The stable oxygen isotope (δ18O) composition of ancient teak log coffins captures the Asian monsoon 2000 years ago in northwestern Thailand

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The stable oxygen isotope ($\delta^{18}O$) composition of ancient teak log coffins captures the Asian monsoon 2000 years ago in northwestern Thailand

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Abstract

The past climate in northwestern Thailand remains insufficiently understood because of the limitation of climate proxies. We present a new record of paleoclimate activity during 2,050 -1,551 years BP (before the present), based on the analysis of the oxygen isotope ratios ($\delta^{18}O$) of tree- ring cellulose in ancient teak log coffins excavated from Namjang Cave in Mae Hong Son Province, northwestern Thailand. The ages of the teak log coffin samples were measured using C-14 dating. The CoffinNJ $\delta^{18}O$ value ranged from 21.23‰ to 25.42‰. The average CoffinNJ $\delta^{18}O$ value was 23.48 ± 0.77‰. The mean May-October (MO) rainfall reconstructed from the CoffinNJ $\delta^{18}O$ data was 274 mm. These MO rainfall data were correlated with stalagmite $\delta^{18}O$ data from Laos, and the two datasets show a significant negative correlation ($r = -0.254$, $p<0.01$), indicating the existence of a weak monsoon during the formation period of the stalagmite in Laos. Additionally, the MO rainfall data were also correlated with reconstructed rainfall in Tibet, and the two datasets show a significant positive correlation ($r = 0.347$, $p<0.01$). Spectral analysis of the CoffinNJ $\delta^{18}O$ values reveals centennial cycles related to the sunspot number. The CoffinNJ $\delta^{18}O$ values have a positive significant correlation with the sunspot number ($r = 0.410$, $p<0.01$) for the entire period. Moreover, we found a highly significant positive correlation ($r = 0.644$, $p<0.01$) between the CoffinNJ $\delta^{18}O$ values and stalagmite $\delta^{18}O$ values from Wanxiang Cave, China and this correlation is related to the variation in the Asian monsoon. We conclude that the CoffinNJ $\delta^{18}O$ data reflect the Asian monsoon from 2000 years ago and have the potential to be a paleoclimate proxy in northwestern Thailand.

Keywords Cellulose; Stable oxygen isotope; Teak log coffin; Archaeology; Mae Hong Son province; Thailand

Declarations

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1 Introduction

Thailand is a significant location for monitoring the effect of the Asian monsoon which is a factor that controls the variability of Earth's climate by transferring heat and humidity from the equator to high latitude regions (Yang and Lau 2006). The Asia monsoon consists of subsystems, including the Western North Pacific monsoons, the East Asian monsoon, and the South Asia-Indian monsoon (Ding 2007). These subsystems have a great impact on human life and agriculture throughout Asia (Loo et al. 2015). Thailand is mainly affected by two monsoon climate systems, the southwest monsoon from the Indian Ocean and the northeast monsoon from the Pacific Ocean (Nieuwolt 1981). Studying the interaction of different monsoon subsystems is very important but unfortunately, the meteorological data obtained by instrumental equipment in Thailand are limited both in spatial and temporal aspects.

Paleoclimatology is the study of the climate and Earth's atmosphere in the past. It is not the direct measurement by using instrumental equipment but a study using climatic proxies such as ice core (Sjolte et al. 2019; Steffensen et al. 2008), lake and ocean sediments (Conroy et al. 2008; Fontugne and Duplessy 1986; Klauda and Sandler 2005), tree rings and speleothems (Band and Yadava 2020; Fang and Li 2019; Yang et al. 2019). These analyses are combined with proxy dating techniques to determine the climate of the past (Bradley 1999). The paleoclimate in northern Thailand has been recorded in many proxies, such as tree rings (Buckley et al. 2007), stalagmites (Cai et al. 2010; Muangsong et al. 2014; Muangsong et al. 2011), and sediments (Chawchai et al. 2013; Tanabe et al. 2003; White et al. 2004). Since most of these archives' proxies are not the data in annual scale, which is not the high resolution, they cannot be used independently to pinpoint rapid environmental changes on the interannual scale and, in most cases, not even with decadal precision, except tree-ring proxy.

Tree-ring width chronology in Thailand can access the past climate, and the longest chronology is 448 years (Buckley et al. 2007). The longest stable oxygen isotope ($\delta^{18}O$) record in tree rings is 338 years (Pumijumnong et al. 2020a). Stable oxygen isotopes in tree rings have also been extensively applied to the reconstruction of past environmental conditions and their changes over time (Danis et al. 2006; Ferrio et al. 2015; Wang et al. 2020). The stable oxygen isotope proxy in tree rings has more advantages than tree-ring width because it is not affected by the juvenile effect (Young et al. 2011). Moreover, it can be used to investigate the moisture source because it reflects the variation in the $\delta^{18}O$ value of the source water (Farquhar and Lloyd 1993; Yakir 1992) and can record the isotopic signature of precipitation events (Leonelli et al. 2017); therefore, it can be used to characterize precipitation events from different origins (Ferrio et al. 2015). Most log coffins found in northwestern Thailand have come from cave in Mae Hong Son Province which have long been studies in research on many aspects of human history (Shoocongdej 2016). Coffin culture found in this region which explicated since in the Iron Age (Shoocongdej 2014). Log coffin were used for burial ancient people. Log coffin head had many styles and have been studies that the styles of coffin head not related to the age of log coffin but might related to the status of the deceased persons or the skill of the coffin maker (Pumijumnong and Wannasri 2015; Shoocongdej 2014; Wannasri et al. 2007). Most log coffins are made from teak trees, which are well known for paleoclimate studies (Pumijumnong et al. 1995). Teak is a good proxy to access the past climate in northwestern Thailand. Thus, this study aims to assess the past climate by using the cellulose stable oxygen isotope ratios ($\delta^{18}O$) from a teak log coffin and to determine the rainfall variability during the study period affected by the Asian monsoon. This study presents the longest series dating back to 106 BC based on alpha cellulose stable oxygen isotope ratios ($\delta^{18}O$) in tree rings from a highland archeological site (a teak log coffin) in Pang Mapha District, Mae Hong Son Province, northwestern Thailand.

