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Authors

Liu, JingHua
Zhang, PingZhong
Cheng, Hai
et al.

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Asian summer monsoon precipitation recorded by stalagmite oxygen isotopic composition in the western Loess Plateau during AD1875–2003 and its linkage with ocean-atmosphere system

LIU JingHua¹, ZHANG PingZhong^{1†}, CHENG Hai², CHEN FaHu¹, YANG XunLin^{1,3}, ZHANG DeZhong¹, ZHOU Jing¹, JIA JiHong¹, AN ChunLei¹, SANG WenCui¹ & Kathleen R. JOHNSON⁴

¹ Key Laboratory of Western China's Environmental System of Ministry of Education, College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China;

² Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, USA;

³ School of Geographical Sciences, Southwest University, Chongqing 400715, China;

⁴ Department of Earth System Science, University of California, Irvine, CA 92697, USA

Based on 5 high-precision ^{230}Th dates and 103 stable oxygen isotope ratios ($\delta^{18}\text{O}$) obtained from the top 16 mm of a stalagmite collected from Wanxiang Cave, Wudu, Gansu, variation of monsoonal precipitation in the modern Asian Monsoon (AM) marginal zone over the past 100 years was reconstructed. Comparison of the speleothem $\delta^{18}\text{O}$ record with instrumental precipitation data at Wudu in the past 50 years indicates a high parallelism between the two curves, suggesting that the speleothem $\delta^{18}\text{O}$ is a good proxy for the AM strength and associated precipitation, controlled by “amount effect” of the precipitation. Variation of the monsoonal precipitation during the past 100 years can be divided into three stages, increasing from AD 1875 to 1900, then decreasing from AD 1901 to 1946, and increasing again thereafter. This variation is quite similar to that of the Drought/Flooding index archived from Chinese historical documents. This speleothem-derived AM record shows a close association with the Pacific Decadal Oscillation (PDO) between AD 1875 and 1977, with higher monsoonal precipitation corresponding to cold PDO phase and vice versa at decadal timescale. The monsoonal precipitation variation is out of phase with the PDO after AD 1977, probably resulting from the decadal climate jump in the north Pacific occurring at around AD 1976/77. These results demonstrate a strong linkage between the AM and associated precipitation and the Pacific Ocean via ocean/atmosphere interaction. This relationship will aid to forecast future hydrological cycle for the AM monsoon region, and to improve forecasting potential of climatic model with observation data from cave.

stalagmite from Wanxiang Cave, oxygen isotope, monsoonal strength and precipitation, western Loess Plateau, Asian summer monsoon

The Asian Monsoon (AM) is an important part of global climate system and significantly influences the climate of the AM region via an interaction among the ocean-land-atmosphere systems. Previous studies^[1–4] have shown that the variation of ocean-atmosphere systems in the Pacific and Indian oceans at interdecadal and inter-annual timescales could lead to changes in the AM cir-

culation and associated precipitation at the same time-scales. For example, Krishnan and Sugi^[1] found that

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[†]Corresponding author (email: pzzhang@lzu.edu.cn)

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there was a coherent negative correlation between interdecadal Pacific sea surface temperatures (SST) and the Indian monsoon rainfall during the last century. The warm phase of the Pacific Decadal Oscillation (PDO) corresponded with decreasing monsoonal precipitation and rising surface temperatures on the Indian subcontinent, while vice versa for the cool phase of the PDO. Precipitation associated with the AM circulation plays an important role in human liveliness and agricultural development for 60% of the world's population^[5]. Therefore, additional research examining how AM precipitation varies on interannual to interdecadal timescales will contribute to a better understanding of how dramatic climatic fluctuations driven by anthropogenic greenhouse gases and aerosol will impact monsoonal precipitation. Currently instrumental data sets from most of China's monsoonal regions are too short (less than 60 years) to better understand and explore any temporal trends in monsoonal precipitation. Therefore in order to test current climate models it is necessary to develop precisely dated high-resolution proxies for monsoonal precipitation. Cave stalagmites have been widely used to study the AM because they are high sensitivity to climatic variation and can be precisely dated with U-series method^[6–14]. Many significant results have been obtained on the variation and strength of AM^[7–11,13,14] and the relationship between the AM and solar insolation on glacial/interglacial, millennial and centennial timescales using stalagmites^[7–9,11,13–16]. In particular, it was recently found that the stalagmite oxygen isotopic composition ($\delta^{18}\text{O}$) of stalagmite calcite could record interannual variation of the AM^[17] and some historical severe famine events in tropics and subtropics^[18] that corresponded to a weakening of the AM. Moreover, that the monsoonal precipitation was strongly linked to ocean-atmosphere systems in the Pacific Ocean and the North Atlantic Ocean, e.g., PDO, El Niño/Southern Oscillation (ENSO)^[15] and North Atlantic Oscillation^[19].

