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Research Article

Mid-Late Holocene Stalagmite $\delta^{18}O$ and $\delta^{13}C$ Records in Naduo Cave, Guizhou Province, China

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Global warming and climate anomalies have attracted worldwide attention. The study of global climate change has received increasing attention from all countries and fields worldwide. Paleoclimate research is an important way to understand past global change and environmental evolution and to simulate and predict future climate development. A stalagmite ND3 collected in Naduo Cave was used to reconstruct the history of local climate and environmental changes from 0.55 to 5.07 ka BP based on the data of 13 ^{230}Th ages and 642 groups of oxygen and carbon stable isotopes. First, according to correlation analysis, $\delta^{18}O$ and $\delta^{13}C$ were significantly correlated (correlation coefficient $r = 0.308$, $n = 318$, $P < 0.001$) during the 5.07–2.00 ka BP period. However, during the period of 2–0.55 ka BP, there was no significant correlation ($P > 0.05$). The $\delta^{18}O$ and $\delta^{13}C$ data indicate that the climatic environment changed asynchronously during the period of 2.00–0.55 ka BP. During the period of 5.07–2.00 ka BP, the influence of human activities was weak, and $\delta^{18}O$ and $\delta^{13}C$ indicate similar climatic and environmental conditions, both of which changed in the same direction (positive correlation). In other words, when $\delta^{18}O$ was positive, it indicated weak summer monsoons and lower precipitation, which led to declines in vegetation, weakened biological activity, and decreased soil CO_2 and positive $\delta^{13}C$. The reverse patterns were also true. Since 2.0 ka BP, the intensity of human activities and the transformation and influence of surface vegetation have increased, and native vegetation has been destroyed in large quantities. Therefore, the climatic and environmental significance indicated by $\delta^{13}C$ and $\delta^{18}O$ has been well demonstrated. Second, the $\delta^{18}O$ records showed that stalagmite ND3 responded to the weak monsoon drought events of 4.2 ka BP and 2.8 ka BP in the Holocene in a discontinuous deposition manner, which brings up new directions for future research.

1. Introduction

Paleoclimate research is an important way to understand past global change and environmental evolution and to simulate and predict future climate development. Among all kinds of high-resolution palaeoenvironmental record carriers, karst cave stalagmites have become an important carriers of late Quaternary palaeoenvironmental research because of their highly-precise age dating and reliability as palaeoenvironmental records. In the historical evolution of human society, human survival and climate change are closely related, and climate change has had a profound impact on the development of human society. Climate change in the mid-late Holocene was closely related to several changes in civilization throughout human history. The discussion on climate change is not only an important scientific issue but also an important issue concerning the survival and development of human society.

Karst cave stalagmites have enabled remarkable achievements in paleoclimate research because they allow for accurate dating and high-resolution continuous records [1–6]. However, with the broadening research, many important technical and scientific problems still need to be solved. The timing, cycle, and mechanism of millennial-scale climate fluctuations during the Holocene are controversial [7–9]. On a multidecadal scale, these climate fluctuations also show complex characteristics, which are closely related to solar activity and the internal variability of the Earth system due to the PDO (Pacific Decadal Oscillation) and NAO (Northern Atlantic Oscillation) [10], for example. On the interdecadal scale, fluctuations may be closely related to sunspot activity [11–13]. On the interannual scale, fluctuations may be mainly controlled by the 2- to 7-year ENSO (El Niño-Southern Oscillation) cycle [14–16]. Therefore, it is helpful to study the timing, duration, and internal characteristics of millennium climate events, especially those from the mid-late Holocene, to better understand the climate interaction mechanism between the land, atmosphere, and ocean, and to deepen the understanding of the characteristics and mechanisms of global climate change. Current climate simulations [17, 18] and modern climate research [19] have conducted extensive studies on the interannual-decadal-multidecadal scale, but there are still many problems, such as the driving mechanism of the ENSO cycle. The characteristics of climate change and its driving mechanism at different time scales are different. In conclusion, the climate anomalies accurately recorded, with high precision and high resolution, by Holocene stalagmites, are associated with the development of human society, and the study of the paleoclimate and palaeoenvironment in the mid-late Holocene is of great importance to the sustainable development of human society.

Based on the data of 13 ^{230}Th ages and 642 groups of oxygen and carbon stable isotopes of stalagmite in Naduo Cave, Guizhou, China, the history of climate and environmental changes in the study area during the period of 0.55 to 5.07 ka BP is discussed in this paper.

