corresponding authors:
J. Dong, College of Geosciences, Nantong University, Nantong, China, email:
dongjinguo1111@163.com (J. Dong). Tel: +86 13626278364; Fax: +86 513 85015880;

C.-C. Shen, HISPEC, Department of Geosciences, National Taiwan University, Taipei, Taiwan ROC
Email: **river@ntu.edu.tw (C.-C. Shen).** Tel: +886 2 33665878; Fax: +886 2 23636095.

Abstract:

A multidecadal-resolved stalagmite $\delta^{18}O$ record from two nearby caves, Lianhua and Dragon, in Shanxi Province, northern China, characterizes the detailed East Asian summer monsoon (EASM) intensity changes at 114.6-108.3 ka during Marine oxygen isotope stage (MIS) 5d. Our record shows an intensification of the EASM at 114.6-109.5 ka, subsequently followed by a rapid weakening at 109.5-108.4 ka. These millennial-scale strong/weak monsoonal events appear to be correlated to both warm Greenland Interstadial (GI) 25 and cold Greenland Stadial (GS) 25 events within respective dating errors. The GI 25 monsoonal event registered in our record is also documented in various published time series from different regions of China. The lines of evidence indicate that this event occurred over entire monsoonal China and was also broadly anti-phase similar with the corresponding event on millennial timescale in the South American monsoon territory. In our record, one 700-yr weak monsoon event at $110.7^{+0.6}/_{-0.5}$ to $110.0^{+0.8}/_{-0.4}$ ka divides the GI 25 into three substages. These multi-centennial-to-millennial scale monsoon events corresponds to two warm periods and an intervening cold interval for the intra-interstadial climate oscillations within GI 25, thus supporting a persistent coupling of the high-low latitude climate systems over the last glacial period.

Keywords: East Asian summer monsoon; North Atlantic; Stalagmite; Millennial-centennial scale event; Marine oxygen isotope stage 5d; Greenland interstadial 25; Greenland stadial 25

INTRODUCTION

The transition from the last interglacial to the last glacial period occurred between ~120 and 110 thousand years (ka, before 1950 AD) ago and was characterized by progressive ice sheet growth in response to the climatic amplification of astronomical forcing through the Earth′s internal feedback (Landais et al., 2006; Capron et al., 2010, 2012 and reference therein). At least one-quarter of ice sheet volume during full glacial conditions reached marine oxygen isotope stage (MIS) 5d. This transition is also associated with an abrupt millennial-scale warming event first identified in North Atlantic marine records (Chapman and Shackleton, 1999; Oppo et al., 2006) and named Dansgaard-Oeschger (DO) event 25 in NGRIP $\delta^{18}O$ record (NGRIP project members, 2004).

DO events are one of the classical features for the last glacial period (NGRIP project members, 2004). A DO event in Greenland is classically described as abrupt warming of 8-16 ºC within a few decades (Kindler et al., 2014, and references therein), leading to peak interstadial conditions, denoted as GI for Greenland Interstadial (GI), followed by a gradual cooling and finally ending in rapid return to the cold stadial state, called Greenland Stadial (GS). These abrupt climate changes have been recorded in numerous paleoclimatic archives worldwide (Porter and An, 1995; Chapman and Shackleton, 1999; Leuschner and Sirocko, 2000; Wang et al., 2001; Voelker, 2002; NGRIP project members, 2004; EPICA community member, 2006; Zhao et al., 2010; Baumgartner et al., 2014; Zhang et al., 2020) and persisted through the entire last glacial period.

As an abrupt climate event during the MIS 5d, GI 25 is very similar in pattern and transition to the ones observed during MIS 3 in Greenland ice core $\delta^{18}O$ record (NGRIP project members, 2004; Rasmussen et al., 2014). Such climate excursion is also clearly registered in cave records from southern Europe, providing the first direct, independent, and radiometrically derived estimates for the timing of GI 25 and GI 24 (Drysdale et al., 2007; Boch et al., 2011; Columbu et al., 2017; Moseley et al., 2020). A detailed comparison of the North-GRIP record with multiple indicators shows the GI 25 does not match hydroclimate changes at low-latitude zones (Capron et al., 2012). Such an equivocal fingerprint questions whether GI 25 is simply a rapid event. Interestingly, two high-resolution stalagmite $\delta^{18}O$ records from Sanbao Cave in central China and Bittoo Cave in northern India, respectively, provided unambiguous evidence of strengthened GI 25 monsoon event at MIS 5d, which concurred with the contemporaneous event in Greenland $\delta^{18}O$ record (Wang et al., 2008; Kathayat et al., 2016). But records from the caves of Suozi (Zhou et al., 2008) and Wanxiang (Johnson et al., 2006) in monsoonal China yet show no clear evidence for this abrupt event (Fig. 1). Thus, it is still in debate whether the decoupling between low- and high-latitude climate conditions occurred during the last glacial inception (Zhou et al., 2008; Wu et al., 2020).