Here we reported the $\delta^{18}\text{O}$ record for the past 100 years reconstructed from the top part of a precisely dated stalagmite, WX42B, collected from Wanxiang Cave, Wudu, which is located in the transition zone between the Qinghai-Tibetan Plateau and Loess Plateau (western Loess Plateau). We compare this $\delta^{18}\text{O}$ record with the instrumental precipitation data from the second half of 20th century and Chinese historical documents from the past 100 years, in order to investigate interdecadal varia-

tions in monsoonal precipitation over the past 100 years and its linkage with ocean-atmosphere systems such as PDO.

1 Sampling and experimental

1.1 Cave site and subsampling

Stalagmite WX42B was collected from Wanxiang Cave (33°19'N, 105°00'E, 1200 m a.s.l.), located in the Wudu county, Gansu province of China, and situated in a low altitude of the transition zone between the eastern Qinghai-Tibetan Plateau and the western Loess Plateau. This site is near the northern limit of the modern AM and thus is very sensitive to the advance and retreat of the AM and is an important climatic geophysical site. The cave is capped with 30–250 m of Carboniferous limestone, which is overlain with ~10 m of Loess sediments. The surface soils support local natural vegetation that is composed mainly of C_3 forest-shrub plant, characteristic of warm-temperate zone. Inside the cave, water percolation from the surface has generated a great amount of modern carbonate stalagmite deposits^[11,20,21].

The WX42B is 116 mm in length and compactly crystallized calcite with white and some light gray stripes, without recrystallization. Field investigations showed that there was plenty of dripwater originating from the cave ceiling and water membrane on its top. Combined with ^{230}Th dating, it was confirmed that the stalagmite was active when it was collected in 2003. The WX42B stalagmite was halved lengthwise and subsamples were collected along the growth axis for O-C isotope analysis by scraping surface using a knife. To avoid cross-overlapping of subsamples, alternative subsamples were selected for analysis^[17]. Four layers with clear growth lamina were selected to do the Hندی test. Subsamples for ^{230}Th -dating were collected from five layers, 0.6–0.8 mm in thickness, using a 0.3 mm medical dental drill. Collection of these subsamples were performed in the Ultra-clean Laboratory of the Department of Geology and Geophysics, University of Minnesota.

1.2 Analytical methods

Carbon dioxide for isotopic analysis was produced with the McCrea's phosphoric acid method^[22], i.e., calcite powder reacts with 100% phosphoric acid in a pretreatment system and the released carbon dioxide is analyzed using a Finnigan-Delta-Plus mass spectrometer housed in the Key Laboratory of Western China's Environ-

mental Systems, Ministry of Education, Lanzhou University. Oxygen data are reported in δ notation relative to the VPDB, where $\delta^{18}\text{O} = [({}^{18}\text{O}/{}^{16}\text{O}_{\text{sample}}/{}^{18}\text{O}/{}^{16}\text{O}_{\text{std}}) - 1] \times 1000$. The error for each analysis is $< \pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ based on NBS-19. ${}^{230}\text{Th}$ dating was conducted at the Isotopic Geochronology Laboratory in the Department of Geology and Geophysics, University of Minnesota, USA. The ${}^{230}\text{Th}$ dating procedures and methods were described in refs. [23, 24], and the 2σ errors are reported in Table 1.

2 Results and discussion

2.1 Age model for the WX42B

Five ${}^{230}\text{Th}$ dates for the top 16 mm of the WX42B (Table 1) showed that the stalagmite was deposited between AD 1875 and 2003. The average growth rates between dated points are 0.08 mm/a (0–1 mm), 0.15 mm/a (1–4 mm), 0.15 mm/a (4–8.1 mm), 0.11 mm/a (8.1–13.2 mm) and 0.10 mm/a (13.2–16 mm), respectively (Figure 1). It is obvious that the growth rate of the WX42B is relatively constant especially for the 1–13.2 mm section, and the average growth rate of 0.12 mm/a is relatively high. The WX42B has a very high uranium concentration with ${}^{238}\text{U}$ content ranging from 7454.3 to 10847.7×10^{-9} and averaging $\sim 9162.0 \times 10^{-9}$, and a low detrital thorium (${}^{232}\text{Th}$ content is between $(264\text{--}2235) \times 10^{-12}$ and averages $\sim 867.4 \times 10^{-12}$). Therefore, extremely high-precision ${}^{230}\text{Th}$ dates were obtained with average dating error (2σ) less than 1 year (Table 1). The age model for WX42B was established by linearly interpolation between dated points (Figure 1).