2 Materials and methods

2.1 Study area and climatology

The teak log coffin samples were collected from Namjang (NJ) Cave, which is located in the Pang Mapha District of Mae Hong Son province in northwestern Thailand (98°12′12″E, 19°40′30″N, with a cave entrance elevation of ~923 m), as shown in Fig. 1a. The local climate of the study area in the present time was recorded at the Mae Hong Son meteorological station, which is far from Namjang Cave (approximately 45 km southwest of the cave), during 1951–2019 AD. It was reported that the total annual rainfall is approximately 1,262.7 mm, the mean annual temperature is approximately 26.26 °C, the maximum temperature of the hottest month (May) is 43.6 °C, and the minimum temperature of the coldest month (November) is 3.9 °C (Thai Meteorological Department 2019) (Fig. 1b). Most areas of Pang Mapha are mountainous and feature karst topography. It was reported that the climate in this area was influenced by the Asia monsoon cycle (Muangsong et al. 2014). The wet season usually begins around the beginning of May, lasts until the end of October, and peaks in August. The wet season was divided into the early wet season (during May–July) and late wet season (from August–October). The dry season occurred from November to April.

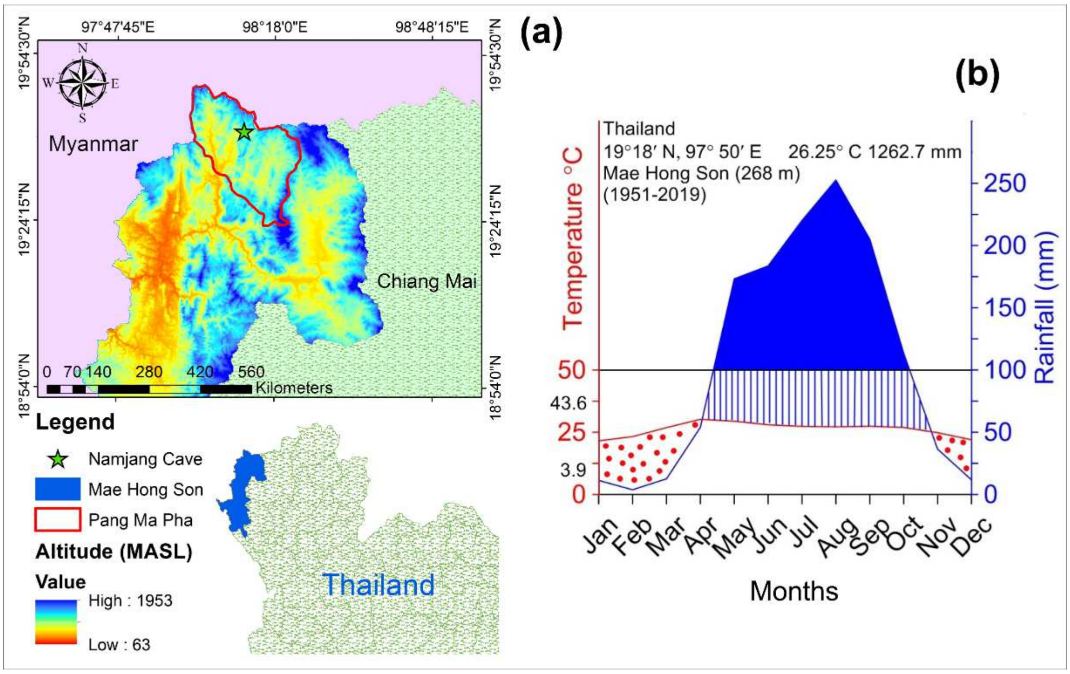

Fig. 1 (a) Location of the study site: the star indicates the location of Namjang Cave, the red line is the boundary of the Pang Mapha district and the blue area is Mae Hong Son Province. (b) Climate diagram for the Mae Hong Son meteorological station; the blue line represents a rainfall curve, and the red line represents the temperature. The red dotted area indicates relatively dry period, blue stripe area indicates relatively humid period and blue solid area indicates mean monthly rainfall > 100 mm. Values on the left axis are the maximum temperature of the warmest month and the minimum temperature of the coldest month. The upper right corner of the diagram shows the annual average temperature and annual total precipitation. The period of the climate data is 1951–2019 AD.

2.2 Sample collection and preparation

The log coffin is archaeological evidence recovered from in the NJ cave. Most of the log coffins are made from teak (*Tectona grandis* L.f.). NJ cave has many log coffins that are decaying over times and have been disturbed by humans, as shown in Fig. 2a. The samples were collected by using a 12 -mm- diameter increment borer. For one log coffin, we collected a sample on both opposite sides which is across the piece from each other. In the laboratory, the samples were mounted on supported wood and fixed with glue. After that, the core samples were polished using sandpaper to make the ring boundary more visible. The core samples after polishing are shown in Fig. 2b.

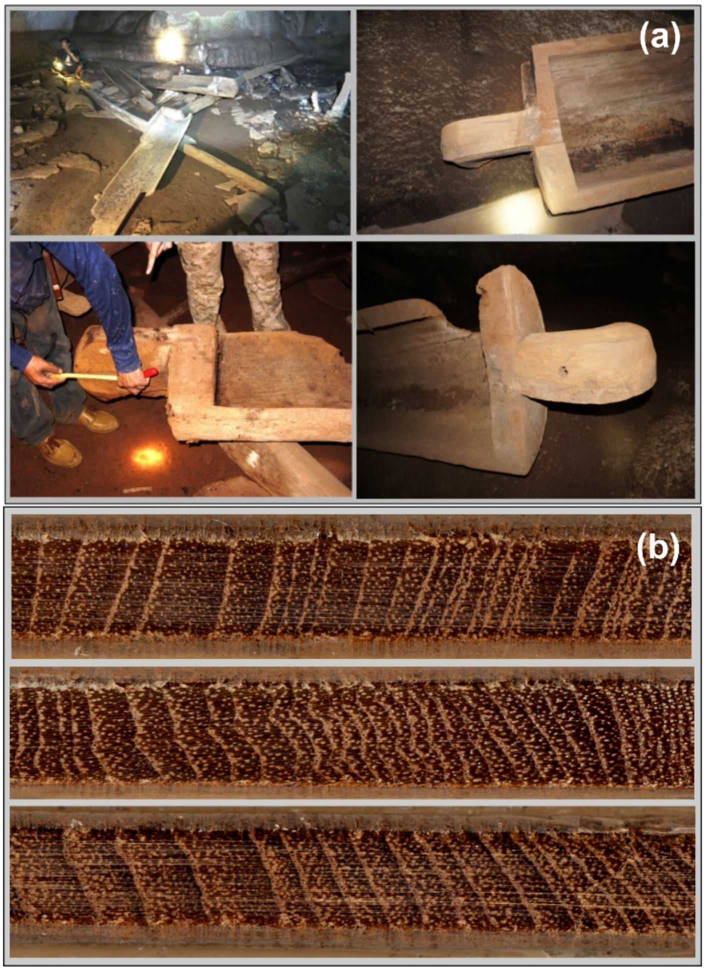

Fig. 2 (a) The characteristics of log coffins inside Namjang Cave, Pang Mapha District, Mae Hong Son Province, northwestern of Thailand; (b) The log coffin core samples after polishing.