2. Materials and Methods

2.1. Overview of the Study Area. The research area is located in southwestern Guizhou Province, China (Figure 1(a)). It belongs to the ridge slope of the eastern part of the Yunnan-Guizhou Plateau and the south side of the Guangxi hilly slope. There are rolling mountains with high terrain in the northwest and low terrain in the southeast. The landforms are undulating and complex. Carbonate rocks are widely distributed, with many caves, wells, springs, depressions, and overlying river sections. The soil mainly includes mountain brown-yellow soil, yellow soil, red soil, nonzonal lime soil, and purple soil. Jointly influenced by the East Asian monsoon and the southwest monsoon, the region is a typical subtropical monsoon humid climate zone. According to the meteorological data in this region, the average annual rainfall is 1 268 mm, and the average annual temperature is 16.2°C. The dry and wet seasons in the study area are obvious. The rainy season is from May to October, and the precipitation from this season accounts for more than 80% [20, 21] of the total precipitation annually.

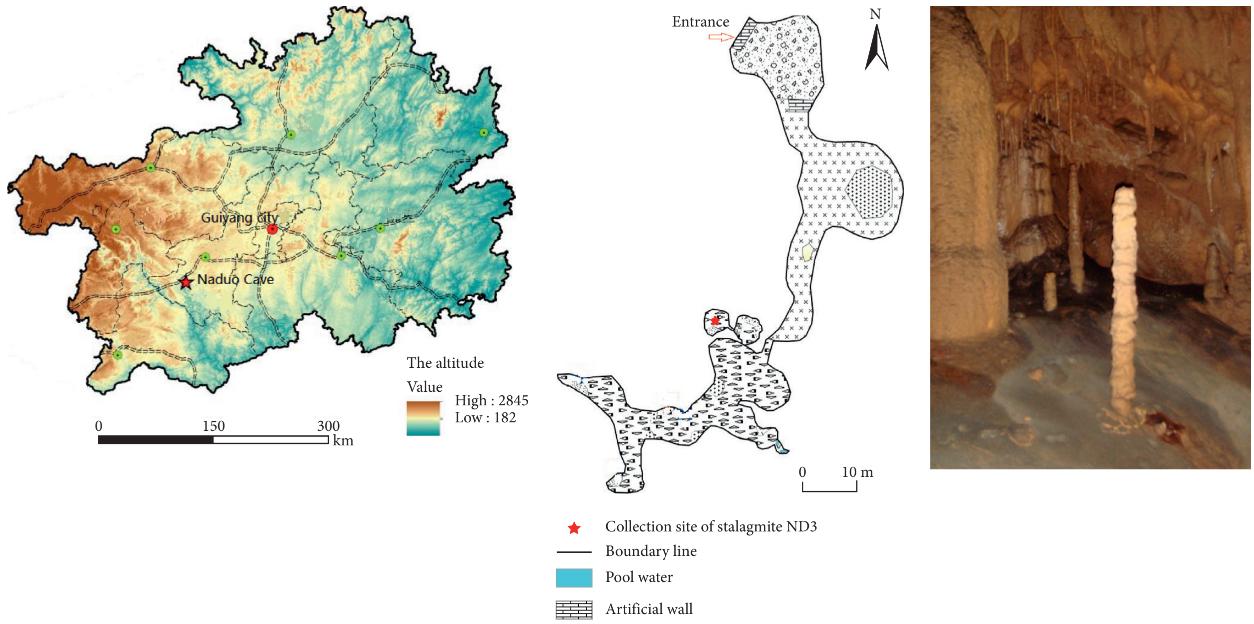
The research site, Naduo Cave (105°35′ E, 25°49′ N, and elevation ~1.191 m), is located in Xiangluo Village on the north bank of the Beipan River, approximately 143 km away from Guiyang City (Figure 1(a)). The cave is developed in the Triassic Yongningzhen Formation (T_1yn). It is mainly composed of light gray to dark gray limestone, argillaceous limestone and dolomite, interspersed with gray-yellow, and yellowish green and purple sandy shales. The stalagmite ND3 was collected in the third cave hall from the cave entrance. There is a narrow passage approximately 5 m long between the second and third great cave halls, and the cave environment is relatively closed (Figure 1(b)) [20, 22].

2.2. ^{230}Th Age Dating and Oxygen and Carbon Stable Isotopes

2.2.1. Description of Stalagmite ND3. The stalagmite ND3 was collected in July 2012 in Naduo Cave, approximately 210 m away from the entrance of the cave. It grew in the middle of a relatively closed, small cave hall next to the third hall of the upper cave, with a height of approximately 645 mm and water dropping from a height of approximately 2.1 m above it (Figure 1(c)). Stalagmite ND3 is columnar with stable growth, and the diameter does not change much from top to bottom. The top diameter is approximately 55 mm, and the bottom diameter is approximately 70 mm, which is suitable for paleoclimatic reconstruction. The stalagmite is composed of calcite with a weathering crust on the outer edge and no recrystallization. After cutting and polishing along the growth axis, the section from the top to a depth of 234 mm was found to be off-white, and the stalagmite gradually darkened with increased depth.