Recently, significant and rapid cold-warm climate oscillations within DO events have been documented in Greenland ice cores, especially at the MIS 5 (Capron et al., 2010; Rasmussen et al., 2014). Such multi-centennial scale climate excursions were also reported in Alpine Cave records (Boch et al., 2011), southern Italian lacustrine sediments (Martin-Puertas et al., 2014), and Mediterranean Cave deposits (Columbu et al., 2017). For example, a high-resolution cave record from Sardinia firstly revealed a cool-dry to warm-wet oscillation independently associated with the first intra-GI/GS events GI-25a-b-c (Columbu et al., 2017). However, no proxy records with detailed structure for

DO 25 in the low-latitude Asian monsoon region were available. To fully understand the monsoonal climate variability on multi-centennial-to-millennial scales, high-resolution and absolute-dated cave records are required.

Here, we report a multi-decadal-resolved stalagmite $\delta^{18}O$ record from the Lianhua and Dragon Caves in northern China, near the eastern boundary of the Chinese Loess Plateau (CLP), where very limited well-dated proxy records are currently available. High resolution and more U-Th dates with uncertainties of ±100s yr allows us to reconstruct the East Asian summer monsoon (EASM) evolution on multi-centennial to millennial timescales during MIS 5d. Our new Lianhua-Dragon records show millennial-scale GI/GS 25 monsoon events occurring at 114.6-108.3 ka, substages of intra-interstadial oscillations of GI 25 monsoon event, and the linkage to low- and high-latitude hydroclimates at MIS 5d.

STUDY SITE

Two caves, Lianhua (38º10'N, 113º43'E, 1200 m a.s.l) and Dragon (36º46'N, 113º13'E, 1600 m a.s.l), 150 km apart in Shanxi Province, northern China, were selected for the present study (Fig. 1). Both caves had small entrances, 1 m in height and 2 m in width, and developed in the same carbonate bedrock, Ordovician limestone. Their narrow passages, 1-2 m in height, were 250 and 1000 m long, respectively. Relative humidity in the inner part, 170 m to the cave entrance, reaches 98-100% in both caves. The overlying soil layer on the limestone above the caves is thin, only 0-1 m, favorable to rapidly communicate with the external climate signal into the cave (Dong et al., 2015, 2018a). The EASM strongly influences this area and the hydroclimate is characterized by warm-wet summer and cool-dry winter. The region receives maximum precipitation (almost 75% of the annual rainfall) between June and September when summer monsoon prevails (Dong et al., 2015, 2018a, 2018b).

Local ground air temperature is 11.0 ºC, and annual precipitation is 515 mm (1970-2000 AD), recorded in a meteorological station, Yangquan, 20 km from Lianhua Cave. For the Dragon Cave, the local air temperature is 10.3 ºC, and the local annual precipitation is 530 mm (1970-2000 AD; meteorological station Wuxiang, 18 km from the cave).

SAMPLES AND METHODS

One stalagmite LH36, 206 mm in length and 80-110 mm in diameter, was collected in a chamber, 200 m from the entrance of Lianhua Cave. Another 126 mm-long stalagmite L4, 55-70 mm in diameter, was collected in the gallery, 600 m from the entrance of Dragon Cave. Both stalagmites were sectioned along the vertical growth axis using a water-cooled saw (Fig. 2). For LH36, alternating changes of the petrography are observed at 33-35 and 153-155 mm length intervals from the top (Fig. 2a), indicating possible growth discontinuities. The lower part from 155-206 mm is characterized with milky white layering. Stalagmite L4 is very clean and composed of transparent and compact calcite throughout the whole growing period. An only white clay belt is observed at 115 mm from the top, showing a possible hiatus (Fig. 2b).