2.3 Sample chronology and carbon-14 dating

All core samples from log coffins were measured for ring width using the TSAP-Win™ software package (Rinn 2011). Crossdating of coffin ring-width series was checked and verified with the COFECHA program, which is assesses the quality of crossdating and measurement accuracy of tree-ring series (Holmes 1983). Statistical descriptions of log coffin chronology, including average ring width (mm), series intercorrelation, mean sensitivity, autocorrelation, and standard deviation (SD) data, were calculated using the COFECHA program (Holmes 1983). The quality of the chronology was evaluated by calculating the expressed population signal (EPS) and the mean interseries correlation (Rbar) computed over a 30-year window, lagged by 15 years. The accepted value of EPS should be greater than or equal to 0.85 but in some case such as for tropical species the EPS value can be lower than 0.8 (Wigley et al. 1984). In this study, six-core samples from five coffins, including NJ11 (Core NJ11A and NJ11B), NJ12 (Core NJ12B), NJ15 (Core NJ15A), NJ16 (Core NJ16A), and NJ19 (Core NJ19A), were selected for C-14 dating. The wood samples for C-14 analysis were cut from the first ring of both the pith side which is near to the central zone of the trunk and bark side which is the side that near to the hard outer covering of the tree trunk. C-14 dating was performed at the Beta Analytic Radiocarbon Dating Laboratory (Miami, Florida, USA) using accelerator mass spectrometry (AMS) and isotope ratio mass spectrometry (IRMS) (Thermo-Finnigan). C-14 ages reported that the studied ancient teak trees grew between approximately 198-47 BC and 254-305 AD. The details and results of the C-14 dating were described and reported in our previous study (Buajan et al. 2020).

2.4 Cellulose preparation and extraction

After the ring width was measured, each ring from the six core samples was cut separately into very small pieces under a stereomicroscope using a sharp knife for cellulose extraction. The chemical process for extracting cellulose from the sample followed the Jayme–Wise method (Leavitt and Danzer 1993) (Fig. S1). In the first step for removing waxes, oils, and resins, we used a 1:1 solution of toluene and ethanol and it put in a water bath with a 50 °C temperature for 1 hour. This step was repeated 3 times, and the last time, the sample was placed in a water bath for 2 hours. After cooling, the samples were washed using 100% ethanol and placed in an ultrasonic cleaner for 30–50 minutes. In the second step, the lignin was removed by using a mixture of sodium chlorite ($NaClO_2$) and glacial acetic acid (CH_3COOH) and the sample was placed in a water bath at 80 °C for 1 hour. This step was repeated for 3 times. After cooling, the samples were washed using hot deionized water 3 times and normal deionized water 3 times. The final step to removing the hemicellulose was 17.5% sodium hydroxide (NaOH). The samples were placed in a water bath at 80 °C for 45-50 minutes, this step was repeated 3 times. After cooling, the samples were washed the same as in the second step. The cellulose samples were moved from the extract tube to the microtube. Samples were mixed using an ultrasonic homogenizer and dried in a freeze dryer at -80 °C for 24 hours.

2.5 Cellulose oxygen isotope analysis

A total of 753 α-cellulose samples were measured in this study. The samples were weighted to approximately 120-170 µg and wrapped with a silver capsule. The α-cellulose samples were analyzed for stable oxygen isotope ratios ($\delta^{18}O$) using a Thermo Scientific Flash 2000 HT Elemental Analyzer (EA) linked with a MAT-253 mass spectrometer (Thermo Electron Corporation, Bremen, Germany) at the Stable Isotope Centre of Fujian Normal University, China. Between every ten α-cellulose sample measurements, the international standard for $\delta^{18}O$ (IAEA-601, 23.3‰) analyzed to check the accuracy and precision of the results. The values of the isotope are reported in part per mil (‰), relative to the international standard, Vienna Standard Mean Ocean Water (VSMOW), in delta (δ) notation. The process followed was described in our previous studies (Buajan et al. 2016; Muangsong et al. 2016; Muangsong et al. 2019).

2.6 Data analysis

The six series of stable oxygen isotope ($\delta^{18}O$) ratios (NJ11A, NJ11B, NJ12B, NJ19A, NJ16A and NJ15A) were combined and continued according to the C-14 dating values which reported in our previous studies (Buajan et al. 2020). The average value of the stable oxygen isotope $\delta^{18}O$) ratios was used, and the series was named the "CoffinNJ $\delta^{18}O$" series. Spectral analysis using the REDFIT (Schulz and Mudelsee 2002) was used to extract periodic cycles from the CoffinNJ $\delta^{18}O$ series via the PAleontological STatistics (PAST) software package version 3.02 (Hammer 2014). The rectangle was selected for the window parameter on the original series, and the values of the oversample and segments were two. The "Window" parameter is controlling the shape of the window. If select the "Rectangle" position, the analysis will be carried out on the original series. The different windows will give different trade-offs between resolution. The "Segments" parameter controls how many segments to use. A value of 1 means no segmentation. The larger the number of segments, the less noise in the result, but the reduction in the length N of each segment will also decrease the spectral resolution (Hammer 2007). Confidence limits were estimated using a Monte Carlo simulation (Schulz and Mudelsee 2002). The amount of rainfall from May–October was calculated based on the equation reconstructed from 338 years of stable oxygen isotope values of living teak trees from Mae Hong Son (Pumijumnong et al. 2020a). The paleoclimate data used to validate the reconstructed May–October rainfall were the stalagmite $\delta^{18}O$ values from Tham Doun Mai Cave, Laos (Wang et al. 2019) and rainfall reconstructed from a tree-ring width chronology in the northeastern Tibetan Plateau (Yang et al. 2014). Spearman's and Pearson's correlations were used to test the correlation of the overlap period of six stable oxygen isotope ratio series and the correlation between the CoffinNJ $\delta^{18}O$ series and other proxies, such as the reconstructed sunspot number (Solanki et al. 2004), and stalagmite $\delta^{18}O$ values from Wanxiang Cave, China (Zhang et al. 2008). These analyses were performed using SPSS version 20 (SPSS®, Chicago, USA).