2.2 Modern cave carbonate-water isotopic system and the Hendy test

The prerequisite for the paleoclimatic application of speleothem $\delta^{18}\text{O}$ is that speleothem calcite is deposited under isotopic equilibrium. The equilibrium condition

requires that (1) Modern cave dripwater displays a $\delta^{18}\text{O}$ value consistent with that of modern meteoric precipitation and (2) the speleothem calcite was precipitated in isotopic equilibrium with cave dripwater and there is no secondary alternation of speleothem carbonate. Previous studies have suggested that the Wanxiang cave dripwater and its $\delta^{18}\text{O}$ is controlled by local meteoric precipitation and the speleothem carbonate was formed in isotopic equilibrium with the dripwater [11,20]. The WX42B is compactly crystallized and shows no sign of secondary alternation. In this study, four layers (A–D) at different distance from the top of the WX42B were selected and along each layer six subsamples were obtained to do the Hendy test [25]. Dense arc-like laminas are present in WX42B and the bands are blurry, so accurate subsampling may not be done strictly within individual layer. The variation of $\delta^{18}\text{O}$ values of C layer is larger (about 0.3‰) than those of the other three layers (almost no more than 0.2‰). The result shows that $\delta^{18}\text{O}$ values in each layer are basically consistent (Figure 2(a)) and there is no positive correlation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in a single growth layer (Figure 2b). Figure 3 compares the $\delta^{18}\text{O}$ data of the WX42B measured by

Figure 1 The age model for the top part of the WX42B (The vertical bars indicate the 2σ errors).

Table 1 Results of ${}^{230}\text{Th}$ dating for WX42B^{a)}

Sample number	Depth (mm)	${}^{238}\text{U}$ ($\times 10^{-9}$)	${}^{232}\text{Th}$ ($\times 10^{-12}$)	${}^{230}\text{Th}/{}^{232}\text{Th}$ (atomic 10^{-6})	$\delta^{234}\text{U}^*$ (measured)	${}^{230}\text{Th}/{}^{238}\text{U}$ (activity)	${}^{230}\text{Th}$ age (a) (uncorrected)	${}^{230}\text{Th}$ age (a) (corrected)
WX42B-2-2	1	9034.4 ± 1.2	990 ± 21	56 ± 2	1927.2 ± 0.9	0.000370 ± 0.000006	13.8 ± 0.2	12.7 ± 0.6
WX42B-1	4	10847.7 ± 1.4	503 ± 21	317 ± 14	1884.4 ± 0.6	0.000891 ± 0.000009	33.7 ± 0.3	33.3 ± 1.0
WX42B-2-3	8.1	9955.3 ± 1.1	2235 ± 29	121 ± 2	1878.9 ± 0.7	0.001648 ± 0.000010	62.5 ± 0.4	60.2 ± 1.2
WX42B-2	13.2	8518.2 ± 1.1	345 ± 19	1135 ± 64	1846.4 ± 0.8	0.002782 ± 0.000012	106.7 ± 0.5	106.3 ± 0.5
WX42B-2-4	16	7454.3 ± 0.7	264 ± 17	1640 ± 105	1833.4 ± 0.7	0.003523 ± 0.000016	135.8 ± 0.6	135.5 ± 0.6

a) $\lambda_{230} = 9.1577 \times 10^{-6} \text{ a}^{-1}$, $\lambda_{234} = 2.8263 \times 10^{-6} \text{ a}^{-1}$, $\lambda_{238} = 1.55125 \times 10^{-10} \text{ a}^{-1}$; $\delta^{234}\text{U} = ([{}^{234}\text{U}/{}^{238}\text{U}]_{\text{activity}} - 1) \times 1000$, ${}^{234}\text{U}_{\text{initial}} = {}^{234}\text{U}_{\text{measured}} \times e^{234 \times T}$; corrected ${}^{230}\text{Th}$ ages assume that the initial ${}^{230}\text{Th}/{}^{232}\text{Th}$ atomic ratio is $(4.4 \pm 2.2) \times 10^{-6}$.