Twenty-eight subsamples, 19 from LH36 and 9 from L4 (Fig. 2; Table 1), with a weight range from 100-200 mg, were drilled parallel to the growth plane for U-Th chemistry (Shen et al., 2003) and dating (Shen et al., 2002; 2012). U-Th isotopic measurement was performed on a multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS), Thermo Finnigan NEPTUNE, housed at the High-precision

Mass Spectrometry and Environment Change Laboratory (HISPEC), Department of Geosciences, National Taiwan University, and at the Nanjing Normal University Isotope Laboratory (Shen et al., 2012; Shao et al., 2019). A gravimetrically calibrated (Cheng et al., 2013) triple-spike, ^{229}Th-^{233}U-^{236}U, isotope dilution method was applied to correct the mass bias and determine the U-Th contents and isotopic compositions (Shen et al., 2012). Uncertainties in isotopic data and dates relative to 1950 AD, are given at the two-sigma (2σ) level or two standard deviations of the mean ($2\sigma_m$). Half-lives of nuclides used for age calculation is given in Cheng et al. (2013). StalAge algorithm techniques (Scholz and Hoffmann, 2011) were used to construct the age models.

For stable isotope analysis, carbonate subsamples were drilled out with a 0.3 mm-diameter carbide dental bur at 1-mm intervals for the upper segment of 30-153 mm and 0.5-mm intervals for the lower part of (153-206 mm) of the stalagmite LH36. Subsamples were retrieved at 1-mm intervals for the depth range of 0-116 mm for the stalagmite L4 (Fig. 2). Stable isotope analysis was carried out on 340 powdered samples, each weighing 20-40 μg using a Finnigan-MAT 253 mass spectrometer equipped with an automated Kiel Carbonate Device at the College of Geography Science, Nanjing Normal University. Carbonate $\delta^{18}O$ (‰) are expressed relative to the Vienna Pee Dee Belemnite (VPDB) reference standard. An international standard, NBS-19, was measured every 15-20 subsamples to confirm that a six-month 1-sigma external error was better than ±0.06‰ for $\delta^{18}O$.

RESULTS

Chronology

Determined U-Th isotopic compositions, contents, and ^{230}Th dates are listed in Table

1. Relatively low ^{238}U contents of 0.09-0.34 x 10^{-6} g/g and high ^{232}Th of 10^{-1}-10^{2} x 10^{-9} g/g on layers of LH36 result in age uncertainties of ±0.1-2.2 ka. Most (16/19) of the corrected ^{230}Th ages are in stratigraphic order. StalAge algorithm techniques (Scholz and Hoffmann, 2011) show that an age model from 34.6 ± 0.1 to 110.7 ± 0.9 ka with two growth hiatuses at depths of 33-35 and 153-155 mm from the top (Fig. 2), identified at 34.6-41.1 and 61.4-108.0 ka, respectively (Fig. 3).

For stalagmite L4, high ^{238}U levels are 1.0-2.4 x 10^{-6} g/g. For most layers (8/9), ^{232}Th contents are only 0.005-0.097 x 10^{-9} g/g to yield small errors of ±0.4-0.7 ka. The exceptional high ^{232}Th content of 5.93 x 10^{-9} g/g on the subsample L4-117 causes a large error of ±1.1 ka (Table 1). The determined ages for the top eight layers at a depth interval of 10-114 mm range 111.6-114.8 ka (Fig. 3c). At a depth of 117 mm from the top, the measured age of 197 ka, dramatically different from others, indicates a hiatus at a depth of 115 mm. The calculated deposition rates are 6 μm yr^{-1} for the upper section at 0-150 mm and 21 μm yr^{-1} for the lower section at 155-206 mm for the stalagmite LH36. The estimated deposition rate is 36 μm $yr^{-1}$for a depth interval of 0-114 mm for the stalagmite L4.

LH36/L4 oxygen isotope records

We have compared the $\delta^{18}O$ results obtained from the stalagmites investigated in the present study with the previously published Lianhua-Dragon stalagmite $\delta^{18}O$ records at 60-0 ka (Dong et al., 2015, 2018a; Zhang et al., 2021), as illustrated in Figure 4. This comparison also clearly shows an absence of significant offsets between $\delta^{18}O$ records at the overlapping growth intervals. We argue that the spliced $\delta^{18}O$ record at 115-108 ka (Fig. 5a) with two LH36 and L4 stalagmites in this study can unambiguously reflect changesin monsoonal intensity over GI 25 and GS 25.

