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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

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An oxygen isotope record of a stalagmite from Huanglong Cave in the eastern Qinghai-Tibet Plateau dated with ²³⁰Th and ²¹⁰Pb methods provides variations of the Asian monsoon with an average resolution of 1 year over the past 50 years. This study shows that the $\delta^{18}\text{O}$ of dripwater in the cave represents the annual mean $\delta^{18}\text{O}$ of local meteoric precipitation and the stalagmites were deposited in isotopic equilibrium. A comparison of the stalagmite $\delta^{18}\text{O}$ record with instrumentally meteorological data indicates that shifts of the $\delta^{18}\text{O}$ are largely controlled by the amount effect of meteoric precipitation conveyed through the southwest monsoon (the Indian monsoon) and less affected by temperature. Therefore, the variations of $\delta^{18}\text{O}$ record reflect the changes in monsoon precipitation on inter-annual time scales under the influence of the southwest monsoon. Like many other stalagmite $\delta^{18}\text{O}$ records in the Asian monsoon regions, the $\delta^{18}\text{O}$ record of the stalagmite from Huanglong Cave also reveals a gradually enriched trend during the past 50 years, i.e. relatively enriched in ¹⁸O. This trend may indicate the decline of the Asian monsoon intensity which is consistent with the decrease of monsoon indices. The weakening of the modern Asian monsoon well matched with the temperature changes in stratosphere, which may illustrate that the weakening of the monsoon mainly results from the lowering of solar radiation.

stalagmite, oxygen isotopic composition, Asian monsoon, high-resolution, Qinghai-Tibet Plateau

Stalagmite record has a much longer time span and reserves integrated information^[1], so it is a valuable supplement archive to records of ice core, loess, lake sediment and peat core, etc^[2]. Furthermore, stalagmite is an ideal material for precise U-series dating and yields independent time scales^[3]. Therefore, stalagmite has become a major data source for continent paleo-climate reconstruction. Among multi-proxy records in stalagmite including stable carbon/oxygen isotope, trace element

and laminae, the stalagmite $\delta^{18}\text{O}$ is the most widely used proxies at present^[4]. There are multi-answers in explaining oxygen isotopic compositions of stalagmites from different regions because the shifts of the stalag-

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mite $\delta^{18}\text{O}$ values are controlled by many factors, such as $\delta^{18}\text{O}$ in precipitation^[5,6], depositing process of calcite, cave temperature during depositing period, especially in the regions strongly influenced by summer monsoon^[7,8]. Therefore, it is necessary to study oxygen isotopic composition and its implications of modern stalagmite systematically. Currently, great progress in history, amplitude and driving factors of the Asian monsoon variation has been made by the stalagmite records on glacial/interglacial and millennial time scales^[9–11]. Although, Burns et al.^[12] discussed the relation between the stalagmite $\delta^{18}\text{O}$ records and instrumental monsoon precipitation in southern Oman on inter-decadal scales, much research work is still needed on modern stalagmite depositing process and the changes of oxygen isotope composition in responses to the climate change on short time scales. Thus, based on the research of modern carbonate-water oxygen isotope system and the instrumental observation data, this paper probes into the stalagmite oxygen isotopic composition and its implications from a high-elevation cave — Huanglong Cave in the eastern Qinghai-Tibet Plateau, and discusses the relationship between monsoon precipitation and upper stratospheric temperature changes over the past 50 years, which would help us improve understanding the variations of the Asian monsoon and the future climate.

1 Sample description and analytical methods

1.1 Study site and sample description

Huanglong Cave (32°43'N, 103°49'E, 3588 m a. s. l.) is formed in Triassic limestone at Huanglong Ravine with high-elevation mountainous climate in the eastern Qinghai-Tibet Plateau^[13]. This site is sensitive to monsoon change at fringe zone of the eastern Qinghai-Tibet Plateau influenced by interaction of the southwest monsoon and the East Asian monsoon with mean annual temperature (MAT) of 4°C and mean annual precipitation (MAP) of 759 mm. Therefore, it is an attractive place to explore relationship between the stalagmite $\delta^{18}\text{O}$ records and the Asian monsoon precipitation.

We sampled vertically along the growth axes of two huge stalagmites using portable core drilling and obtained two stalagmite cores in length of 300 mm (HL021) and 135 mm (HL022) with diameter of 30 mm, respectively. Field investigations showed that there was plenty

of dripwater in the cave and a great deal of water membrane on the top of stalagmites, indicating that the two stalagmites were actively growing in May, 2002 when samples were collected. The following ^{210}Pb dating and study of modern carbonate deposit also confirmed that the two stalagmites were still growing. HL021 and HL022 were compactly crystallized with light white and some gray laminas in the top, and with no apparent hiatus. In order to understand the process of modern stalagmite deposition and to compare the stalagmite $\delta^{18}\text{O}$ records with instrumental meteorological data, the paper mainly presents the results from the top 6 mm of HL021 and the top 10 mm of HL022. We also systematically collected some samples of cave dripwater from entrance to the end of the cave and some actively dripping, un-crystal growing soda straw stalactites sagged from the roof of the cave in October, 1999 and May, 2002. Meanwhile several glass slides were also put in the cave at the dripping location to collect depositing carbonate. The data-logger for detecting the cave temperature and relative humidity (RH) was set in the deepest site from the entrance in the cave, which automatically and continuously worked from May, 2001 to May, 2002.