Finnigan Delta Plus MS and fifty-nine data measured by Kiel IV-MAT 253 MS. The high coherence suggests accurate measurements of the $\delta^{18}\text{O}$ ratio by the two methods (Figure 3). Results of the Hendy test (Figure 2) suggest an equilibrium deposition of carbonates in the WX42B. The $\delta^{18}\text{O}$ of the WX42B depend mainly on cave temperature and the $\delta^{18}\text{O}$ of meteoric precipitation^[25,26], and thus is appropriate for reconstruction of paleoclimate.

2.3 Comparison of the WX42B $\delta^{18}\text{O}$ record with instrumental precipitation data

Stalagmite $\delta^{18}\text{O}$ records from the AM region mainly reflect the variations of $\delta^{18}\text{O}$ values of monsoonal precipitation on glacial-interglacial, millennial to centennial timescales^[7-9,11,13,14,27]. Some recent studies^[12,17,28,29] suggested that there is an apparent negative correlation between stalagmite $\delta^{18}\text{O}$ values and rainfall amount on shorter timescale, i.e., mainly influenced by “rainfall amount” effect. Johnson and Ingram’s investigation^[30] showed a large spatial and temporal variability in the stable isotope systematics of modern precipitation in China, and the degree of the $\delta^{18}\text{O}$ variation influenced by rainfall amount was gradually reduced and that by temperature was gradually increased from monsoonal to non-monsoonal region. The modern stalagmite $\delta^{18}\text{O}$ of Wanxiang Cave, a site close to the northern limit of

modern summer monsoon, is possibly influenced both by meteoric precipitation $\delta^{18}\text{O}$ and temperature. Johnson and Ingram’s investigation^[30] suggested further that stalagmite $\delta^{18}\text{O}$ values from Wanxiang Cave mainly inherit the characteristics of local meteoric precipitation. The temperature dependent calcite-water fractionation of $\delta^{18}\text{O}$ is negative ($-0.23\text{‰}/^{\circ}\text{C}$)^[31] and cancel the temperature effect of rainfall $\delta^{18}\text{O}$ ($0.24\text{‰}/^{\circ}\text{C}$)^[32]. In order to further ascertain the climatic and environmental implications of the $\delta^{18}\text{O}$ record from Wanxiang Cave and its relationship with the AM on shorter timescale, it is necessary to compare the WX42B $\delta^{18}\text{O}$ record over the past 50 years with the instrumental data between 1951 AD and 2003 AD from the meteorological station at Wudu. The WX42B $\delta^{18}\text{O}$ record (the $\delta^{18}\text{O}$ values ranging from -8.6‰ to -7.9‰ , in amplitude of 0.7‰) correlates negatively with precipitation amount (the correlation coefficient is -0.30 , significant at the 95 % confidence level, Figure 4(a)). Moreover, in order to eliminate the year to year deviation between ^{230}Th dates and instrumental dates during the recent 50 years, a five-year running smoothing was conducted on both the $\delta^{18}\text{O}$ data and instrumental data and a much higher correlation (the correlation coefficient is -0.64 , significant at the 99% confidence level, Figure 4(b)) was found between the two records. These show that the WX42B $\delta^{18}\text{O}$ record is

Figure 2 Results of the Hendy tests carried out on the WX42B. (a) $\delta^{18}\text{O}$ values change of different layers, the distance from the top to layers A, B, C and D are 22 mm, 35 mm, 48 mm and 70 mm respectively; (b) relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ for layers A, B, C and D.

Figure 3 Comparison of the $\delta^{18}\text{O}$ data of the WX42B measured by Finnigan Delta Plus MS and Kiel IV-MAT253 MS, respectively. Analyzing standard is NBS-19 and the error of each analyze is $\pm 0.06\text{‰}$ for $\delta^{18}\text{O}$.

significantly affected by the amount of precipitation conveyed through the AM, and therefore can be used to indicate the variation of the AM and associated precipitation in shorter timescale.

Global investigation^[33–36] suggested that stable isotope of precipitation shows a significant “amount effect” in monsoonal region at middle and low latitudes, i.e., stable isotope ratio of precipitation correlated negatively with rainfall amount. The $\delta^{18}\text{O}$ value of precipitation in the most parts of China influenced by the AM circulation is lower in summer than in spring^[37]. In Wanxiang

Cave site, the $\delta^{18}\text{O}_w$ values of cave dripwater, collected in different seasons from 1999 to 2002, range from -9.6‰ to -8.7‰ (VSMOW) with the mean value of -9.1‰ (VSMOW) in the summer, relatively enriched in ^{16}O , and from -9.4‰ to -8.0‰ (VSMOW) with the mean dripwater $\delta^{18}\text{O}_w$ of -8.8‰ (VSMOW) in the spring, relatively enriched in ^{18}O . These indicate that modern precipitation in Wanxiang Cave site derives still from the monsoonal circulation. The stable isotope studies on meteoric precipitation in high-elevation section of the western Qilian Mountain in 2002 also presented that shifts in precipitation $\delta^{18}\text{O}$ are influenced by rainfall amount originated from the monsoonal circulation rather than by temperature^[38].