The average temporal resolution of $\delta^{18}O$ data points of stalagmites LH36 and L4 plotted in Figure 5a is 27-37 years. The stalagmite $\delta^{18}O$ record, ranging from –7.5 to –10.1‰, is characterized with a decreasing trend from -7.5‰ at 114.6 ka to -9.4‰ at 111.4 ka, followed by a 0.7-kyr gap to 110.7 ka. The time window from 110.7 to 108.4 ka in the LH36 record is marked by two episodes of enrichment in terms of oxygen isotope ratios. The first one took place at 110.7-110.0 ka with an enrichment of 1.2‰ in ^{18}O while the second at 109.5-108.4 ka records 2.5‰ enrichment. An abrupt decrease of 2.6‰ in the $\delta^{18}O$ record at 108.4 ka marked the end of the GS 25.

DISCUSSION

The interpretation of stalagmite $\delta^{18}O$ records

An essential prerequisite for using stalagmite $\delta^{18}O$ to reconstruct paleoclimate change is that the stalagmite was precipitated under isotopic equilibrium conditions. Good between-cave reproducibility of contemporaneous $\delta^{18}O$ records at 115-108 ka for stalagmites LH36 of Lianhua Cave, L4 of Dragon Cave, and SB23 of Sanbao Cave, is also expressed in Figure 5a and 5c. Moreover, 7 stalagmite $\delta^{18}O$ records of Lianhua and Dragon Caves over the past 60 ka also show high similarities in terms of event, trend, and amplitude during overlapping growth intervals (Fig.4b). All lines of evidence indicate a solid replication test (Dorale and Liu, 2009) and a negligible kinetic effect on Lianhua-Dragon $\delta^{18}O$ records, which are primarily of climatic origin.

Modern instrumental observations (Zhang et al., 2004; Li et al., 2017; Wan et al., 2018), proxy records (Zhang et al., 2008; Orland et al., 2015; Tan et al., 2015; Dong et al., 2015, 2018a), and model simulations (Liu et al., 2014; Cheng et al., 2021) over the past two decades showed that Chinese stalagmite $\delta^{18}O$ variations, under isotopic equilibrium conditions, can generally reflect the change in monsoon intensity (Cheng et al., 2019; Zhang et al., 2021). The regional precipitation $\delta^{18}O$ signal, eventually recorded in speleothem, in the EASM region is governed by upstream and local moisture sources (Liu et al., 2014). Rainfall amounts in southern and central China may not completely reflect monsoonal intensity (Liu et al., 2015; Chen et al., 2015). Lianhua and Dragon Caves are located in the northwest frontier of the EASM in northern China, and the regional precipitation change is very sensitive to variation in monsoon intensity, demonstrated by instrumental data and simulated results (Liu et al., 2015). Under the strong EASM conditions, high rainfall with a negative $\delta^{18}O$ value is delivered to this region (Orland et al., 2015; Tan et al., 2015). The regional Holocene stalagmite $\delta^{18}O$ records from Caves of Lianhua (Dong et al., 2015, 2018b) and Zhenzhu (Yin et al., 2017) match a pollen-based rainfall reconstruction from Bayanchagan Lake in northern China (Jiang et al., 2006, Fig. 4a) and a local dry-wet index over the past 1000 years (CAMS, 1981), respectively. The $\delta^{18}O$ record of stalagmite L30 from Dragon Cave covaries with a quantitatively proxy inferred summer rainfall record in the western CLP during the last glacial period (Dong et al., 2018a, Fig. 4). The comparison in Figure 4 and the recent proxy, empirical, and modeling studies (Liu et al., 2014; Orland et al., 2015; Cheng et al., 2019, Zhang et al., 2021) support that the Lianhua-Dragon stalagmite $\delta^{18}O$ records can reflect monsoonal precipitation in northern China and register EASM intensity, with low value expressing a strong summer monsoon condition, and vice versa.

EASM and ISM during the GI 25 event

To better understand the regional nature of the millennial-scale climate event, GI 25, during the last glacial inception, we compared the Lianhua-Dragon record with absolute dated contemporaneous stalagmites records from other Chinese Caves, including Sanbao (Wang et al., 2008), Wanxiang (Johnson et al., 2006), Suozi (Zhou et al., 2008), Sanxing (Jiang et al., 2016), and Dongge (Yuan et al., 2004; Kelly et al., 2006), located in different climatic regions zones of the East Asian monsoon realm (Fig. 5). We also compared the Lianhua-Dragon $\delta^{18}O$ record to the continuous high-resolution stalagmite BT5 record from Bittoo Cave in northern India (Kathayat et al., 2016 and reference therein), where the local climate is influenced by the pure Indian summer monsoon (ISM)(Fig. 5g).