2.2.2. ^{230}Th Age Dating. Table 1 shows the test results of the stalagmite ND3 ^{230}Th age dating. The samples at depths of 477.5 mm, 411.0 mm, 347.9 mm, and 9.5 mm were tested in the Isotope Chronology Laboratory at the Department of Geology and Geophysics at the University of Minnesota, and the rest of the dating samples were tested in the Isotope Laboratory at Xi'an Jiaotong University. To reduce dating errors, a spiral alloy dental drill with a diameter of 0.5 mm was used to drill powder along the growth layer of the sample near the growth axis of the stalagmite in the Isotope Laboratory at Xi 'an Jiaotong University. Considering the low uranium content of the sample (^{238}U: 65–110 PPB, PPB stands for 10^{-9} g/g), approximately 200–300 mg powder samples were collected for dating tests. Chemical separation steps were performed according to the methods of Edwards et al. [23] and Cheng et al. [24], and the uranium and thorium obtained after separation were tested by Neptune-Plus (MC-ICP-MS). External calibration of the instrument was performed using a uranium isotope standard solution, a mixture of the NBL-112A (New Brunswick Laboratory) uranium isotope standard (where the ^{234}U/^{238}U atomic ratio is 0.000052841, ^{234}U is equal to −38.5, and the ^{235}U/^{238}U atomic ratio is 0.0072543), and a lab-configured diluent, in which the ratio of ^{235}U to ^{233}U in the mixed solution was usually approximately 10 : 1. Using this laboratory standard, Peakcenter (estimated by measuring the 237/238 ratio), trailing calibration, and instrument stability testing (evaluated by comparing standard measurements with real values) could be carried out, and samples could be tested when the instrument was ready. The U isotope and Th isotope samples were measured alternately. The ^{230}Th dating results of the stalagmite ND3 are shown in Table 1.

2.2.3. Oxygen and Carbon Stable Isotopes. The oxygen and carbon isotopes of stalagmites were measured by Kiel IV automatic carbonate samplers coupled with a Delta V Plus mass spectrometer and analyzed in the Isotope Laboratory of the School of Geographic Sciences at Southwest University.



(a) (b) (c)

Figure 1: Stalagmite ND3 and the location and plan of Naduo Cave.

The main purpose of the experiment was to conduct a $CaCO_3$ powder and H_3PO_4 reaction, and then, perform a series of measures such as cooling and heating to remove impurities such as inert gases and water vapor gas to separate the pure CO_2 gas, and then, isolate the CO_2 gas mass spectrometer to test the final sample of the alternating gas with standard gas for ion source detection. During the oxygen and carbon isotope tests, a total of 46 samples were measured each time. Two laboratory standard samples (SWU-1) were first measured to ensure the stability of the instrument before the samples were taken for more accurate results. After that, one standard sample was measured for every nine samples, with $\delta^{18}O$ and $\delta^{13}C$ deviations <0.1%, relative to the V-PDB (Vienna Pee Dee Belemnite) standard.

3. Results and Discussion

3.1. The Age Model. In this study, 13 ^{230}Th age dating data were obtained from 5.07 ka BP to 0.55 ka BP (Table 1). The age errors at stalagmite depths of 411.0 mm and 477.5 mm were ±186 years and ±178 years, respectively. 10 ^{230}Th years were obtained from 0 to 234 mm. The age error was ±23–66, and the mean error was ±45 years. Based on 13 ^{230}Th ages, the Origin program was used to establish the age model of stalagmite ND3 (Figure 2). From 5.07 ka BP to 0.55 ka BP, the stalagmite depth was 477.5–4 mm, and the average growth rate was approximately 0.10 mm/a. As shown in Figure 3, the growth rate from 215.7 mm to 9.5 mm was fast, the growth age was approximately 2.07 ka BP to 0.58 ka BP, and the average growth rate was approximately 0.14 mm/a. Below 234 mm from the top, the stalagmite contained more impurities, less uranium, and more thorium; thus, the ^{230}Th age dating error was larger.