In order to obtain high-resolution oxygen isotopic records, we firstly halved the stalagmites vertically from the bottom to the top along the growth axes, polished their cutting surfaces, and then, with about average interval of 50 μm , scraped sub-samples off along successive laminations. To avoid cross-contamination of sub-samples, alternative sub-samples were selected for analyzing. 52 $\delta^{18}\text{O}$ data were obtained along the growth axis of HL021, resulting in an average resolution of ~1 year, and 22 $\delta^{18}\text{O}$ data were obtained from HL022 with a time resolution of ~2 years. One sample is taken off to parallel the growth banding of stalagmite from HL021 and HL022 respectively, for MC-ICPMS ^{230}Th -dating; 8 samples from HL021 and 7 samples from HL022 for ^{210}Pb -dating were symmetrically collected downwards from the top at intervals of 2.5 mm with knife (Table 1).

1.2 Analytical methods

The $\delta^{18}\text{O}$ and δD values of cave dripwater were measured at the Center of Isotope Geochemistry, University of California, Berkeley, where δ notation represents hydrogen and oxygen data, respectively, $\delta = [(R_{\text{sample}}/R_{\text{std}}) - 1] \times 1000$, in which R stands for D/H and $^{18}\text{O}/^{16}\text{O}$. The $\delta^{18}\text{O}$ of cave dripwater samples was measured by the equilibrium methods between water and CO_2 ; and the δD of all

water samples was analyzed with a VG Prism II isotope ratio mass spectrometer. All $\delta^{18}\text{O}$ and δD values are reported relative to VSMOW. The precision for each analysis is $\pm 0.01\%$ for $\delta^{18}\text{O}$ and $\pm 0.1\%$ for δD .

Carbon dioxide for isotopic analysis was produced with McCrea's phosphoric acid method [14]. Modern stalagmite oxygen isotope analysis was carried out with Finnigan-Delta-Plus mass spectrometer in the Key Laboratory of Western China's Environmental Systems, Ministry of Education, Lanzhou University. Oxygen data are reported in δ notation relative to the VPDB, where $\delta = [(R_{\text{sample}}/R_{\text{std}}) - 1] \times 1000$, in which R stands for $^{18}\text{O}/^{16}\text{O}$. The precision for each analysis is $\pm 0.1\%$ for $\delta^{18}\text{O}$. The ^{230}Th dating was finished in Isotopic Chronology Laboratory of Department of Geology and Geophysics, University of Minnesota, USA. The ^{230}Th dating procedures and methods were described in ref. [15], and the 2σ errors are reported. The ^{210}Pb activity of stalagmite was measured by low background multi-channel alpha spectrometry in the Radioisotope Lab of the Academia Sinica, Taiwan, China. The ^{210}Pb dating procedures were described in refs. [16, 17].

2 Results and discussion

2.1 Stalagmite age model

Stalagmite HL022 and HL021 are young with dense texture and no hiatus; they have high uranium concentration and appear neither recrystallization, nor erosion phenomena. So they are suitable for ^{230}Th and ^{210}Pb dating methods.

^{210}Pb has a half-life of 22.3 years, so ^{210}Pb dating

method is suitable for constructing a precise timescale of stalagmite in the cave where ^{210}Pb is relatively enclosed during the deposition for a short period [16]. The top 20mm of HL021 and HL022 is in single color, which implies relatively smooth growth rates during this interval. The determination of ^{210}Pb age and the calculation of stalagmite growth rates are based on the ^{210}Pb activity decay with time for the last 50 years. We plotted the ^{210}Pb activity against the depth (Table 1, Figure 1). The stalagmite ^{210}Pb activity exhibits an exponential decay until the depth of 16.25 mm. The ^{210}Pb activity remains a constant below this depth, indicating that the ^{210}Pb activity below this depth is equilibrated with its supported source (background values), so we can draw a conclusion that the sample is younger than 100 years and the ^{210}Pb activity mostly comes from excess ^{210}Pb of water and atmosphere above this depth. The growth rates of HL021 and HL022 were obtained by exponentially fitting of the decrease of the ^{210}Pb activity with the depth. The maximum growth rates of HL021 and HL022 determined by total ^{210}Pb (y_{tot}) activity are 0.246 mm/a and 0.144 mm/a, respectively. Assuming that the ^{210}Pb activity below 16.25 mm represents the radioactive background value of ^{210}Pb , the average growth rates of the two stalagmites determined by excess ^{210}Pb (y_{ex}) activity are 0.104 mm/a (HL021) and 0.143 mm/a (HL021), respectively.