Lianhua-Dragon $\delta^{18}O$ record in northern China shows strong/weak EASM conditions at GI 25/GS 25 (Fig. 5a). High-resolution loess and desert sections in the Loess Plateau, nearby Lianhua-Dragon region, feature the same strong monsoon, characterized by a relatively high magnetic susceptibility and organic content at GI 25 (Du et al., 2012; Guan et al., 2007). Similar results can also be expressed in other stalagmite records, including Tianmen Cave in Tibetan Plateau, China（Cai et al., 2010） and Bittoo Cave in northern India (Fig. 5g, Kathayat et al., 2016 and reference therein). The evidence generally expresses an intensified Asian summer monsoon (ASM, including the EASM and ISM) circulation at GI 25, with more monsoon precipitation permeating the interior as far as the China-Mongolia border. Subsequently, the ASM intensity abruptly decreased during the transition to GS 25 (Fig. 5a, 5c, 5g), although it appears to be muted in Dongge record (Fig.5f).

In northwestern China, the 50 yr-resolution WX-52 $\delta^{18}O$ record with large dating uncertainty of ± 2-4 ka from Wanxiang Cave documents an ^{18}O-depleted peak of

0.5-1.0‰ (Johnson et al., 2006) (Fig. 5b). Both Sanbao $\delta^{18}O$ record of central China (Fig. 5c) and Sanxing $\delta^{18}O$ record of southwestern China (Jiang et al., 2016) (Fig. 5e) show an obvious ^{18}O-depleted peak of 1.0‰ after the cold GS 26 event. A continuously 60 yr-resolved stalagmite YYZ1 $\delta^{18}O$ record from Yangzi Cave in southwestern China captures the clear monsoon event with an ^{18}O depletion of 1.0‰ (Shi et al., 2021). All stalagmite records show that this relatively small GI 25 monsoon event occurred over the Asian monsoon realm. The amplitudes of GI 25 monsoon event recorded in Chinese stalagmite $\delta^{18}O$ records are 1.0-2.2‰ smaller than ones of subsequent rapid interstadial events (Wang et al., 2008; Jiang et al., 2016). Different from 1‰ depletion in Sanbao record of central China (Fig. 5c), the obscure peak in stalagmite SZ2 $\delta^{18}O$ record of Suozi Cave from the same district (Zhou et al., 2008) (Fig. 5d) could be attributed to the different regional responses of this small strong monsoon event in the Asian monsoon realm. Or the muted signal in Suozi Cave could be related to the complicated karst aquifer system.

Lianhua-Dragon record (Fig. 5a) in northern China expresses an enrichment of 2‰ in ^{18}O at GS 25, 1‰ higher than that in Sanbao record (Fig. 5c) in central China, 1.5-2‰ higher than those of Yangzi (Shi et al., 2021) and Dongge records (Fig. 5f) in southwestern China (Fig. 5). In northern India, stalagmite BT5 $\delta^{18}O$ record of Bittoo Cave shows an ^{18}O enrichment of 1.8‰ at GS 25 (Fig. 5g). The different ^{18}O enrichment among stalagmite records (Fig. 5) revealed the heterogeneity of the weak regional monsoon conditions, and the fringe regions were more severe than other regions. The difference in hydroclimatic changes may partly account for the phenomenon of the muted GS 25 monsoonal events as recorded in the southern Chinese stalagmites (Kelly et al., 2006; Wu et al., 2020).

Comparison with the Greenland ice core $\delta^{18}O$ record

High northern latitudes witnessed significant millennial-scale fluctuations in temperature during MIS 5d (114.6-108.3 ka), characterized with a warm interstadial (GI 25) and two cold stadials (GS 25 and 26) in the NGRIP ice core (Fig. 6b, NGRIP Project members, 2004). Those events were also clearly registered in the precise-dated stalagmite $\delta^{18}O$ records from Corchia (Drysdale et al., 2007) and Alps Caves in South Europe (Fig. 6c). Similar millennial-scale climate abrupt events occurred along the ancient Silk Road at the beginning of the last glacial. For example, after the end of the cold GS 26 event, the Greenland air temperature rapidly increased by 5 ℃ in less than 100 years at 115.3±2.5 ka and maintained warm stage until the next cold stage of GS 25 (Kindler et al., 2014). Stalagmite L4 of Dragon Cave began to deposit at 114.8±0.4 ka after a hiatus, and its $\delta^{18}O$ values show a decreasing trend, suggesting an increasing EASM over the whole GI 25 event, confirmed by Sanbao record (Fig. 5c, Wang et al., 2008). Moreover, a rapid transition into the cold GS 25 as recorded by the Lianhua-Dragon record at 109.5 ka concurred with the European counterpart in NALPS stalagmites at 110.3 ka (Boch et al., 2011; Moseley et al., 2020) and NGRIP ice core record at 110.6 ka within age errors (Fig. 6).