2.5 Comparison between the WX42B $\delta^{18}\text{O}$ record and Chinese historical documents from AD 1875 to AD 2003

The $\delta^{18}\text{O}$ values of the WX42B range from -8.6‰ to -7.8‰ with a mean value of -8.2‰ , and amplitude of 0.8‰ over the past 100 years (Figure 5(a)). This record can be divided into three stages: (i) AD 1875–1900, the $\delta^{18}\text{O}$ values are lower than average, indicating a stronger AM period and an enhanced monsoonal precipitation; (ii) AD 1901–1946, increased $\delta^{18}\text{O}$ values reflect weakening of the AM and reduced monsoonal precipita-

Figure 4 Comparison of the WX42B $\delta^{18}\text{O}$ values with the instrumental precipitation data from Wudu Meteorological Station from AD1951 to 2003. (a) Precipitation data (black square) and the WX42B $\delta^{18}\text{O}$ record (triangle); (b) 5-year running mean of the precipitation data (black square) and the WX42B $\delta^{18}\text{O}$ record (triangle).

Figure 5 Comparison of the variation of monsoonal precipitation over the past 100 years recorded by the WX42B $\delta^{18}\text{O}$ with the drought/flooding index. (a) The WX42B $\delta^{18}\text{O}$ record; (b) Drought/Flooding index (1, flood; 2, sub-flood; 3, normal; 4, sub-drought; 5, drought). Horizontal line indicates the mean values of the $\delta^{18}\text{O}$ and the Drought/Flooding index in (a) and (b), two dot lines indicate 5-year running mean of the WX42B $\delta^{18}\text{O}$ values and Drought/Flooding index in (a) and (b), respectively.

tion; (iii) AD 1947–2003, the $\delta^{18}\text{O}$ values decreased, suggesting a recovery of the AM and associated precipitation but a less extent than in the first stage.

During weakening periods of the AM, the monsoonal precipitation decreases and serious famine will occur. On the contrary, floods will appear during periods of stronger summer monsoon anomaly^[5]. Therefore, the comparing the WX42B $\delta^{18}\text{O}$ record (Figure 5(a)) with the Drought/Flooding sequence (Figure 5(b)) in Wudu archived by Chinese historical documents^[39–41] over the past 100 years illustrates that the monsoonal precipitation is consistent with the Drought/Flooding index (Figure 5(a) and 5(b)), and the three typical monsoonal variation periods can also be reflected by Drought/Flooding index as well. In the increasing period of monsoonal precipitation between AD 1875 and AD 1900, 46.1% of the years had flood or sub-flood event, and only 11.5% of the years experienced drought or sub-drought; while during decreasing period of the monsoonal precipitation between AD 1901–1946, years experiencing drought and sub-drought amount to 33 % with frequent crop failures and widespread famines; and during the secondary enhanced period of the monsoonal precipitation between AD 1947–2003, years experi-

encing sub-drought and drought are almost the same as those experiencing sub-flood and flood.

Within age errors due to ^{230}Th dating method and sampling of subsamples for ^{230}Th dating (about 5 years), decreasing or increasing monsoonal precipitation correlates well with famine or flooding events recorded by Chinese historical documents despite some small deviations between the two records. Especially some dramatic drought (AD 1878, 900, 1926–1930, 1936–1938, 1955, 1970–1971 and AD 1996–1998) and flooding events (AD 1879, 1889, 1917, 1947, 1962, 1984 and AD 1990) in historical documents of Wudu^[40] are well reflected in the WX42B $\delta^{18}\text{O}$ record during AD 1875 to 2003.

2.6 Linkage of the AM precipitation to the ocean-atmosphere system from the Pacific Ocean during the past 100 years

The AM system (including the East Asian Monsoon and Indian Monsoon) were driven by thermal contrast between ocean and continent, so it should be closely linked to the Pacific Ocean and the Indian Ocean circulation.