The ^{230}Th dating results of HL022 and HL021 are shown in Table 2. The average growth rates of HL022 and HL021 are estimated by the ^{230}Th dating in order to test the reliability of the ^{210}Pb dating results. According to the ^{230}Th dating data, the average growth rates are

Table 1 ^{210}Pb activity analyses of stalagmite HL021 and HL022

Sample No.	Depth (mm)	Tot $^{210}\text{Pb}^{\text{a}}$ (dpm · g ⁻¹)	Ex $^{210}\text{Pb}^{\text{a}}$ (dpm · g ⁻¹)	Sample No.	Depth (mm)	Tot $^{210}\text{Pb}^{\text{a}}$ (dpm · g ⁻¹)	Ex $^{210}\text{Pb}^{\text{a}}$ (dpm · g ⁻¹)
HL021-01	1.25	5.962±0.221	5.742	HL022-01	1.5	3.419±0.170	3.051
HL021-02	3.75	6.262±0.343	6.042	HL022-02	4.75	2.296±0.131	1.929
HL021-03	6.25	4.384±0.270	4.164	HL022-03	8.25	2.847±0.142	2.479
HL021-04	8.75	2.418±0.188	2.198	HL022-04	11.25	2.041±0.110	1.674
HL021-05	11.25	1.389±0.144	1.169	HL022-05	13.75	1.103±0.079	0.735
HL021-06	13.75	0.567±0.093	0.347	HL022-06	16.25	0.569±0.093	0.201
HL021-07	16.25	0.274±0.061	0.054	HL022-07	18.75	0.368±0.081	0
HL021-08	18.75	0.220±0.045	0				

a) Tot ^{210}Pb represents the total ^{210}Pb ; Ex ^{210}Pb represents excess ^{210}Pb .

Table 2 The results of MC-ICPMS U-series dating for HL021 and HL022^{a)}

Sample No.	Depth (mm)	^{238}U ($\times 10^{-9}$)	^{232}Th ($\times 10^{-12}$)	$^{230}\text{Th}/^{32}\text{Th}$ atomic (10^{-6})	$\delta^{234}\text{U}$ (measured)	$^{230}\text{Th}/^{238}\text{U}$ (activity)	^{230}Th age (a) (uncorrected)	^{230}Th age (a) (corrected)
HL021-01	58	201.3±0.4	216±5	114±3	423.4±2.4	0.0074	568±8	553±9
HL022-02	134	179.6±0.4	368±17	100±5	426.9±3.2	0.0124	951±19	922±22

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

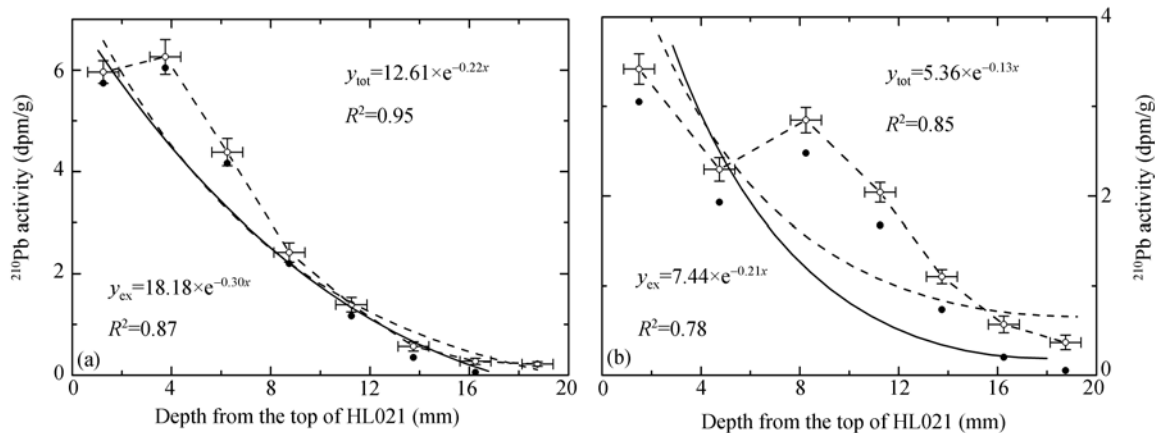


Figure 1 ^{210}Pb activity plotted against the depth from the top of HL021 (a) and HL022 (b). Dash lines with error bars indicate the ^{210}Pb activity against the depth of stalagmite; dash curves and solid curves using the exponential fitting indicate the total ^{210}Pb activity and excess ^{210}Pb activity against the depth of stalagmite, respectively.

0.105 mm/a for HL021 and 0.145 mm/a for HL022, which are almost in agreement with the average growth rates based on excess ^{210}Pb . Moreover, the ^{210}Pb dating results show a marked peak value in the vicinity of 1963 which probably resulted from a great scale proliferation of radioactive material in nuclear tests of the 1960s^[18,19], which indirectly proved the reliability of the ^{210}Pb dating results of stalagmite in Huanglong Cave. Therefore, using the result of the excess ^{210}Pb (y_{ex}) dating, we established an absolute-dated oxygen isotope record from Huanglong Cave over the past 50 years.

2.2 Modern cave carbonate-water isotopic system

A key issue is whether Huanglong Cave stalagmite $\delta^{18}\text{O}$ values can be interpreted by the $\delta^{18}\text{O}$ in meteoric precipitation and cave temperature during calcite precipitation^[20,21]. Huanglong Cave is a relatively closed cave with low MAT and RH of 100%. Systemic research on modern stalagmite deposition conditions and cave dripwater isotope composition was performed to test whether the cave dripwater came from meteoric precipitation or not. Identical replication tests of two stalagmites in the same cave are virtually criteria to check stalagmite equilibrium deposition in the cave temperature over the contemporaneous growth period^[20,21].