3 Results

3.1 Tree- ring chronology and Stable oxygen isotope ($\delta^{18}O$) ratios of NJ log coffin cellulose

The statistic description of 10 core samples of log coffin ring width chronology is shown in Table 1. The variation of tree-ring width of 10 core samples are shown in Fig. S2. According to the C-14 ages, the oldest teak tree (NJ11A) grew from 198–76 BC to AD 200–205, whereas the youngest tree (NJ15A) grew from AD 139–346 to AD 314–407 (Buajan et al. 2020). The time spans of the CoffinNJ $\delta^{18}O$ series are in cross-dated position according to the C-14 dating data (Fig. S3). The CoffinNJ $\delta^{18}O$ series was developed from a combination of C-14 ages of six coffin cores, and the highest correlation coefficient value (*r*) of the overlap period for each sample. The length of the CoffinNJ $\delta^{18}O$ series was 488 years from 106 BC to AD 382. The length of the CoffinNJ $\delta^{18}O$ series was not the same as the CoffinNJ ring width index (Buajan et al. 2020) because of samples NJ12B, NJ19A, NJ16A and NJ15A were shifted as NJ12A was shifted up 14 years, NJ19A was shifted down 2 years, NJ16A was shifted down 14 years and NJ15A was shifted down 12 years. This improvement led to the strong correlation between the variables. The variations in the $\delta^{18}O$ in each core sample including the correlation coefficients (*r*) of the overlap period and the CoffinNJ $\delta^{18}O$ series are shown in Fig. 3. The CoffinNJ $\delta^{18}O$ values ranged from 21.23‰ to 25.42‰. The average CoffinNJ $\delta^{18}O$ value was 23.48±0.77 ‰. The dated of chronology was plus/minus 30 years according to the error of C-14 dating ages.

Table 1 Statistic description of log coffin ring width chronology

Statistic	Statistic value
Average ring width (mm)	0.226
Series intercorrelation	0.480
Mean sensitivity	0.342
Autocorrelation	0.743
Standard deviation (SD)	0.165
Mean EPS	0.661
Mean Rbar	0.526

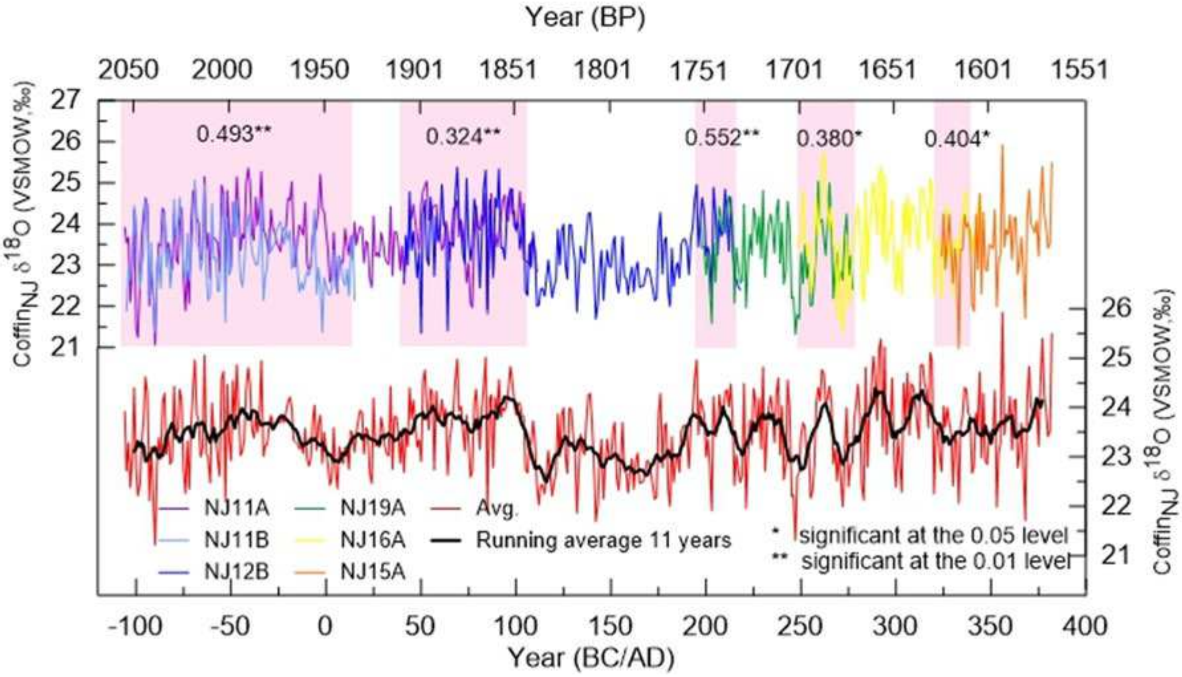

Fig. 3 CoffinNJ $\delta^{18}O$ series variation and cross-dating position according to the C-14 dating data of each Namjang log coffin sample. The pink shaded area indicates the overlap periods, and correlation coefficients (*r*) are shown at the top of each overlap period.

3.2 Spectral analysis

The spectral periodicities of the CoffinNJ $\delta^{18}O$ series displayed cycles (99% confidence level) at century (~129 years), and annual (3.4, 3.1, and 2.5 years) time scales as shown in Fig. 4.

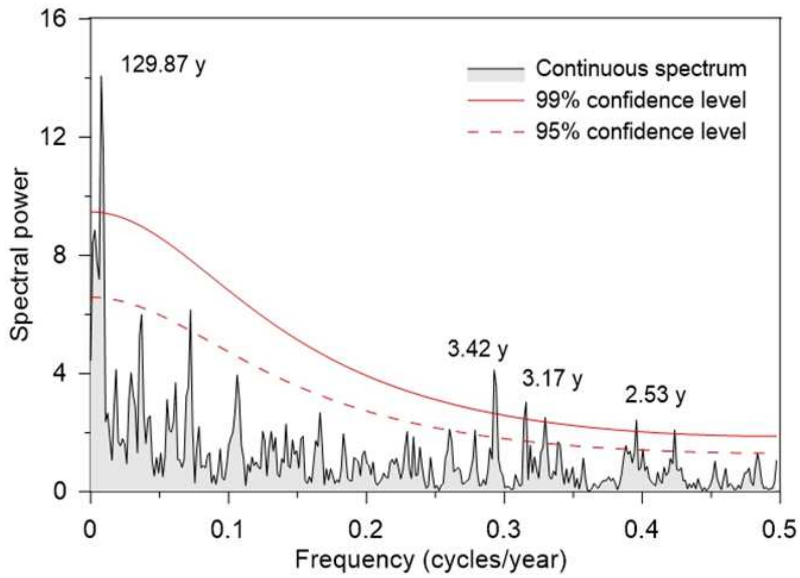

Fig. 4 Spectral analysis of the CoffinNJ $\delta^{18}O$ series using REDFIT (Schulz and Mudelsee 2002). The gray area indicates the power spectrum of the $\delta^{18}O$ value. The red lines and red dashed line represent the 99% and 95% confidence levels, respectively, relative to the red-noise spectrum. The confidence levels were estimated using a Monte Carlo simulation. Significant peaks are labeled for each period.