In order to explore the relationship between the monsoonal precipitation and the PDO, the WX42B $\delta^{18}\text{O}$

Figure 6 Comparison of the WX42B $\delta^{18}\text{O}$ record (a) with the annual average PDO index (b). I–IV indicated relationships between strengthening/weakening periods of AM and cold/warm phase of PDO index; the PDO index is from <http://jisao.washington.edu/pdo/PDO.latest>; dot lines indicate 5-year running mean of $\delta^{18}\text{O}$ values and PDO index, respectively.

record is compared systematically with the PDO index^[42] during 1900–2003 AD (Figure 6). The two records parallel each other well with a higher correlation coefficient of 0.71 (significant at the 99.00% confidence level) before AD 1977 after 5-year running average. Two cold phases indicated by the PDO index during (I) AD 1900–1924/25 and (III) AD 1947–1976/77, respectively, are in accordance with two periods of increasing monsoonal precipitation, and one warm phase during (II) AD 1925–1946/47 is consistent with decreasing monsoonal precipitation. This correspondance of the monsoonal precipitation with the PDO indicates an increasing surface temperature contrast between middle Northwest Pacific Ocean and middle to high latitude of the East Asia continent associated with abnormally low sea surface temperature (SST) in the former region and the relationship between exceptionally high SST in the North Pacific region and cold SST in the tropical mid-east Pacific^[43], respectively. These demonstrates that the oscillation of ocean-atmosphere systems of Pacific Ocean on timescale of five years or longer (including the decadal) may lead to persistent anomaly of the East Asian monsoon for several years^[44], and result in de-

cadal climate variations of the Pacific Ocean and its surrounding regions including China. This is consistent with modern observation on the Pacific^[45,46].

Moreover, a notable decadal climate jump occurred at around AD 1976/77 in the north Pacific Ocean (IV in Figure 6), a rapid change of PDO from cold phase into warm phase which is not consistent with the monsoonal precipitation variations illustrated by the WX42B $\delta^{18}\text{O}$ record. This inconsistency may result from a transition of dominant factor controlling the East Asian summer monsoon from SST anomaly in the North Pacific prior to AD 1976 to SST anomaly in the equator mid-east Pacific Ocean thereafter, a so-called decadal shift of the key zone of interannual SST anomalies^[43].

3 Conclusions

The WX42B $\delta^{18}\text{O}$ record from Wanxiang Cave sensitively recorded changes of the AM strength and associated monsoonal precipitation in the AM marginal zone on short timescales.

Over the past 100 years, the AM strengthened and associated monsoonal precipitation increased during AD 1875–1900 and AD 1947–2003, respectively, and

relatively weakened during AD 1901 – 1946. The WX42B $\delta^{18}\text{O}$ record correlates negatively to local precipitation over the past 50 years. Comparison between the AM variation recorded by the WX42B $\delta^{18}\text{O}$ data and Drought/Flooding index reconstructed from Chinese historical documents indicates a good coherence between the two records within ^{230}Th dating errors, with more frequent flooding events corresponding to stronger AM and higher monsoonal precipitation and drought events to reduced AM and monsoonal precipitation.

Variation of the AM strength recorded by the WX42B $\delta^{18}\text{O}$ data suggests that it was closely related to the PDO during the past 100 years with a warm PDO phase corresponding to decreasing monsoonal precipitation and vice versa on interdecadal timescale. However, The

monsoonal precipitation variation became out-of-phase to the PDO after AD 1977, which may be a reflection of the decadal climate jump in the North Pacific at around AD 1976/77. All of these results indicate that variations of the AM strength and associated monsoonal precipitation are closely linked to the Pacific Ocean via an interaction ship between ocean and atmosphere systems. This relationship will aid to forecast future hydrological cycle for the AM region, and to improve forecasting potential of climatic model with observation data from cave.