To characterize modern cave dripwater, we plotted the δD and $\delta^{18}\text{O}$ values of the cave dripwater samples collected in May, 2002 on the Local Meteoric Water Line (LMWL) constructed by Zhang et al.^[22] (Figure 2), $\delta\text{D} = 7.3 \delta^{18}\text{O} + 2.3$ ($R = 0.98$). We found that δD and $\delta^{18}\text{O}$ values were directly plotted on LMWL, suggesting that the cave water had not been significantly affected by

evaporative processes and cave dripwater originated from meteoric precipitation. Therefore, the isotopic composition of the dripwater in Huanglong Cave could reflect the isotopic composition of meteoric precipitation.

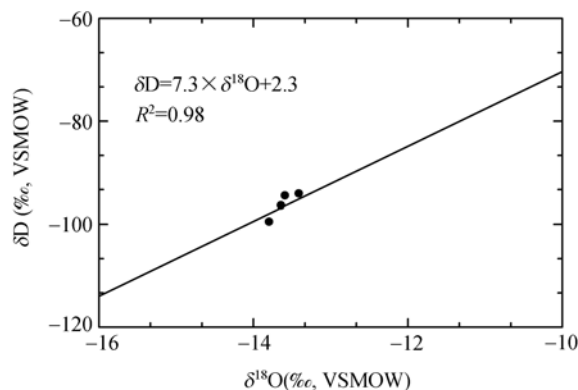


Figure 2 Distribution of dripwater isotopic composition in Huanglong Cave on the LMWL^[22]. Solid line and dots indicate LMWL and dripwater isotopic composition, respectively.

The $\delta^{18}\text{O}$ values of 14 unconsolidated carbonate powder samples, collected from May, 2001 to May, 2002 using ground glass slices, range from -9.50‰ to -11.07‰ (VPDB) with the mean value of -10.00‰ . The $\delta^{18}\text{O}$ values of 9 actively growing soda straw stalactite tips, collected in October, 1999 and in May, 2001, range from -10.07‰ to -11.10‰ with the mean value of -10.75‰ . So, the total mean $\delta^{18}\text{O}$ value of modern uncrystallized surface carbonate deposits in Huanglong Cave is -10.29‰ . The $\delta^{18}\text{O}_{\text{w}}$ values of cave dripwater vary from -13.07‰ to -13.91‰ (VSMOW) with the mean dripwater $\delta^{18}\text{O}_{\text{w}}$ of -13.75‰ (VSMOW). The

mean temperature in the cave recorded by data logger was 4.64°C from May, 2001 to May, 2002. On the basis of O'Neil's equation^[23], we can theoretically obtain that the $\delta^{18}\text{O}_c$ value of carbonate deposits should be -10.17‰ (VPDB) if the carbonate deposits are in isotopic equilibrium with the dripwater. The theoretical $\delta^{18}\text{O}_c$ value (-10.17‰) is close to the mean measured $\delta^{18}\text{O}_c$ value (-10.29‰) of uncrystallized carbonate deposits, which indicates modern calcite is precipitating under isotopic equilibrium with the dripwater in Huanglong Cave^[21].

Another robust test is the comparison of $\delta^{18}\text{O}$ from contemporaneous stalagmite records in the same cave. The $\delta^{18}\text{O}$ records of HL021 and HL022 are virtually identical during the period when the two stalagmites grew contemporaneously (Figure 3). According to Hendy test criteria^[21], the stalagmites of Huanglong Cave were deposited in isotopic equilibrium during the whole growth period, and the $\delta^{18}\text{O}$ values of stalagmite mainly depend on cave temperature and $\delta^{18}\text{O}$ of meteoric precipitation^[21,22].

2.3 Stalagmite $\delta^{18}\text{O}$ record

The $\delta^{18}\text{O}$ values of HL021 range from -11.55‰ to -10.07‰ (VPDB) with the mean value of -10.82‰, and variation amplitude of 1.5‰ over the past 50 years. Dongge Cave (25°02'N, 108°05'E, 680 m a. s. l.) is located at low altitude in the southwest of China^[24]; the

stalagmite $\delta^{18}\text{O}$ values of Dongge Cave range from -7.53‰ to -7.18‰, with the mean value of -7.31‰ and the amplitude of only 0.35‰ at the same growth period^[24]. In Kahf Defore Cave of southern Oman (17°07'N, 54°05'E, 150 m a. s. l.), located in tropical zone with low-altitude^[12,25], the stalagmite $\delta^{18}\text{O}$ values range from 0.20‰ to -1.01‰, with the mean value of -0.38‰ in the same growth period^[12,25]. Affected by the elevation and the distance from moisture source regions, the changing range and amplitude of the $\delta^{18}\text{O}$ values in Huanglong Cave are larger than those in Dongge Cave and Kahf Defore Cave, which suggests that the $\delta^{18}\text{O}$ variations in Huanglong Cave are more sensitive to climate than those in Dongge Cave and Kahf Defore Cave.