3.3 Amount of May–October rainfall during 106 BC to AD 382

The seasonal in northern Thailand can divide into 3 seasons; rainy, summer and winter. The rainy season started from May to October (Fig. 1a). The rainfall in rainy season positively related to the tree ring formation and its can capture the oxygen isotopes in the rain (Muangsong et al. 2020; Pumijumnong 2012). The equation of May–October rainfall obtained from 1904–2015 years of stable oxygen isotopes of living teak trees from Mae Hong Son is Rainfall May-October = 772.985+(-21.25) × $\delta^{18}O$ and can explain 35.20% of the May–October rainfall. For more information about calibration or verification statistics please see Pumijumnong et al 2020 (Pumijumnong et al. 2020a). This equation was generated from climate data gridded CRU TS4.03, latitude: 17-19°N and longitude: 97-98°E (http://climexp.knmi.nl) with a resolution of 0.5° × 0.5°. From the equation, we use CoffinNJ $\delta^{18}O$ values to calculate the amount of May–October rainfall from 106 BC to AD 382, as shown in Figure 5. The mean reconstructed May–October rainfall is 274 mm, while the mean ± standard deviation (σ) is 290 and 258 mm, respectively.

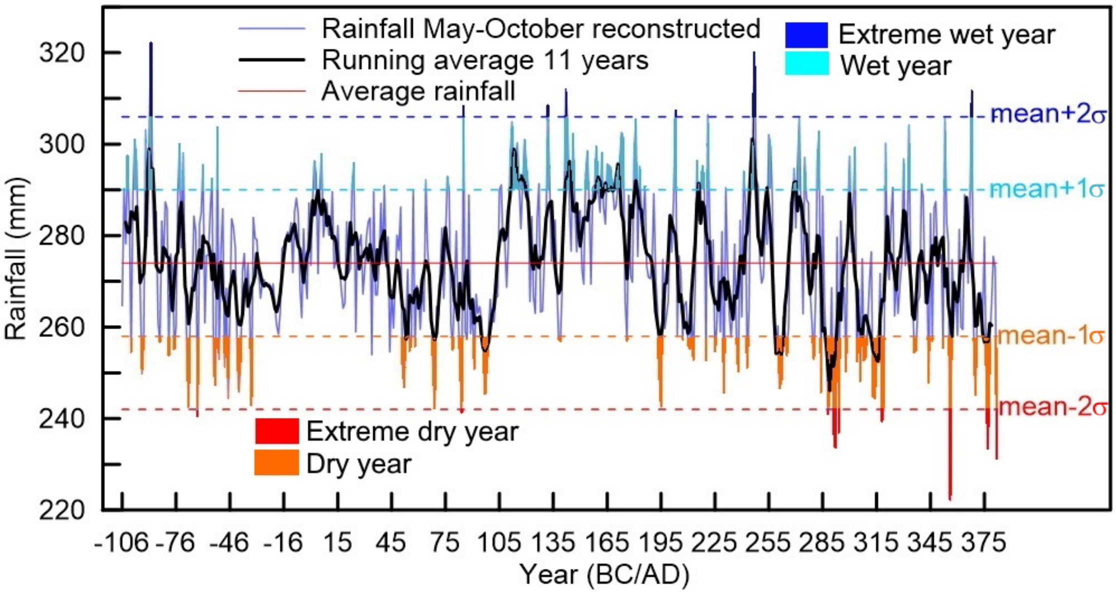

Fig. 5 May to October rainfall (mm). The blue line is a reconstructed May to October rainfall (mm) calculated from the linear regression of 338 years of stable oxygen isotopes of living teak trees from Mae Hong Son: Rainfall $_{\text{May-October}}$ = 772.985+(-21.25) × $\delta^{18}O$ (Pumijumnong et al. 2020a). The black line is the running average of 11 years. The horizontal red and dotted colored lines indicate an average rainfall of 274 and dry/wet (the mean ± 1σ) and extreme dry/wet events (the mean ± 2σ), respectively. σ indicate a standard deviation value.

4 Discussion

4.1 A dendrochronological study using a short period

The short period of overlapping may not be reliable in our CoffinNJ $\delta^{18}O$ series. In general, the study of dendrochronology requires the aging of trees to represent past climates and environments. The index extension technique is to use wood from various sources that are expected to grow from similar environments to extend the index. By using the initial rings of the known age and overlapping the unknown age. This technique is called cross-dating (Ferguson 1970). In areas where there are multiple sources of timber, such as living trees, houses, churches, museums, especially in temperate regions, it has been successful in extending the index, a length of several thousand years (Friedrich et al. 2004). But trees in the tropics, especially teak, a tree that has the potential to study dendrochronology. It has a durable wood, beautiful wood grain and is highly economically valued. This is the reason why teak, especially in Thailand, has been a long-term exported product (Laohachaiboon and Takeda 2007). It is an important reason that we cannot find very few old teak trees or if older teak is found, only a few are found. Besides, teak from archaeological sites found in Thailand is not much, which we do not know why. Therefore, extending the teak index from archaeological sites, the more difficult it is to achieve a large number of overlapping years. However, we should be honest about the number of years we have been extending the example so that the user or reader of the index knows the reliability of the data. Also, we may be able to increase the number of unknown age to the C-14 dating technique, this may help to expand the index to be longer. To increase the reliability of the results, we are committed to making our teak index reliable. It was possible to find more wood samples in the missing age range, as well as using a wiggle technique-matching to achieve a narrower C-14 dating value.

4.2 Cross-dating study of tropical species from Asia

Teak was the first tropical species in Southeast Asia (Indonesia, Thailand, Myanmar) and in South Asia (India) to determine its age and study dendrochronology. For example, Java teak was studied in tree ring-width (Berlage 1931), and later studies were developed for both teak tree ring-width for monsoon drought over Java (D'Arrigo et al. 2006), reconstruction streamflow, (D’Arrigo et al. 2011) and stable oxygen isotope in the Java Teak tree-ring (Hisamochi et al. 2018; Poussart et al. 2004; Schollaen et al. 2013). That Java teak is a good indicator for the El Niño phenomenon. A concrete study of teak dendrochronology in Thailand (Pumijumnong et al. 1995). Later, teak tree ring-width was studied in other areas such as in Tak Province, northern Thailand (Preechamart et al. 2018), Mae Hong Son Province, northwestern Thailand (Buckley et al. 2007; Pumijumnong 2012), Nakhon Ratchasima province, northeastern Thailand (Palakit et al. 2015). The results of the study generally found that the amount of total rainfall in the first half of the rainy season affected teak tree ring-width. Besides, the longest living teak trees from Mae Hong Son province of 448 years (Buckley et al. 2007) and Tak Province 462 years (Preechamart et al. 2018) are reported. Since the analysis of stable oxygen isotope becomes more possible and stable oxygen isotope in tree ring can accurately determine the source of moisture. The study of stable oxygen isotope in Thai teak has progressed in both sub-annual (Muangsong et al. 2016; Muangsong et al. 2020) and annual (Buajan et al. 2016). Currently, the longest stable oxygen isotope in teak tree-ring is 338 years (Pumijumnong et al. 2020a). There is a growing number of teak dendrochronology in Myanmar (D'Arrigo and Ummenhofer 2015; D’Arrigo et al. 2013; Pumijumnong et al. 2020b; Zaw et al. 2020), as does the long-established teak study in India (Borgaonkar et al. 2010; Managave et al. 2010; Ram et al. 2008).