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- Krishnan R, Sugi M. Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. *Clim Dyn*, 2003, 21: 233–242[[doi](#)]
- Dugam S S, Kakade S B, Verma R K. Interannual and long-term variability in the North Atlantic oscillation and Indian summer monsoon rainfall. *Theor Appl Climatol*, 1997, 58: 21–29[[doi](#)]
- Chang C P, Zhang Y, Li T. Interannual and interdecadal variations of the East Asian summer monsoon and the tropical Pacific SSTs, Part I. Roles of the subtropical ridge. *J Clim*, 2000, 13: 4310–4325[[doi](#)]
- Chan J C L, Zhou W. PDO, ENSO and the early summer monsoon rainfall over south China. *Geophys Res Lett*, 2005, 32(8): L08810[[doi](#)]
- Webster P J, Magana V, Palmer T N, et al. Monsoons: Processes, predictability, and the prospects for prediction. *J Geophys Res*, 1998, 103: 14451–14510[[doi](#)]
- Henderson G M, Caving in to new chronologies. *Science*, 2006, 313: 620–622[[doi](#)]
- Yuan D X, Cheng H, Edwards R L. Timing, duration and transition of the last interglacial Asian Monsoon. *Science*, 2004, 304: 575–578[[doi](#)]
- Wang Y J, Cheng H, Edwards R L, et al. A high-resolution absolute dated Late Pleistocene monsoon record from Hulu Cave, China. *Science*, 2001, 294: 2345–2348[[doi](#)]
- Wang Y J, Cheng H, Edwards R L, et al. The Holocene Asian Monsoon: Links to Solar Changes and North Atlantic Climate. *Science*, 2005, 308: 854–857[[doi](#)]
- Fleitmann D, Burns S J, Mudelsee M, et al. Holocene forcing of the Indian Monsoon recorded in a stalagmite high-resolution speleothem $\delta^{18}\text{O}$ record from southern Oman. *Science*, 2003, 300: 1737–1739[[doi](#)]
- Johnson K R, Ingram B L, Warren D S, et al. East Asian summer monsoon variability during marine isotope stage 5 based on speleothem $\delta^{18}\text{O}$ records from Wanxiang Cave, central China. *Palaeogeogr, Palaeoclimatol, Palaeoecol*, 2006, 236: 5–19[[doi](#)]
- Burns S J, Fleitmann D, Mudelsee M, et al. A 780-year annually resolved record of Indian Ocean monsoon precipitation from a speleothem from south Oman. *J Geophys Res*, 2002, 107(D20): 4434[[doi](#)]
- Cheng H, Edwards R L, Wang Y J, et al. A penultimate glacial monsoon record from Hulu Cave and two-phase glacial terminations. *Geology*, 2006, 34: 217–220[[doi](#)]
- Wang Y J, Cheng H, Edwards R L, et al. Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years. *Nature*, 2008, 451: 1090–1093[[doi](#)]
- Asmerom Y, Polyak V, Burns S J, et al. Solar forcing of Holocene climate: New insights from a speleothem record, southwestern United States. *Geology*, 2007, 35(1): 1–4[[doi](#)]
- Neff U, Burns S J, Mangini A, et al. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature*, 2001, 411: 290–293[[doi](#)]
- Yang X L, Zhang P Z, Chen F H, et al. Modern stalagmite oxygen isotopic composition and its implications of climatic change from a high-elevation cave in the eastern Qinghai-Tibet Plateau over the past 50 years. *Chin Sci Bull*, 2007, 52(9): 1238–1247[[doi](#)]
- Sinha A, Cannariato K G, Stott L D, et al. A 900-year (600 to 1500AD) record of the Indian summer monsoon precipitation from the core monsoon zone of India. *Geophys Res Lett*, 2007, 34, L16707 [a href="#">doi]
- Beynen P E V, Asmerom Y, Polyak V, et al. Variable intensity of teleconnections during the late Holocene in subtropical North America from an isotopic study of speleothem from Florida. *Geophys Res Lett*, 2007, 34, L18703 [a href="#">doi]
- Zhang P Z, Johnson K R, Chen Y M, et al. Modern systematics and environmental significance of stable isotopic variations in Wanxiang Cave, Wudu, China. *Chin Sci Bull*, 2004, 49(15): 1649–1652[[doi](#)]
- An C L, Zhang P Z, Dai Z B, et al. Comparison of $\delta^{18}\text{O}$ record during MIS 5 in Wanxiang Cave stalagmite, Gansu province of western Loess plateau and those of southern China stalagmites. *Quat Sci (in Chinese)*, 2006, 26(6): 985–990
- McCrea J M. On the isotopic chemistry of carbonates and a paleotemperature scale. *J Chem Phys*, 1950, 18: 849–857[[doi](#)]
- Chen C C, Edwards R L, Cheng H. Uranium and thorium isotopic and