3.2. Stable Isotope Records. A total of 642 sets of oxygen and carbon stable isotope data were obtained using stalagmite ND3. Combined with the age model, the oxygen and carbon isotope time series were established (Figure 3), with an average resolution of approximately 6–7 years. The $\delta^{18}O$ values ranged from −7.0% to −10.8%, with a range of 3.8% and an average of −9.0%. The $\delta^{13}C$ values ranged from −1.9% to −12.3%, with a large variation of approximately 10.5% and an average of −8.9%. From 5.07 ka BP to 2.0 ka BP, the $\delta^{18}O$ and $\delta^{13}C$ values of stalagmite ND3 showed the same trend, but from 2 ka BP to 0.55 ka BP, $\delta^{13}C$ showed high-frequency oscillation with two strong, positive stages. Correlation analysis was conducted using SPSS statistical software. The Pearson linear correlation coefficients of $\delta^{18}O$ and $\delta^{13}C$ from 5.07 ka BP to ~2 ka BP were $r = 0.308$ ($n = 318$, $P < 0.001$), but $\delta^{18}O$ and $\delta^{13}C$ did not pass the correlation test between 2.0 ka BP and 0.55 ka BP ($P > 0.05$). The reason for this was that the $\delta^{18}O$ and $\delta^{13}C$ indicators of climate and environment changed asynchronously from 2.0 ka BP to ~0.55 ka BP due to the addition of external forces. From 5.07 to 2.0 ka BP, the influence of human activities was weak, and $\delta^{18}O$ and $\delta^{13}C$ indicated a similar climatic environment, which means that they changed in the same direction (positive correlation): when $\delta^{18}O$ was positive, this indicated a weaker summer monsoon and decreased precipitation, which led to declining vegetation, a weakening of biological activities, decreased soil CO_2, and finally, a positive $\delta^{13}C$. The reverse pattern was also true; when $\delta^{18}O$ was negative, this indicated a stronger summer monsoon and increased precipitation, which led to flourishing vegetation, a strengthening of biological activities, increased soil CO_2, and finally, a negative $\delta^{13}C$. However, since 2.0 ka BP, the intensity of human activities has increased, which has transformed and influenced surface vegetation and destroyed much native

Table 1: ^{230}Th age dating results of the stalagmite ND3 from Naduo Cave.

Depth (mm)	^{238}U (ppb)		^{232}Th (ppt)		$^{230}Th/^{232}Th$ (atomic·10^{-6})		$\delta^{234}U$ (measured)		$^{230}Th/^{238}U$ (activity)		$\delta^{234}U_{Initial}$ (corrected)		^{230}Th age (a BP*) (corrected)	
9.5	82.0	±0.1	54	±1	197	±13	286.5	±2.1	0.0078	±0.0005	287	±2	587	±41
17.5	70.1	±0.1	52	±1	196	±15	292.5	±1.9	0.0088	±0.0006	293	±2	663	±54
36.5	77.8	±0.1	83	±2	151	±5	293.6	±1.4	0.0098	±0.0002	294	±1	740	±24
54.5	74.9	±0.1	128	±3	103	±3	295.5	±1.5	0.0107	±0.0002	296	±2	797	±34
84.8	96.9	±0.1	332	±7	69	±3	339.5	±1.9	0.0142	±0.0005	341	±2	1025	±66
102.5	101.3	±0.1	76	±2	359	±10	366.5	±1.4	0.0164	±0.0002	368	±1	1232	±23
146.0	81.0	±0.1	198	±4	145	±5	385.1	±1.8	0.0215	±0.0007	387	±2	1585	±65
164.0	96.4	±0.1	180	±4	230	±6	441.5	±2.1	0.0261	±0.0004	444	±2	1888	±40
215.7	85.7	±0.1	84	±3	427	±14	445.4	±2.2	0.0274	±0.0005	448	±2	2074	±42
234.0	75.4	±0.1	147	±3	308	±8	457.9	±2.4	0.0363	±0.0007	461	±2	2645	±58
347.9	66.1	±0.1	129	±3	397	±13	412.8	±2.6	0.0471	±0.0011	417	±3	3648	±95
411.0	67.1	±0.1	468	±10	131	±6	544.9	±4.0	0.0554	±0.0022	551	±4	3846	±186
477.5	81.1	±0.2	947	±19	95	±2	410.4	±2.8	0.0672	±0.0007	416	±3	5072	±178

*BP = before the present; the present = 1950 AD.

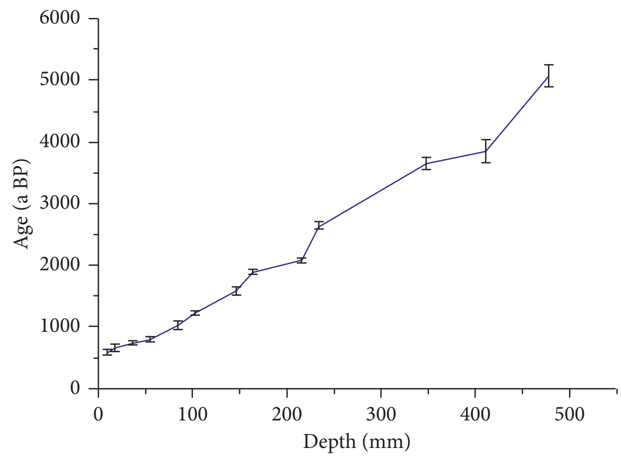


FIGURE 2: The age model of stalagmite ND3 in Naduo Cave (linear interpolation).