Previous studies verified that the stalagmite $\delta^{18}\text{O}$ records from the Asian monsoon regions mainly reflected the variations of the Asian monsoon intensity on the glacial/interglacial or stadial/interstadial scales and represented the temporal oxygen isotope information of the precipitation^[11,20,24-27]. But there are many uncertainties about climatic implications of the stalagmite oxygen isotopic composition in the Asian monsoon regions on shorter time scales and inter-annual resolution. Based on correlative analysis, we found that HL021 $\delta^{18}\text{O}$ record of Huanglong Cave significantly and negatively correlates to summer precipitation from the Songpan Meteorological Station in Sichuan Province during the period

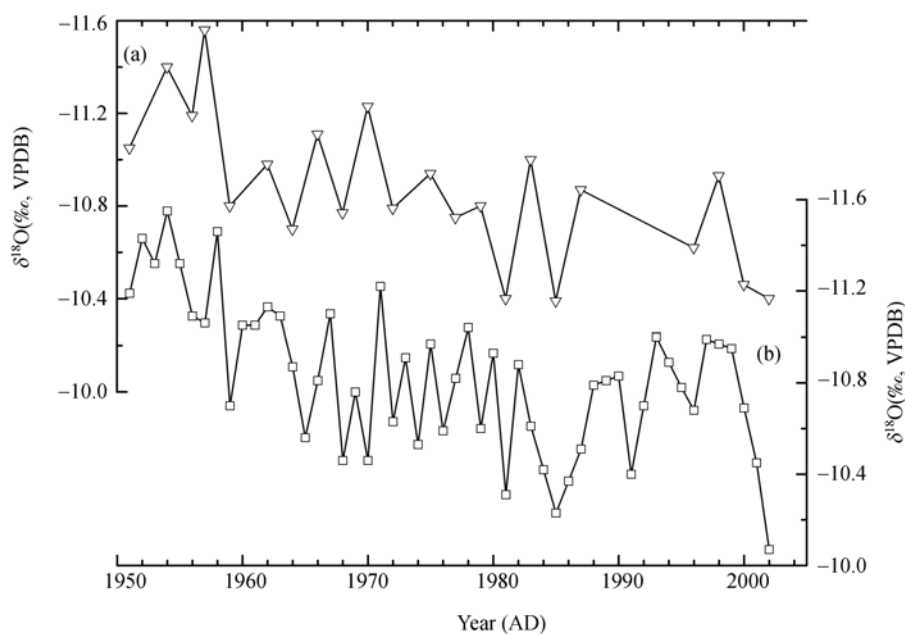


Figure 3 Comparison of $\delta^{18}\text{O}$ curves between HL022 (a) and HL021 (b) from Huanglong Cave.

of 1951–2002. The correlation coefficient for the full record is -0.53 (significant at the 99.95% confidence level), which indicates that the oxygen isotopic composition of HL021 is significantly affected by the amount of precipitation (known as “amount effect”) (Figure 4). The regions near Huanglong Cave are controlled by the southwest monsoon. More than 80% of total annual precipitation falls during the summer monsoon months (May to October) when the convergence between the low-level southwest monsoon winds off the Bay of Bengal and the cold, dry Siberian air off to southward brings more rain amount and stronger monsoon. Thus, HL021 $\delta^{18}\text{O}$ record reflects inter-annual variations of the southwest monsoon and the $\delta^{18}\text{O}$ information of the southwest monsoon precipitation.

Fleitmann and Burns have previously demonstrated that the $\delta^{18}\text{O}$ record of Kahf Defore Cave mainly reflected the variations of the southwest monsoon [12,25]. By comparing HL021 $\delta^{18}\text{O}$ record of Huanglong Cave with the $\delta^{18}\text{O}$ record of Kahf Defore Cave from 1951 to 1996, we find that they have a positive correlation with a correlation coefficient of 0.33 (significant at the 99.00% confidence level) (Figure 5). The $\delta^{18}\text{O}$ changes of both caves mentioned above are similar to the $\delta^{18}\text{O}$ changes in Dongge Cave affected by the southwest monsoon during the same period, which further proves that the stalagmite $\delta^{18}\text{O}$ record of Huanglong Cave mainly indicated the inter-annual changes of the southwest monsoon. The stalagmite oxygen isotopic composition from

the three caves mentioned above all became step-like heavier during the period, which suggested that the southwest monsoon has become weaker since the 1950s. HL021 $\delta^{18}\text{O}$ record is similar to the contemporaneous $\delta^{18}\text{O}$ record of the Shihua Cave affected by the East Asian monsoon [28,29], suggesting that the East Asian monsoon and the southwest monsoon have consistent variations over the past half-century. Moreover, the $\delta^{18}\text{O}$ records from Dongge Cave and Hulu Cave [27,30] also show that the southwest monsoon and the East Asian monsoon have similar variations on millennial time scales.