- concentration measurements by magnetic sector inductively coupled plasma mass spectrometry. *Chem Geol*, 2002, 185: 165–178[[doi](#)]
- 24 Cheng H, Edwards R L, Hoff J A, et al. The half-lives of uranium-234 and thorium-230. *Chem Geol*, 2000, 169, 17–33[[doi](#)]
 - 25 Hendy C H. The isotopic geochemistry of speleothems—I. The calculation of the effects of different modes of formation on the isotopic composition of speleothems and their applicability as paleoclimate indicators. *Geochim Cosmochim Acta*, 1971, 35: 801–824[[doi](#)]
 - 26 Cheng H, Edwards R L, Wang X F, et al. Oxygen isotopic records of stalagmites from southern China. *Quaternary Sci* (in Chinese), 2005, 25 (2): 157–163
 - 27 He Y Q, Wang Y J, Kong X G, et al. High resolution stalagmite $\delta^{18}\text{O}$ record over the past 1000 year from Dongge Cave in Guizhou. *Chin Sci Bull*, 2005, 50(10): 1003–1008[[doi](#)]
 - 28 Yadava M G, Ramesh R, Pant G B. Past monsoon rainfall variations in peninsular India recorded in a 331-year-old speleothem. *The Holocene*, 2004, 14(4): 517–524[[doi](#)]
 - 29 Fleitmann D, Stephen J B, Neff U, et al. Palaeoclimatic interpretation of high-resolution oxygen isotope profiles derived from annually laminated speleothems from Southern Oman. *Quat Sci Rev*, 2004, 23: 935–945[[doi](#)]
 - 30 Johnson K R, Ingram B L. Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: Implication for paleoclimate reconstructions. *Earth Planet Sci Lett*, 2004, 220(3-4): 365–377[[doi](#)]
 - 31 O'Neil J R, Adami L H and Epstein S. Revised value for the ^{18}O fractionation factor between H_2O and CO_2 at 25°C . *United States Geol Sur Res*, 1975, (3): 623–624
 - 32 Zheng S H, Hou F G, Ni B L. Study for hydrogen and oxygen of the precipitation in China, *Chin Sci Bull* (in Chinese), 1983, 13: 801–806.
 - 33 Vuille M., Werner C M, Bradley R S, et al. Stable isotopes in precipitation in the Asian monsoon region. *J Geophys Res*, 2005, 110(D23108) [[doi](#)]
 - 34 Dansgaard W. Stable isotopes in precipitation. *Tellus*, 1964, 16(4): 436–468
 - 35 Jouzel J, Froehlich K, Schotterer U. Deuterium and oxygen-18 in present-day precipitation: data and modeling. *J Hydrol Sci*, 1997, 42(5): 747–763
 - 36 AraguÀs-AraguÀs L, Froehlich K, Rozanski K. Stable isotope composition of precipitation over Southeast Asia. *J Geophys Res*, 1998, 103: 28721–28742[[doi](#)]
 - 37 Wei K Q, Lin R F. The influence of the monsoon climate on the isotopic composition of precipitation in China. *Geochimica* (in Chinese), 1994, 23(1): 33–41
 - 38 Zhou S Q, Nakawo M, Sakai A, et al. Water isotope variations in the snow pack and summer precipitation at July 1 Glacier, Qilian Mountains in northwest China. *Chin Sci Bull*, 2007, 52(21): 2963–2972[[doi](#)]
 - 39 Yuan L. Northwest Famine History. Lanzhou: Gansu People's Publishing House, 1994
 - 40 Zeng L. Wudu county annals. Beijing: Sdx Joint Publishing Company, 1998. 193–200
 - 41 Academy of Meteorological Science, China Central Meteorological Administration. Yearly Charts of Dryness/Wetness in China for the Last 500 Years Period. Beijing: Cartographic Publishing House, 1981. 208–260
 - 42 Mantua N J, Hare S T. The Pacific decadal oscillation. *J Oceanogr*, 2002, 58: 35–44[[doi](#)]
 - 43 Li F, He J H. Interdecadal variations of interaction between north Pacific SSTa and East Asian summer monsoon. *J Tropical Meteorol*, 2001, 7(1): 41–52
 - 44 Zhang Y, Wallace J M, Battisti D S. ENSO-like interdecadal variability: 1900–93. *J Clim*, 1997, 10: 1004–1020[[doi](#)]
 - 45 Ma Z G, Fu C B. Evidences of Drying Trend in the Global During the later Half of 20th Century and Their Relationship with Large-Scale Climate Background. *Sci China Ser D-Earth Sci*, 2007, 50(5): 776–788[[doi](#)]
 - 46 Mang Z G, Shao L J. Relationship between dry/wet variation and the Pacific decadal oscillation (PDO) in northern China during the last 100 years. *Chin J Atmos Sci*, 2006, 30(3): 464–474