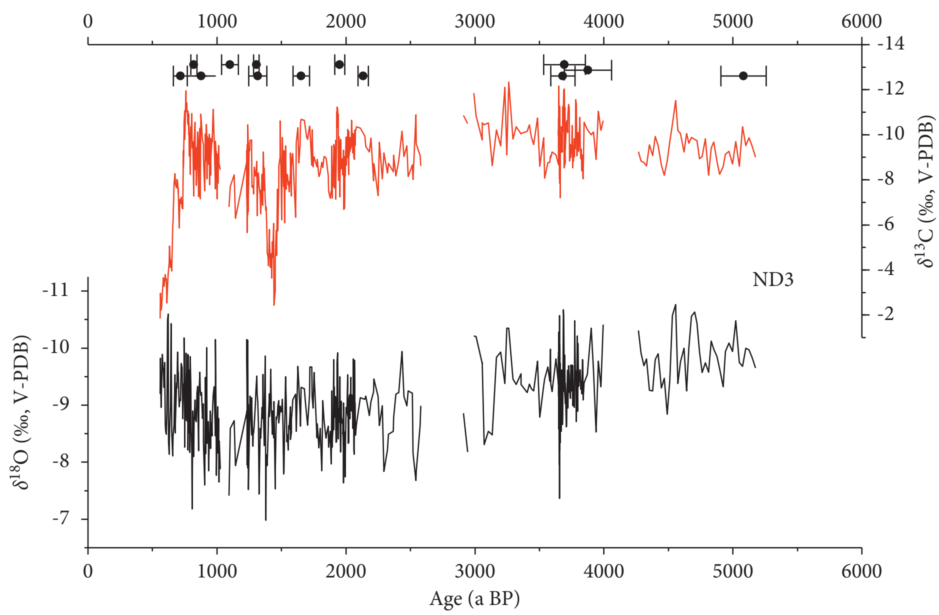


FIGURE 3: Stable isotope records of stalagmite ND3 from Naduo Cave.

vegetation. Therefore, the climatic and environmental significance indicated by δ^{13}C and δ^{18}O were well demonstrated [25].

3.3. Spectral Analysis of Stalagmite δ^{18}O. The periodicity of climate change is an important part of climate change research [26]. There are high-frequency fluctuations in stalagmite ND3 high-resolution oxygen isotope (δ^{18}O) records, especially in the past 2 000 years. In this paper, REDFIT was used to analyze the power spectrum of the stalagmite ND3 δ^{18}O sequence (Figure 4). The results showed that the stalagmite ND3 δ^{18}O sequence had a large number of periodic variations with different time frequencies, and the 250-year, 200-year, 54-year, 25-year, and 21-year periods exceeded 95% confidence. However, considering the 6–7 year isotopic resolution of the samples, smaller periods are not shown in the figure. Further comparison suggests that the 21-year and 200-year cycles may be influenced by solar activity cycles [27]. For example, the study of ice cores in eastern Antarctica has shown that there were 200-year periodic oscillations in atmospheric circulation over the last 5 000 years [28]. The 54-year cycle may be closely related to the Pacific Decadal Oscillation (PDO) on a larger time scale [29, 30]. However, further comparison requires additional stalagmite records and simulation data.

3.4. Middle-Late Holocene Climatic Fluctuations. The oxygen isotopic sequence of stalagmite ND3 can be divided into three stages from 5.07 ka BP to 0.55 ka BP according to the various characteristics of δ^{18}O, namely, positive change, stationary fluctuation, and negative change (Figure 3).

(1) Positive variation stage: from 5.07 ka BP to 2 ka BP, the stalagmite δ^{18}O values continued to be positive, with a fluctuation range of −10.8% to −7.4% and an

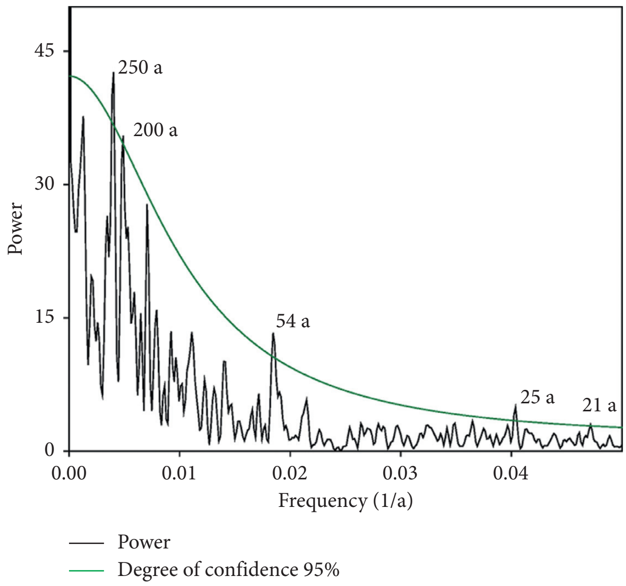


Figure 4: Spectrum analysis of stalagmite ND3 $\delta^{18}O$ sequence by REDFIT.

average of −9.9%. It was found that solar radiation has decreased since 5.07 ka BP [31]. The cooling of the North Atlantic ocean, the change in the temperature gradient of the interhemispheric ocean surface, and the southward movement of the equatorial convergence zone (ITCZ) led to the weakening of the mid-low-latitude monsoon in the Northern Hemisphere [32] and the stalagmite oxygen isotope value changed from a negative state to a positive state [33]. The climate changed from warm to dry. In the periods of 4.26 ka BP to ~3.99 ka BP (2316–2043 B. C.) and 2.91 ka BP to ~2.58 ka BP (907–585 B. C.), stalagmite ND3 occurred after approximately 270 and 320 years of sedimentary discontinuities, respectively. Stalagmite growth was also in response to the weak monsoon events of 4.2 ka BP and 2.8 ka BP. Such centennial-scale variations in weak monsoon events throughout the Holocene were due to the effects of solar activity [34–36] superimposed on atmospheric circulation [37, 38].