HL021 $\delta^{18}\text{O}$ record has a significant negative correlation with the East Asian summer monsoon index (EAMI) constructed by Jiang and Wang [31] using reanalysis data derived from the United States National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) through 1951 to 2002, and the correlation coefficient is -0.58 (significant at the 99.95% confidence level) (Figure 6). HL021 $\delta^{18}\text{O}$ record also has a significant negative correlation with the global monsoon index (GMI) constructed by Wang and Ding [33], using four sets of rain-gauge precipitation data sets compiled for the period of 1948–2003 by climate diagnostic groups around the world, with the correlation coefficient of -0.52 (significant at the 99.95% confidence level). That is to say, as the $\delta^{18}\text{O}$ values of the stalagmite turn lighter, the intensity of the Asian monsoon gets stronger and vice versa. Based on the intensity of the normalized seasonality of wind field, Li and

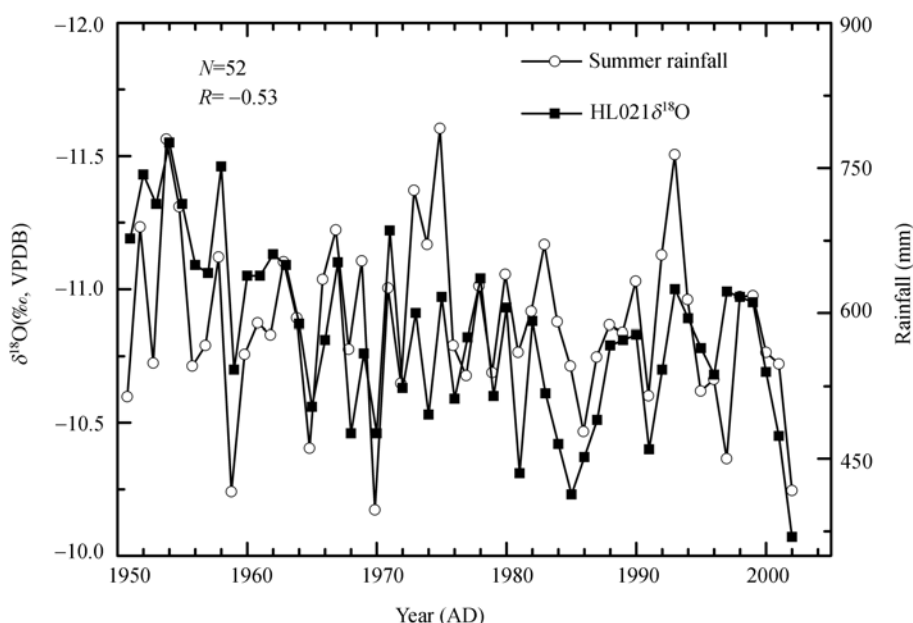


Figure 4 Comparison of HL021 $\delta^{18}\text{O}$ record (1951–2002) with the instrumental summer rainfall record from Songpan Meteorological Station.

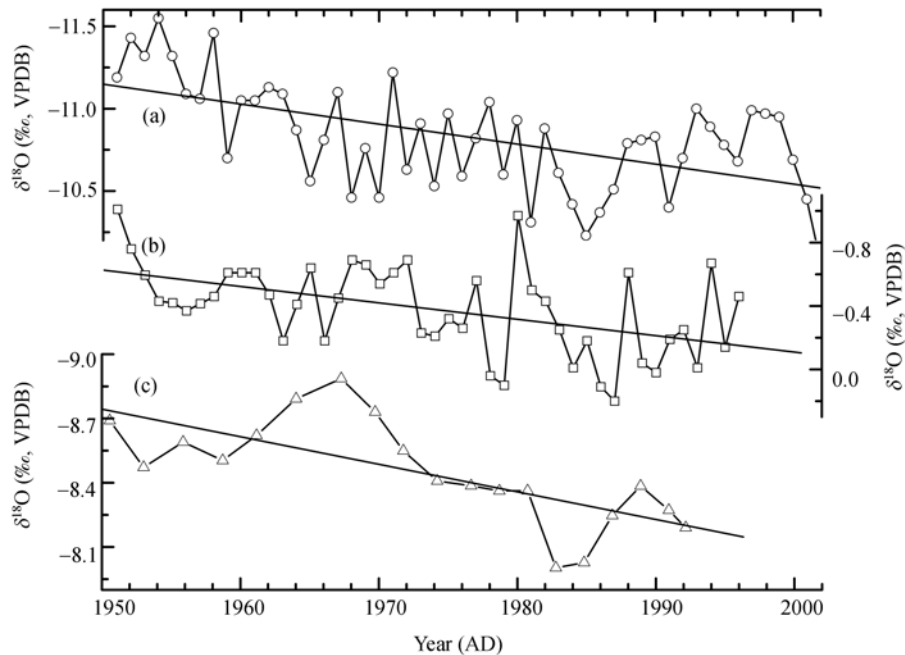


Figure 5 Comparison of HL021 $\delta^{18}\text{O}$ record (1951–2002) with other stalagmite $\delta^{18}\text{O}$ records in the Asian monsoon regions. (a) Huanglong Cave $\delta^{18}\text{O}$ record; (b) $\delta^{18}\text{O}$ record of Kahf Defore Cave, Oman [12,25], (c) Shihua Cave $\delta^{18}\text{O}$ record [28,29]. Oblique lines indicate their trends by linear fitting.