4.3 Stable oxygen isotope ($\delta^{18}O$) ratios of NJ log coffin cellulose

There have been some stable oxygen isotope studies of teak tree rings in Thailand, and the values have varied from site to site. The results show that the range of the CoffinNJ $\delta^{18}O$ series was 21.23‰ to 25.42‰, which is an average value of 23.48 ±0.77‰, which is similar to that of living teak trees near the NJ cave, and to the reported average stable oxygen isotope value of the teak tree ring (NJT06) of 23.6‰ (Muangsong et al. 2019). The value of the CoffinNJ $\delta^{18}O$ series was the same as the stable oxygen isotope cellulose in living teak trees from the Pai wildlife sanctuary, which is approximately 27.76 km south of this study site (Buajan et al. 2016). The value of the CoffinNJ $\delta^{18}O$ series was slightly different from the stable oxygen isotope of living teak trees (Phrae $\delta^{18}O_{Annual}$= 25.12±1.03‰) from Phrae Province which lies to the southeast of the study site by approximately 234.18 km (Muangsong et al. 2020). A recent study of the stable oxygen isotopes in teak tree rings constructed from seven individual study sites in Mae Hong Son Province showed that the average value of the teak $\delta^{18}O_{tr}$ series was 24.44‰ (Pumijumnong et al. 2020a). The $\delta^{18}O$ values of the log coffin teak and a living teak tree were not different, indicating that the amount of rainfall during the period the coffin teak trees grew appears to be similar to the present.

4.4 Spectral analysis

The spectral analysis of the CoffinNJ $\delta^{18}O$ series showed centennial and annual cycles. The short-term periods, of approximately 2–4 years of the CoffinNJ $\delta^{18}O$ series were found to be likely associated with El Niño–Southern Oscillation (ENSO) events (D'Arrigo et al. 2005). The centennial cycles (129 years) might be related to the sunspot number, which influence the Indian summer monsoon (Gupta et al. 2005). The centennial and annual cycles of the CoffinNJ $\delta^{18}O$ series were the same as the $\delta^{18}O$ cycles of living teak trees at Mae Hong Son (Pumijumnong et al. 2020a). Only the annual cycle associated with ENSO of the CoffinNJ $\delta^{18}O$ was related to the oxygen isotopes of teak ring widths in Myanmar (Pumijumnong et al. 2020b). Most of the variation in tree-ring width index and oxygen isotope values of tree-ring cellulose in teak is related to ENSO events, such as the teak $\delta^{18}O$ values in tree-ring cellulose from Indonesia (Schollaen et al. 2015) which has a cycle of 2.2–4 years; and those, in southern Myanmar (Zaw et al. 2020), which reveal periodicities of 2.2–2.7 years. Therefore, ENSO events influence both teak growth and oxygen isotopes in tree-ring cellulose. The spectral plots comparison of each reference as shown in Fig. 6.

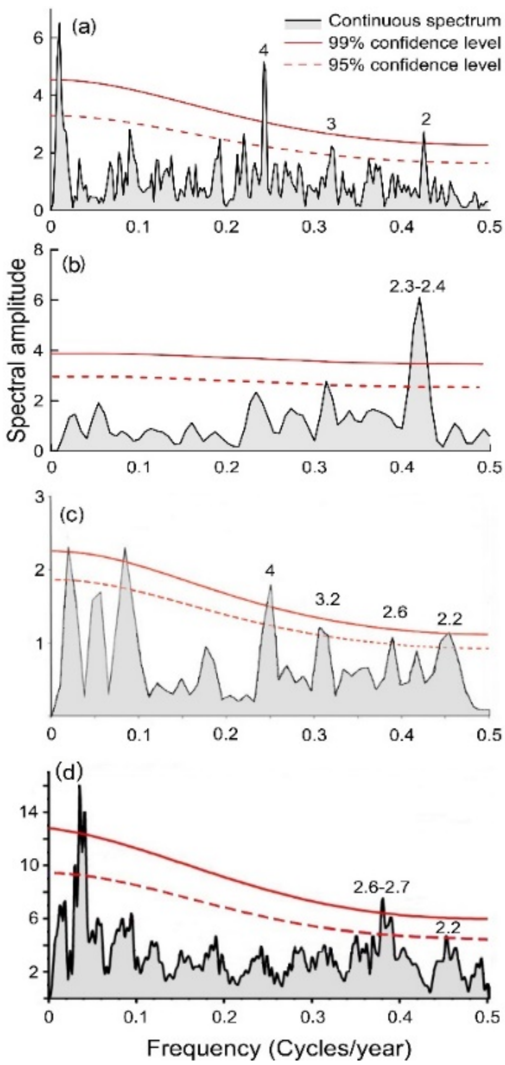

Fig. 6 The spectral plot of (a) the $\delta^{18}O$ cycles of living teak trees at Mae Hong Son (Pumijumnong et al. 2020a); (b) the oxygen isotopes of teak ring widths in Myanmar (Pumijumnong et al. 2020b); (c) the teak $\delta^{18}O$ values in tree-ring cellulose from Indonesia (Schollaen et al. 2015) and (d) those, in southern Myanmar (Zaw et al. 2020).