(2) Stationary fluctuation stage: from 2.0 ka BP to 0.96 ka BP, the $\delta^{18}O$ values varied from −10.2% to 6.9% with an average of −8.7%, which recorded the weak monsoon events at centennial scales of 1.9 ka BP, 1.5 ka BP, and 1.0 ka BP. The climate at this stage was relatively dry and stable. Its dynamic process may have been due to the change in Atlantic meridional overturning circulation and accompanying climatic feedback [39]. The $\delta^{18}O$ of stalagmite ND3 recorded the “2 kyr shift” phenomenon of abnormal Asian monsoon changes from “positive change-stationary fluctuation” [4]. In addition, Heshang Cave [40], Jiuxian Cave [41], Lianhua Cave [42–44], and Xianglong Cave [45] have cave stalagmite $\delta^{18}O$ values that also have a “2 kyr shift” record. Since 2.0 ka BP, the influence of solar radiation has weakened, while the Asian monsoon has increased abnormally, which may be mainly controlled by the Rossby wave [46].

(3) Negative change stage: from 0.96 ka BP to 0.55 ka BP (1031–1445 A.D.), the $\delta^{18}O$ values varied from −10.6% to −7.2%, with an average value of −9.0%. During this stage, the oxygen isotope of the stalagmite gradually became negative, and the climate changed from dry to warm and wet, entering the “Medieval Warm Period” [47].

The $\delta^{18}O$ and $\delta^{13}C$ records changed in opposite directions from approximately 0.75 ka BP to 0.55 ka BP (approximately 1250 A. D to 1445 A. D), with $\delta^{18}O$ gradually becoming negative and $\delta^{13}C$ values becoming nearly positive. During 0.75 ka BP to ~0.55 ka BP, the stalagmite $\delta^{13}C$ ranged from −11.1 to −1.8%, with a variation of 9.3%, indicating that reverse succession occurred over Naduo Cave, which may be similar to today’s rocky desertification landscape [48–50]. After the Southern Song dynasty, human activities increased [51], and vegetation was degraded [25]. In the Ming dynasty, due to the mobilization of troops and reclamation of wasteland, rocky desertification already existed in some areas of Guizhou [52]. During this period, there were frequent human activities, especially military activities, in the Guanling area, and the war caused damage to the local ecological environment. It is speculated that the stone wall at the entrance of Naduo Cave may have been built by local minorities to avoid the war.

3.5. Comparison of Stalagmites Oxygen Isotope Records in Different Regions. As shown in Figure 5, we can see that stalagmite ND3 oxygen isotope records showed depositional breaks during both the “4.2 ka” and “2.8 ka” events, which indicate two significant weak monsoon events in the Holocene [53]. According to the actual observation during the monitoring period from 2013 to 2016, the drip rate of D2 (the drip monitoring point), which was less than 1 meter away from stalagmite ND3, was approximately 1 drop every 3–4 minutes in the dry season, with a small drip quantity [54]. It was observed from the glass sheets of the newly-formed calcium carbonate deposits, placed in situ by collecting stalagmite ND3, that spot deposition could be observed in the rainy season but not in the dry season. Therefore, it was speculated that water drops were intermittent in the dry season, while there were small amounts of water drops in the rainy season, so deposition occurred. Stalagmite ND3 oxygen isotope was recorded in the depositional discontinuities of the “4.2 ka” and “2.8 ka” events, which suggests that drought in the study area resulted in depositional discontinuities during the two weak monsoon events.