Zeng [32,36] constructed the monsoon indices to describe both seasonal variations and inter-annual variability of monsoon in different monsoon regions, and discovered that there existed an overall weakening of the monsoon intensity in South Asian, East Asian, North American and West African monsoon regions since the 1950s. In summary, the above analyses show that the southwest monsoon and the East Asian monsoon, which make up of the Asian monsoon, have a synchronous weakening since the 1950s, and the modern monsoon is globally weakening, but the trend has become inconspicuous after 1980, and these analyses also support the idea that the inter-annual changes in the stalagmite $\delta^{18}\text{O}$ of Huanglong Cave indicate the inter-annual variations of the Asian monsoon.

Yuan et al. [27] and Dykoski et al. [30] pointed out that the $\delta^{18}\text{O}$ values of the stalagmite, deposited under the isotopic equilibrium, could be interpreted mainly in terms of the $\delta^{18}\text{O}$ of precipitation and cave temperature in the Asian monsoon regions [27,30]. The effect of temperature on the stalagmite $\delta^{18}\text{O}$ is quite complex. Changes in the temperature-dependent fractionation between calcite and water are small [37] ($-0.24\text{‰}/\text{C}$). On the other hand, for the high-latitudes, the $\delta^{18}\text{O}$ values of MAP in continental interiors are observed to be positively correlated with MAT, and the modern empirical

relation between MAP $\delta^{18}\text{O}$ values and MAT is about $0.69\text{‰}/\text{C}$ [38]. Other factors, however, may obscure this relation in the Asian monsoon regions especially. Even if temperature positively correlates to the oxygen isotope composition of stalagmites in low-mid-latitude monsoon regions, the temperature effect is relatively weak for it is counteracted by the strong negative relationship between the stalagmite oxygen isotope and the summer precipitation [39,40]. As to Huanglong Cave, we have found that HL021 $\delta^{18}\text{O}$ values weakly and positively correlated with both MAT and the mean summer temperature (MST) observed at local meteorological station, and the correlation coefficient between the $\delta^{18}\text{O}$ values and MST was much greater than that between the $\delta^{18}\text{O}$ values and MAT, but both correlation coefficients failed to reach confidence level at 90.00%. In conclusion, on the inter-annual resolution, the stalagmite $\delta^{18}\text{O}$ values of Huanglong Cave are affected strongly by summer monsoon precipitation and weakly by the temperature, which is also supported by Johnson and Ingram's findings about spatial and temporal variability in the stable isotope systematics of modern precipitation in China.

Lots of researchers have demonstrated that the Asian monsoon was weakening since the 1950s [31–33,36]. The changes of the Asian monsoon on millennial-scale were driven by orbitally induced changing of Northern