One prominent multi-centennial-scale abrupt isotopic anomaly, with an amplitude of 1.2‰ that lasted for 700 years from 110.7 $^{+0.6}/_{-0.5}$ to 110.0 $^{+0.8}/_{-0.4}$ ka, was first distinguished in the Lianhua-Dragon record during the GI 25 (Fig.7c). This weak-monsoon anomaly separates this event with two more strong-monsoon substages, 3.8-ka 25c lasting from 114.6$^{+0.4}/_{-0.3}$ to 110.8 $^{+0.7}/_{-0.5}$ ka and 500-yr 25a from 109.9 $^{+0.7}/_{-0.4}$

to 109.4 $^{+0.5}/_{-0.5}$ ka. The multi-centennial-to-millennial variations displayed in Lianhua-Dragon record are more evident than the stalagmite $\delta^{18}O$ records from central and southwestern China (Fig. 5c-f). We speculate that this difference could be attributable to our study site being closer to the north-boundary of the EASM and more sensitive than other regions (Dong et al., 2015). The high-resolution $\delta^{18}O$ record from Bittoo Cave in northern India, located at the edge of the Indian summer monsoon, also clearly expresses the similar short-lived climate events during GI 25 (Fig. 5g and Fig. 7d).

A detailed comparison with other high-resolution sequences along the south-north longitude transect in North Hemisphere over GI 25 is given in Figure 7. These intra-GI 25 strong/weak monsoon events in Figure 7c-d show a striking similarity to the corresponding two warm periods and an intervening cold interval in the NGRIP ice core $\delta^{18}O$ record (Fig. 7a). For example, a distinct weakening monsoon event lasting from 110.7 $^{+0.6}/_{-0.5}$ to 110.0 $^{+0.8}/_{-0.4}$ ka in the Lianhua-Dragon record (Fig. 7c) is linked to the 500-yr cold-dry excursion of GI-25b from 111.4 to 110.9 ka in the Greenland ice core record (Fig. 7a). A short-lived aridity event occurred at 111.4-112.4 ka in northern India revealed in the Bittoo stalagmite BT5 $\delta^{18}O$ record (Fig. 7d, Kathayat et al., 2016), matches its counterparts in NALPS stalagmite and Greenland ice core records within dating errors (Fig. 7).

The GI 25a marks the earliest glacial “rebound-type event”, depicted as a short-lived warm reversal during the gradual cooling limb of a large GI 25 event in NGRIP record (Fig. 7a) (Capron et al., 2010, 2012). A similar feature is also documented in the European stalagmite records, expressed as a temperature increase in Figure 7b. In the

Asian monsoon region, records of Lianhua-Dragon of northern China and Bittoo of north India (Fig. 7c, d) show an abrupt concurrent persistent monsoonal condition during the GI 25a. The duration of 400 years for this warm GI 25a in NGRIP $\delta^{18}O$ and CH_4 records (Capron et al., 2012; Rasmussen et al., 2014) matches its counterpart in the ASM region, 500 yr in Lianhua and 400 yr Bittoo records (Fig. 7). This concurrency indicates a strong teleconnection between the ASM and temperature change in the North Atlantic on centennial-millennial timescales during MIS 5d.

Interhemispheric comparison

A regional isolation-governed interhemispheric anti-phasing monsoonal pattern on millennial-to-orbital scales during the last glacial period was proposed by Wang et al. (2007) by comparing stalagmite $\delta^{18}O$ records in Brazil and eastern China from 0-90 ka. Here we have further evaluated this relationship by using northern Chinese stalagmite $\delta^{18}O$ records. Changes in Lianhua-Dragon $\delta^{18}O$ records, concurrent with the Sanbao record, are opposite to that in the Botuverá Cave record from southern Brazil (Cruz et al., 2005) on a millennial scale. During the MIS 5d, the South American summer monsoon (SAM) became very weak at warm GI 25 and enhanced at the cold GS 25 (Fig. 6h). Although age uncertainties of stalagmite chronologies hinder a detailed comparison, an interhemispheric anti-phasing similarity is even sound for hydroclimatic changes in northern China. These observations support the bi-polar seesaw hypothesis that explains the time relationship between DO and Antarctic isotope maxima (AIM) events (Broecker, 1998; Barker et al., 2009).