Many high-resolution paleoclimatic records (such as lacustrine sediment, peat, and stalagmites) show that there were several centennial-scale climatic fluctuations in the Holocene, such as in 8.2 ka BP, 4.2 ka BP, and 2.8 ka BP. During weak monsoon events, precipitation generally decreases in southern and northern China. At the same time, there were severe droughts in tropical Africa, southern

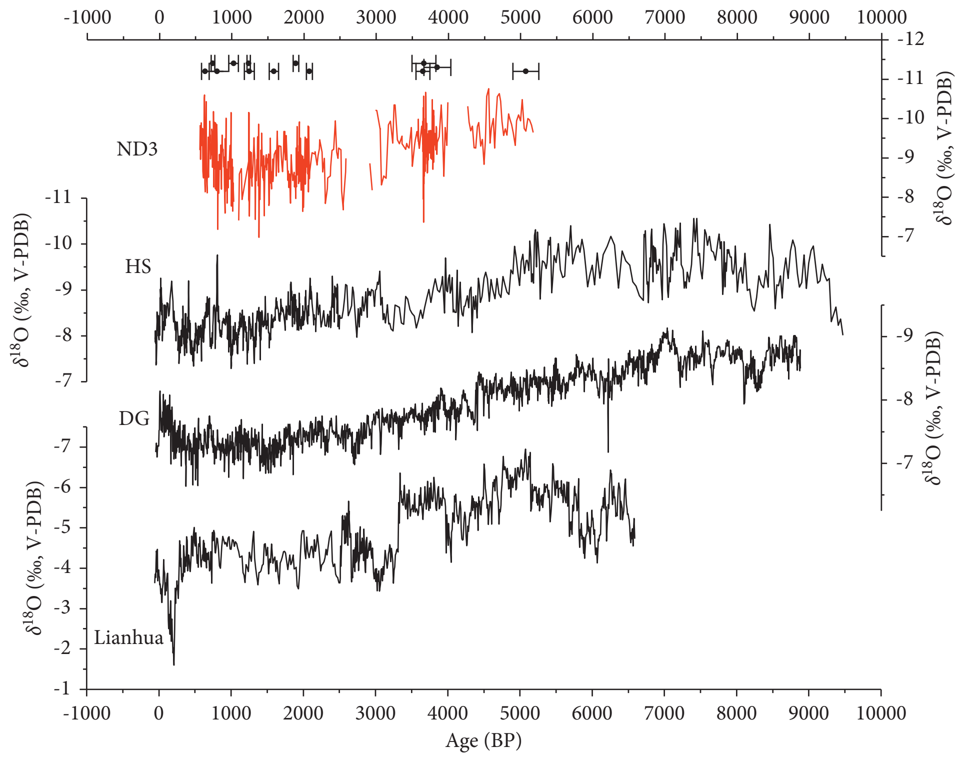


Figure 5: Comparison of stalagmites δ^{18}O records from the mid-late Holocene. HS: Heshang Cave (Hu et al.,), DG: Dongge Cave (Wang et al.,), and Lianhua: Lianhua Cave (Jason et al.,).

Europe, the Middle East, India, Korea, and central North America. In particular, the dry climatic events in 4.2 ka BP and 8.2 ka BP affected the middle and lower latitudes of the Northern Hemisphere. The main causes may be the southward shift of the ITCZ caused by the change in solar radiation, the change in SST (sea surface temperature) over the ocean, and the feedback effect of surface vegetation. However, a thorough study of the incident is warranted. It is important to determine whether this drought event, which spread across the middle and low latitudes of the Northern Hemisphere, was abrupt or gradual in its timing or showed different patterns in different regions.

The records of both the African and North American monsoon regions showed characteristics of abrupt changes, while the Asian monsoon region presented a complex pattern [55]. First, some records showed a strong, abrupt climate [55–59], while some showed transient drought fluctuations superimposed on the overall weakening trend of the Asian monsoon during the Middle Holocene [31, 60–62]. Second, we found that although there were dry climatic events in the middle and low latitudes of the Northern Hemisphere in 4.2 ka BP, the onset time and relative variation range were different in different regions, and the difference in the onset time in some regions could reach hundreds of years. For example, the stalagmite δ^{18}O increased by 1.61% (approximately 0.2 ka) from 4.08 ka BP to 3.89 ka BP, indicating that the climate in this area changed at about 4.1 ka BP and that the summer monsoon rainfall decreased significantly [63]. The stalagmite of Dongge Cave in Guizhou also indicated a decline in the Asian summer monsoon intensity at 4.4 ka BP [64]. This significant decline in monsoon precipitation was also reflected in the stalagmite δ^{18}O records from Baigu Cave in Guizhou [65].

As abovementioned, from 2.91 ka BP to ~2.58 ka BP (c. 907–585 BC to c. 320 BC), the δ^{18}O records of stalagmite ND3 were discontinuous in response to the “2.8 ka” weak monsoon event. Compared with the δ^{18}O values of stalagmite HS from the Heshang Cave [40], stalagmite DG from Dongge Cave [64], and stalagmite from the Lianhua cave [66], the δ^{18}O records of stalagmite ND3 are similar (Figure 5). The weak monsoon events recorded over the centennial scale of 2.8 ka BP, 2.4 ka BP, 1.9 ka BP, 1.5 ka BP, and 1.0 ka BP are reflected in the Asian summer monsoons (Figure 5), and they may be related to the North Atlantic Bond event and weak global monsoon events. In the vicinity of the 4.2 ka event, stalagmite ND3 was discontinuous for approximately 270 years, which is basically consistent with previous studies.