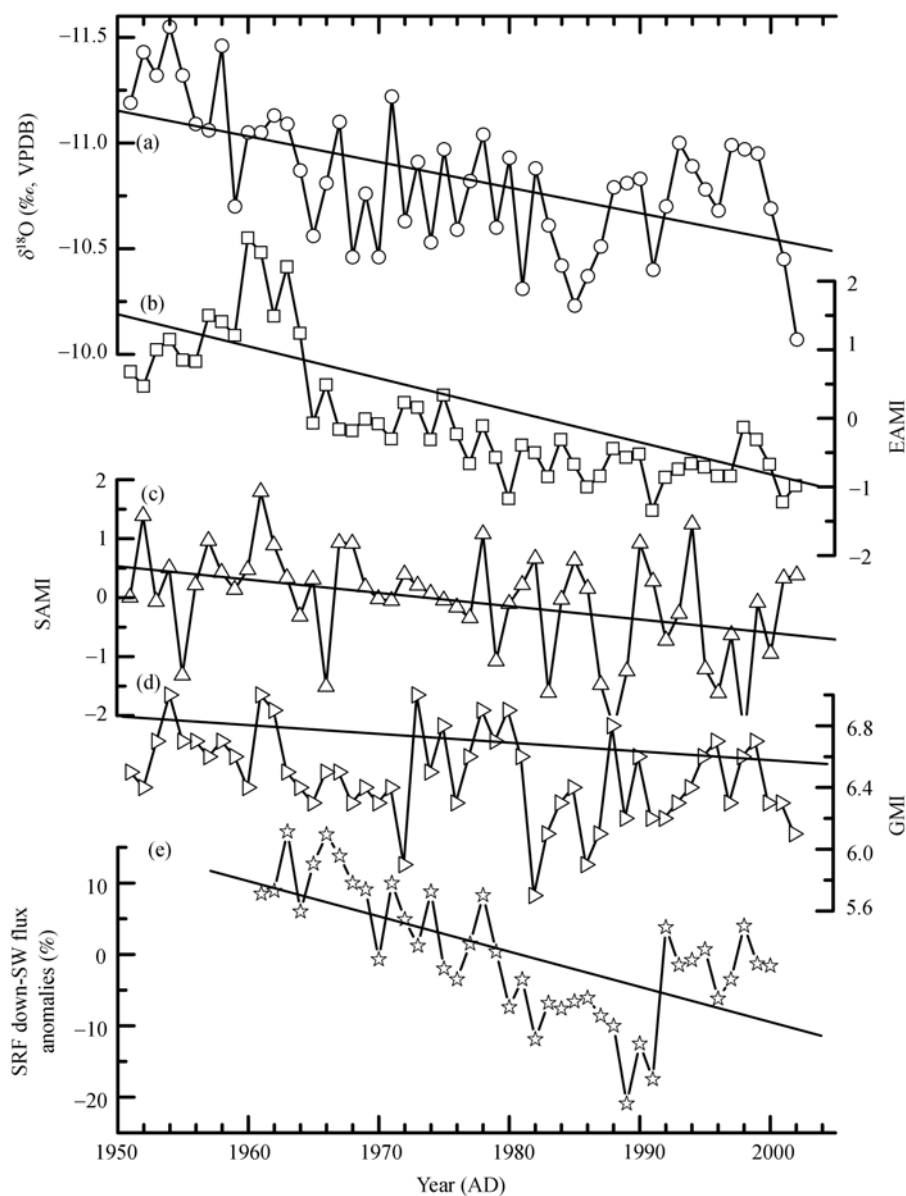


Figure 6 Comparison of HL021 $\delta^{18}\text{O}$ record (1951–2002) with various monsoon indices and insolation in South China. (a) HL021 $\delta^{18}\text{O}$ record; (b) East Asian monsoon index (EAMI)^[31]; (c) South Asian monsoon index (SAMI)^[32]; (d) global monsoon index (GMI)^[33]; (e) solar insolation anomalies in South China (SRF down-SW flux anomalies)^[34]. Oblique lines indicate their trends by linear fitting.

Hemisphere summer solar insolation^[11,26,27,41–43]. However, the causes of the monsoon changes are relatively complex on inter-decadal time scales. Based on instrumental meteorological data provided by NCEP and Climate Data Center of Chinese Meteorological Administration (CDC/CMA), Xia et al.^[34] found that insolation declined significantly in China from 1961 to 2000, and the largest decline appeared in southern China, where solar insolation decreased by 5% per decade. The variations of insolation is negatively correlated to the $\delta^{18}\text{O}$ variations of Huanglong Cave during the same period,

and the correlation coefficient for the full record is -0.36 (significant at the 95.00% confidence level), which suggests that monsoon changes were affected by the changes of insolation on inter-decadal time scales. He et al.^[44] pointed out that the variations of the summer monsoon were closely related to the middle and upper tropospheric temperature variations, and the weakening of the summer monsoon happened in the mid-1960s mainly due to the obvious decline of the troposphere temperature in the East Asian monsoon regions and the African monsoon regions. Based on Microwave Sound-

ing Unit satellite observations and model simulation, Ramaswamy et al.^[45] revealed that the gradual cooling of the global lower stratosphere over 1979–2003 could be attributed to natural and anthropogenic influences on the evolution of the cooling. Box and Cohen^[46] have recently confirmed that the temperature of the upper troposphere and the stratosphere over Greenland was gradually lowering in 1964–2005. Vecchi et al.^[47] pointed out that global warming gradually reduced the sea level pressure gradient of tropical Indo-Pacific, which consequently led to the weakening of the Pacific Walker circulation and influenced the monsoonal circulations over adjacent continents since the mid-nineteenth century. In summary, instrumental observation data indicate that the solar radiation in China monsoon regions is weakening, and the temperature of the stratosphere and the upper troposphere is also decreasing^[44–48]. Therefore, it is a natural cause that possibly leads to the weakening of the Asian monsoon over the past 50 years. Up to now, exploring the reasons of the weakening of the Asian monsoon intensity on short scales is still in a preliminary stage, and better understanding of factor candidates and consequent mechanisms related to the weakening is of great significance for future climate forecast.

3 Conclusions

The changes of the stalagmite $\delta^{18}\text{O}$ of high-elevation Huanglong Cave, located on the eastern margin of the Qinghai-Tibet Plateau, were sensitive to the changes of the Asian monsoon.

The study on modern stalagmite deposition process and replication tests for isotopic equilibrium suggest that cave dripwater mainly originated from meteoric precipitation and the oxygen isotope composition of stalagmite could indicate the climate change outside Huanglong Cave. The high resolution stalagmite $\delta^{18}\text{O}$ record over the past 50 years allows us to compare this record with instrumental meteorological data, and we find that the stalagmite $\delta^{18}\text{O}$ record of Huanglong Cave largely reflected the changes in the $\delta^{18}\text{O}$ of precipitation conveyed through the southwest monsoon, while temperature effect on changes of the stalagmite $\delta^{18}\text{O}$ values is relatively weak. The stalagmite $\delta^{18}\text{O}$ records in the Asian monsoon regions reflect variations of the Asian monsoon and represent the information of the oxygen isotopes of monsoon precipitation not only on glacial/interglacial scales, but also on inter-decadal time scales.

The $\delta^{18}\text{O}$ record of Huanglong Cave and other stalagmite $\delta^{18}\text{O}$ records in the Asian monsoon regions all show that the Asian monsoon was gradually weakening over the past half century. The variations of $\delta^{18}\text{O}$ record in Huanglong Cave are consistent with variations of monsoonal indices reconstructed by meteorological data. The weakening of the modern Asian monsoon is likely to result from the energy reduce of solar radiation, temperature decrease of the high-altitude stratosphere and the upper troposphere, etc.

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