Atlantic meridional overturning circulation (AMOC) have been proposed as the linkage of millennial-scale hydroclimate between the ASM and high-latitude North

Hemisphere (Wang et al., 2001; Caballero-Gill et al., 2012; Deplazes G et al., 2013; Dong et al., 2018a). The AMOC affects the oceanic transport of heat from low latitude to North Atlantic. In turn, it is strongly influenced by the extensive amounts of ice-melting entering the North Atlantic, which attenuates the density-driven thermohaline circulation and leads to climate changes worldwide (Hemming, 2004). Such a mechanism was confirmed by a simulation that coupled the AMOC and ASM (Sun et al., 2012). Results of ODP 1063 suggested that AMOC was relatively unstable on the millennial scale during the last glacial period (Böhm et al., 2015). Two prominent weak EASM anomalies in Lianhua-Dragon and Sanbao $\delta^{18}O$ records correlate well with the North Atlantic ice-rafted detritus (IRD) events C 24 and C 25 (Fig. 6a)(Chapman and Shackleton, 1999 and reference therein) and their counterparts in the NGRIP record (Fig. 6b). The good alignments support the previous hypothesis that the millennial-scale abrupt climate changes in the North Atlantic region may influence the Asian monsoonal climate by the reorganization of large-scale atmospheric circulation patterns (Porter and An, 1995; An and Porter, 1997; Wang et al., 2001). Changes in large-scale atmospheric circulations are linked to the displacement of the intertropical convergence zone (ITCZ), providing a potential association between the observed millennial-scale co-variations in low and high latitudes (Wang et al., 2001; Fleitmann et al., 2007; Wang, X et al., 2007, Zhao et al., 2010).

CONCLUSIONS

Based on 28 precise ^{230}Th dates, we provide a multi-decadal-resolved stalagmite $\delta^{18}O$ record from 114.6 to 108.3 ka from two nearby Lianhua and Dragon Caves in Shanxi Province, northern China. The $\delta^{18}O$ records feature a strengthened monsoon interval associated with the corresponding GI 25 event and two weak monsoon events linked to cold episodes in Greenland and ice-rafting events in the North Atlantic, respectively. On the millennial timescale, our results are broadly consistent with previously published Chinese and Indian stalagmite $\delta^{18}O$ records, but opposite to the stalagmite $\delta^{18}O$ record in southern Brazil. Lianhua-Dragon record captures prominent multi-centennial-to-millennial monsoon events, corresponding to the substages of intra-interstadial climate oscillations in GI 25. Our study shows the strong hydroclimate links between ASM and North Hemisphere high latitudes during MIS 5d.

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FIGURE CAPTIONS

Fig.1. A world map with summer (June-July-August) means 850-hPa vector wind based on NCEP/NCAR Reanalysis (1960-2020). The red triangles represent the Lianhau (LH), and Dragon Caves (LD) (this study), black triangles represent the Sanbao (SB, Wang et al., 2008), Wanxiang (WX, Johnson et al., 2006), Suozi (SZ, Zhou et al., 2008), Dongge (DG, Yuan et al., 2004; Kelly et al., 2006), Sanxing (SX, Jiang et al., 2016). Bittoo (BT, Kathayat et al., 2016) Caves in southeastern Asian monsoon region, and Schneckthe loch (SL, Moseley et al., 2020), Grete-Ruth shaft (GR et al., Boch et al., 2011), Antrodrl-Corchia (AC, Drysdale et al., 2007) and Bue Marino (BM, Columbu et al., 2017) Caves in southern Europe nearby the Mediterranean Sea and Caverna Botuverá Cave (CB, Cruz et al., 2005) in Brazil, southern America, respectively. Black dot and square represent the International Ocean Discovery Program sediment cores (ODP) 985 (Oppo et al., 2006) and North Greenland Ice Core Project, respectively (NGRIP, NGRIP members, 2004). The Asian summer monsoon is a steady flow of warm, moist air from the tropical oceans, while the winter monsoon is a flow of cold, dry air associated with the Siberian–Mongolian High.