There are many possible factors for the occurrence of drought events in the middle and low latitudes of the Northern Hemisphere around 4.2 ka BP, including ocean changes (such as ocean surface temperature (SST) change, North Atlantic Oscillation (NAO), North Pacific Oscillation (NPO), and thermohaline circulation), the position of the equatorial Convergence Zone (ITCZ), El Nino-Southern Oscillation (ENSO), solar activity and volcanic eruption, changes of the Eurasian ice sheet and surface feedback, and atmospheric composition changes (such as CO_2 and CH_4 concentrations). Another abrupt climate change event affecting the Northern Hemisphere occurred at about 8.2 ka

BP during the Holocene, which is believed to have been caused by the retreat of Laurentide cover in North America due to the rising temperatures during the Holocene. The internal dynamics of the ice sheet caused the ice banks of Lake Agassiz to collapse, flooding the Atlantic with fresh water and weakening or halting the thermohaline circulation that then spread throughout the Northern Hemisphere. Thus, ice sheet changes may also have contributed to the emergence of a widespread cold and dry climate in the Northern Hemisphere around 4.2 ka BP; however, since ice sheets had retreated from most of the Northern Hemisphere by around 4.2 ka BP, it is less likely that internal ice sheet dynamics were the main trigger for the 4.2 ka BP event [67]. Most of the knowledge about the factors that triggered this climate event focused on solar radiation and volcanic eruptions, but different researchers have different views on the mechanism of amplification and transmission [57, 62, 68–70]. Some researchers have emphasized the magnification effect of tropical surface conditions such as vegetation coverage, soil moisture, and wetland CH_4 production on solar radiation-related monsoon changes caused by minor earth orbit changes [71, 72]. Hong et al. [68] believed that the change in solar radiation may have led to an increase in floating ice in the North Atlantic and a dilution of sea water, thus slowing the transition of the thermohaline circulation, resulting in an increased temperature in the Indian Ocean, a decreased difference between land and sea temperatures, and a weakening of the Indian monsoon. Fleitmann et al. [62] believed that orbital-driven solar radiation changes caused the weakening of the ITCZ and Asian monsoon since the Middle Holocene, leading to drought in most of the Northern Hemisphere's midlatitudes during the mid-late Holocene transition. Marshall et al. [73] found that the decrease in rainfall in Africa was related to the increase in SST in the South Atlantic and the decrease in SST in the North Atlantic [73]. Gasse pointed out that the cold SST in the North Atlantic around 4.2 ka BP led to the weakening of the African monsoons [74]. Therefore, the $\delta^{18}O$ records of stalagmite ND3 corresponded to 2.8 kyr BP and 4.2 kyr BP drought events, which were closely related to the weakening of the monsoons, and further study is required to determine whether the internal events were sustained by drought.

According to the $\delta^{18}O$ data from the stalagmite in Yongxing Cave, Shennongjia, in the middle reaches of the Yangtze River, China, the evolution of the East Asian summer monsoon with an average resolution of 4 years in the late Holocene resulted in a significant positive deviation of 2.5% between 2.92 ka BP and 2.74 ka BP, indicating a significant weak monsoon event (called the "2.8 ka" event). The internal details and transition characteristics of the event are similar to those of the "8.2 ka" event recorded by stalagmite $\delta^{18}O$ in Heshang Cave, Hubei province, with a two-peak and three-valley structure, which suggests that the characteristics and driving mechanisms of the two cold events in the Holocene may be similar. Both of these weak monsoon events occurred during periods of significantly reduced solar activity and coincided with the Bond 2 and Bond 5 ice drift events in the North Atlantic, respectively, which suggests that the evolution of the East Asian monsoon circulation on a centennial scale was driven by both solar activity and climate in high northern latitudes.

4. Conclusion

(1) From 5.07 ka BP to 0.55 ka BP, the oxygen isotope sequence of stalagmite ND3 could be divided into three stages: positive change, stationary fluctuation, and negative change. Stalagmite ND3 $\delta^{18}O$ recorded the "2 kyr shift" phenomenon of the Asian monsoon anomaly from "positive variation to stationary fluctuation."

(2) From 5.07 ka BP to 2 ka BP, the influence of human activities was weak, and the change in vegetation was mainly controlled by the strength of the monsoons. The $\delta^{18}O$ and $\delta^{13}C$ of stalagmite ND3 showed a synchronous trend. However, since 2.00 ka BP, the intensity of human activities has increased, and the destruction of surface vegetation has accelerated. The reverse succession of native vegetation showed that the influence of human activities on surface vegetation was stronger than that of climate change. The stalagmite $\delta^{13}C$ records showed an abnormal deviation.

(3) In this study, it was found that the carbon stable isotope of stalagmite ND3 from Naduo Cave indicated changes in surface vegetation, and the damage to the natural ecological environment by human activities was also recorded, which provides new directions for future research.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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