4.5 Amount of May–October rainfall during 106 BC to AD 382 form northwest Thailand

Based on the reconstructed rainfall equation of $\delta^{18}O$ value from living teak trees in Mae Hong Son (Pumijumnong et al. 2020a), the CoffinNJ $\delta^{18}O$ series shows that the rainfall from 106 BC to AD 382, interpreted as the mean reconstructed May–October rainfall was 274 mm, while the mean ± SD values were 290 and 258 mm, respectively. The average and mean ± SD of May–October rainfall reconstructed from CoffinNJ $\delta^{18}O$ was higher than that of living teak trees in the present (253 mm of mean rainfall with mean ± SD values of 269 and 237 mm, respectively) (Pumijumnong et al. 2020a). The trend of the amount of May–October rainfall slightly decreased over the study period. We found six years of extremely wet conditions (90 BC, 85, 132, 142, 203, 247 and 368 AD ±30 years), while we found nine years of extremely dry conditions (64 BC, 84, 291, 292, 294, 318, 356, 377 and 382 AD ±30 years) (Figure 5). Generally, in Thailand rainfall during the monsoon season is influenced by the Indian summer monsoon, which is strongest during May–July (and is, called the early monsoon), while the rainfall during August–October is influenced by the western North Pacific summer monsoon (called the late monsoon) (Limsakul et al. 2010). The six extremely wet years indicated that during those years, the monsoon was very strong, while the nine extremely dry years indicated a weak monsoon. Interestingly, 84 AD ±30 years was extremely dry, and year 85 AD ±30 years was extremely wet. The Indian summer monsoon is linked with the El Niño Southern Oscillation (ENSO) (Ihara et al. 2007; Roy and Tedeschi 2016; Wu and Kirtman 2003), which indicates that ENSO also influences rainfall in Thailand, as shown by spectral analysis. Therefore, the CoffinNJ $\delta^{18}O$ series is able to capture the ENSO cycle (2-4 years). The CoffinNJ δ18O period (106 BC to 382 AD) was corresponds to the late Holocene. The Asian monsoon during the late Holocene varied due to the influence of the Earth's atmosphere which is affected by solar activity (Tulunay 1993). The sun is a factor that drive the atmosphere and the source of energy for the Earth (Larkin et al. 2000). Changes in the energy emitted directly causes climate changes on Earth, especially in the tropical zone, where Thailand is located (Medvigy and Beaulieu 2012). Evidence of the solar activity effect on the Asia monsoon during the late Holocene was reported in the speleothem record from Dongge Cave, China (Duan et al. 2014).

To validate the reconstructed May–October rainfall from CoffinNJ $\delta^{18}O$, we found a significant negative correlation ($r = -0.254$, $p<0.01$) with the 31-year running average of stalagmite $\delta^{18}O$ from Tham Doun Mai Cave, Laos (Wang et al. 2019) as shown in Fig. 7a. Our result from reconstructed rainfall is able to capture the weak monsoon period (291–294 AD), the same as the result noted from stalagmite $\delta^{18}O$ data from Tham Doun Mai Cave (Wang et al. 2019). Furthermore, the reconstructed May–October rainfall from this study has a positive significant correlation ($r = 0.347$, $p<0.01$) with the 31-year running average rainfall reconstructed from tree-ring width from the northeastern Tibetan Plateau (Yang et al. 2014) as shown in Fig. 7b.

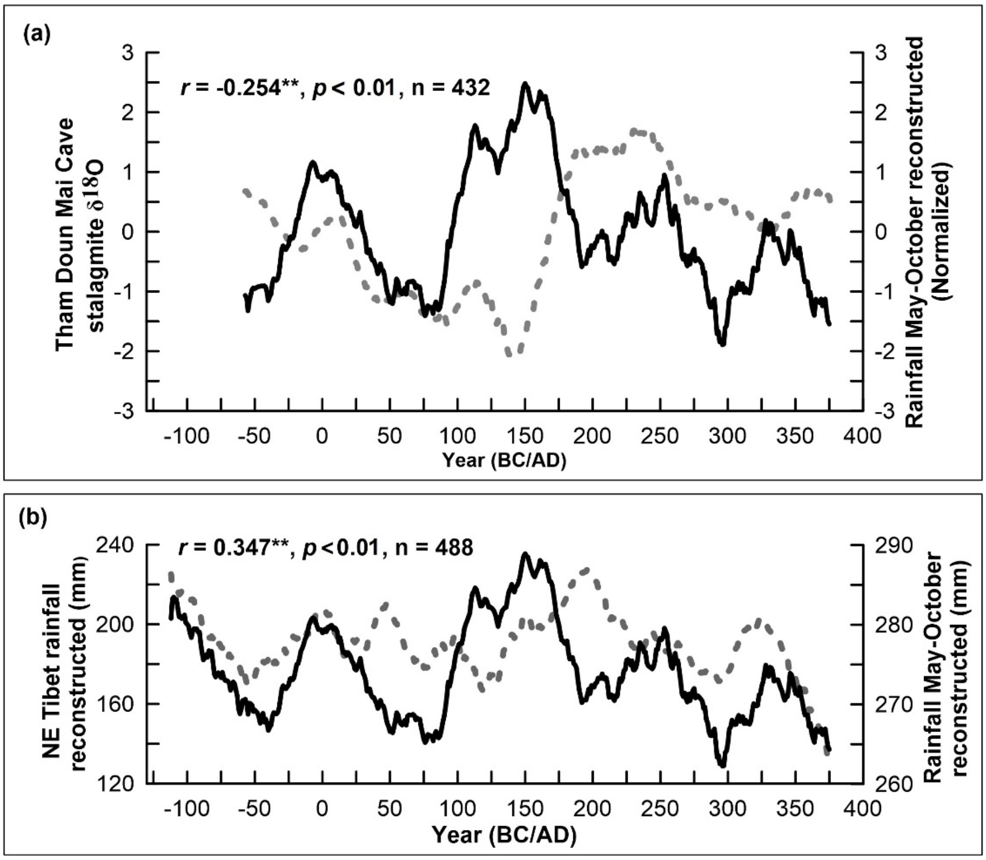

Fig. 7 (a) The stalagmite $\delta^{18}O$ values from Tham Doun Mai Cave, Laos (Wang et al. 2019) (dashed line), and May-October rainfall reconstructed from the CoffinNJ $\delta^{18}O$ series (black line). (b) Northeastern Tibet reconstructed rainfall (Yang et al. 2014) (dashed line) and May–October rainfall reconstructed from the CoffinNJ $\delta^{18}O$ series (black line). Both figures feature a 31-year running average. *r* represents Spearman's correlation coefficient, p indicates a statistically significant value, and n indicates the number of samples.