Fig. 2. Photographs of stalagmite samples (**a**) LH36 of Lianhua Cave and (**b**) L4 of Dragon Cave. Horizontal layers denote the subsamples were drilled for U-Th dating. Black dashed lines represent the depositional hiatuses. Orange vertical dashed lines show the paths for carbon and oxygen isotopic measurement.

Fig. 3. Plots of the age models constructed with the StalAge algorithm (Scholz and Hoffmann, 2011) for two stalagmites of LH36 and L4, respectively. Age models for (a) the top 153 mm and (b) 153-206 mm of LH 36 and (c) L4. Black dots denote ^{230}Th dates and horizontal bars are their 2-sigma errors. Green and red dashed lines are the age models with 95% confidence intervals.

Fig. 4. Comparison between the Lianhua-Dragon stalagmite δ^{18}O and quantitatively reconstructed monsoon rainfall records. (**a**) Pollen-inferred annual precipitation in Bayanchagan Lake, Inner Mongolia, northern China (Jiang et al., 2006). (**b**) Lianhua-Dragon δ^{18}O records (Dong et al., 2015, 2018a; Zhang et al., 2021). Numbers denote DO events. (**c**) Quantitative reconstruction of summer rainfall in western CLP, northern China (Rao et al., 2013). Yellow bars represent weakened EASM periods at Heinrich (H) events and Younger Dryas (YD).

Fig. 5. Stalagmite δ^{18}O records from China and northern India. Stalagmite δ^{18}O records are from Caves of (**a**) Lianhua-Dragon (this study) and (**b**)Wanxiang (Johnson et al., 2006) in

northern China, (**c**) Sanbao and (**d**) Suozi in central China (Wang et al., 2008; Zhou et al., 2008), and (**e**) Sanxing and (**f**) Dongge in southwestern China (Jiang et al., 2016; Kelly et al., 2006). (**g**) Bittoo in northern India (Kathayat et al., 2016). Yellow/gray bars denote increased/decreased ASM periods during the GI/GS 25 event. The values denote the relative-amplitude changes in δ^{18}O during the GS 25 event. ^{230}Th ages and errors are color-coded by stalagmite.

Fig. 6. Comparison of stalagmites δ^{18}O time series with the Greenland Ice core and marine records during MIS 5d. (**a**) Lithic abundance record of core ODP 980 to infer IRD event (Chapman and Shackleton, 1999). (**b**) δ^{18}O record of NGRIP ice core based on GICC05modelext timescale (NGRIP Project members, 2004; Wolff et al., 2010). (**c**) NALPS-19 stalagmite δ^{18}O records from Austria (Boch et al., 2011; Moseley et al., 2020), respectively. Chinese stalagmite δ^{18}O records from Caves of (**d**) Lianhua-Dragon in northern China (this study), (**e**) Sanbao in central China (Wang et al., 2008), (**f**) and Donggge in southern China (Kelly et al., 2006). Stalagmite δ^{18}O records of (**g**) Bittoo Cave in northern India (Kathayat et al., 2016) and (**h**) Botuverá Cave in southern Brazil (Cruz et al., 2005). All records are given with their chronologies with an exception of the marine ODP980 record with a shift of +2.5 ka. GI 25 represents Greenland Interstadial 25 and GS 25 and 26 are Greenland Sstadials 25 to 26 (NGRIP members, 2004), corresponding to marine events C 24 and C 25, respectively (Oppo et al., 2006; Chapman and Shackleton, 1999). Two vertical gray bars indicate two weak ASM events (Wang et al., 2008), associated with GS 25 and 26. ^{230}Th ages with 2-sigma uncertainties are color-coded by stalagmite. The hatched rectangle in Lianhua-Dragon records indicates an 82.2 ka hiatus before the onset of GI 25.

Fig.7. A detailed comparison of the centennial-scale ASM variability with the high-latitude North Atlantic temperature change during the GI 25 event. (**a**) NGRIP ice δ^{18}O record with three substages of a, b, and c, on GICC05 modelext timescale (NGRIP Project members, 2004; Wolff et al., 2010). (**b**) NALPS-19 stalagmite δ^{18}O record from Austria (Boch et al., 2011; Moseley et al., 2020). (**c**) Lianhua-Dragon stalagmite δ^{18}O record from northern China. (**d**) Bittoo BT 5 stalagmite δ^{18}O record from northern India (Kathayat et al., 2016). Gray vertical bar denotes the substage GI 25b.