4.6 Comparisons with other proxies

As mentioned in the spectral analysis section, CoffinNJ $\delta^{18}O$ can capture the centennial cycle associated with the sunspot number, so we compare the sunspot number to the CoffinNJ $\delta^{18}O$ record. We found a significant positive correlation ($r = 0.410$, $p<0.01$) between the 11-year running average of the CoffinNJ $\delta^{18}O$ record and the reconstructed sunspot number (Solanki et al. 2004) (Fig. 8a), indicating that solar activity can influence Asian monsoon variability. The Holocene Asia monsoon is linked to solar activity (Wang et al. 2005), which affects the habitat and growth of vegetation. Solar activity is one factor that affects the variability in the regional climate, such as the Asia monsoon (Li and Tu 2019). The positive correlation between sunspot number and CoffinNJ $\delta^{18}O$ value can be explained by the high sunspot number causing a decrease in solar irradiance (Kopp et al. 2016) corresponding to a weak Asian monsoon (high $\delta^{18}O$ values) (Wang et al. 2005). To evaluate the region of Asian monsoon variability, we compare the stalagmite $\delta^{18}O$ record from Wanxiang Cave, China (Zhang et al. 2008) with our CoffinNJ $\delta^{18}O$ record from NJ Cave. We found that the CoffinNJ $\delta^{18}O$ record has a significant positive correlation ($r = 0.644$, $p<0.01$) with the 21-year running average of the Wanxiang Cave stalagmite $\delta^{18}O$ record (Zhang et al. 2008) during the period 192–382 AD (Fig. 8b). Both proxies reveal similar multidecadal to centennial-scale $\delta^{18}O$ fluctuations over this period, indicating that the Asian monsoon was affected on a regional scale.

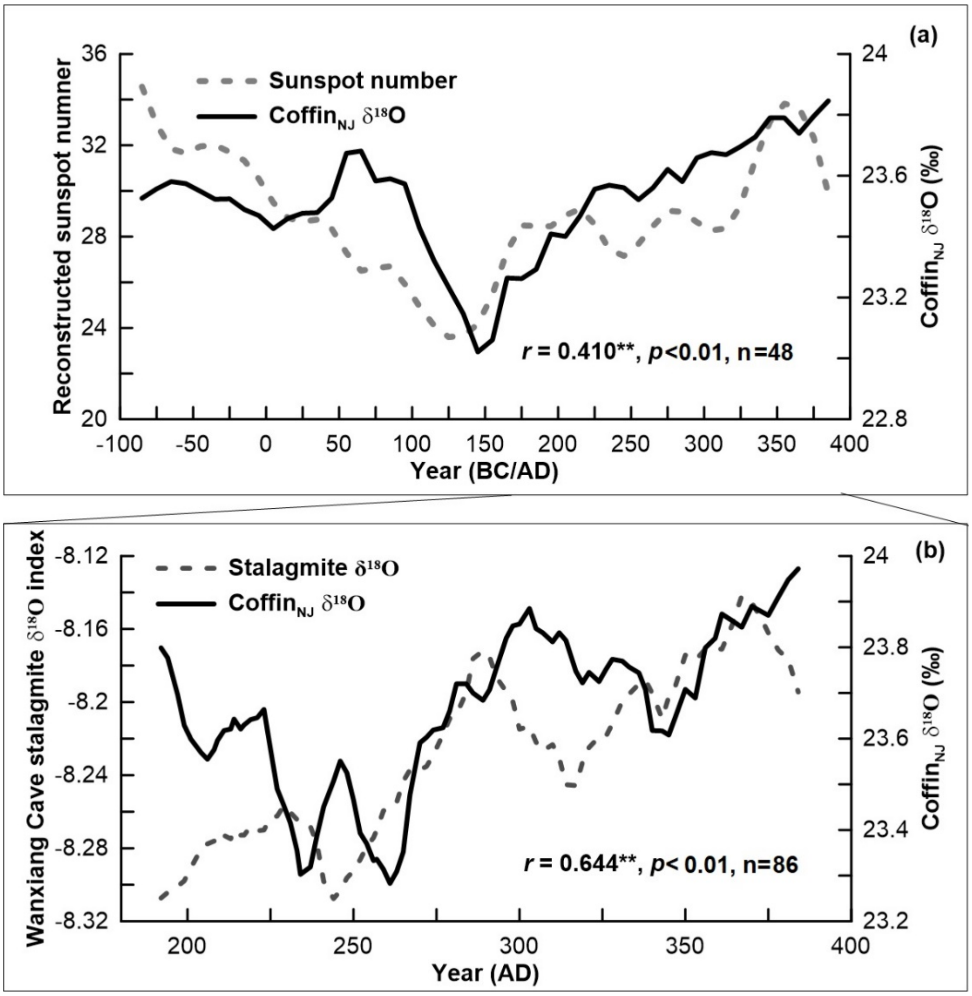

Fig. 8 (a) An 11-year running average of the reconstructed sunspot number (Solanki et al. 2004) (dashed line) and the CoffinNJ $\delta^{18}O$ record (black line). (b) A 21-year running average of the $\delta^{18}O$ record of a stalagmite from Wanxiang Cave (Zhang et al. 2008) (dashed line) and the CoffinNJ $\delta^{18}O$ record (black line). r represents Spearman's correlation coefficient, p indicates a statistically significant value, and n indicates the number of samples.

5 Conclusion

The ancient teak log coffins in Namjang Cave, northwestern Thailand, were used to study the paleoclimate using stable oxygen isotopes ($\delta^{18}O$) in cellulose as a proxy. The sample was dated using C-14 dating. The CoffinNJ $\delta^{18}O$ record spanned 2,050-1,551 years BP (years before the present). The spectral analysis shows centennial (129 year) and annual (3-5 year) cycles, which are related to the centennial cycle of sunspot number (Gupta et al. 2005) and ENSO events (D'Arrigo et al. 2005), respectively. The CoffinNJ $\delta^{18}O$ series reflects the rainfall during the study period based on the equation of May–October rainfall obtained from a 338 years record of stable oxygen isotopes of living teak trees from Mae Hong Son (Pumijumnong et al. 2020a). The mean rainfall (274 mm) reconstructed from CoffinNJ $\delta^{18}O$ was higher than the mean rainfall reconstructed from the living teak trees. The reconstructed rainfall was correlated with stalagmite $\delta^{18}O$ values from Tham Doun Mai Cave, Laos (Wang et al. 2019) and rainfall reconstructed from the northeastern Tibetan Plateau (Yang et al. 2014), with r = -0.254 and 0.347, p<0.01, respectively. Moreover, the CoffinNJ $\delta^{18}O$ series has a significant positive correlation (r = 0.410, p<0.01) with the reconstructed sunspot number (Solanki et al. 2004) and

Wanxiang Cave stalagmite $\delta^{18}O$ record (Zhang et al. 2008) ($r = 0.644$, $p<0.01$), which are related to the Asian monsoon variation. The results from this study indicate that the CoffinNJ $\delta^{18}O$ series reflects the Asian monsoon from 2000 years ago and has the potential to be a paleoclimate poxy in northwestern Thailand.

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Figures

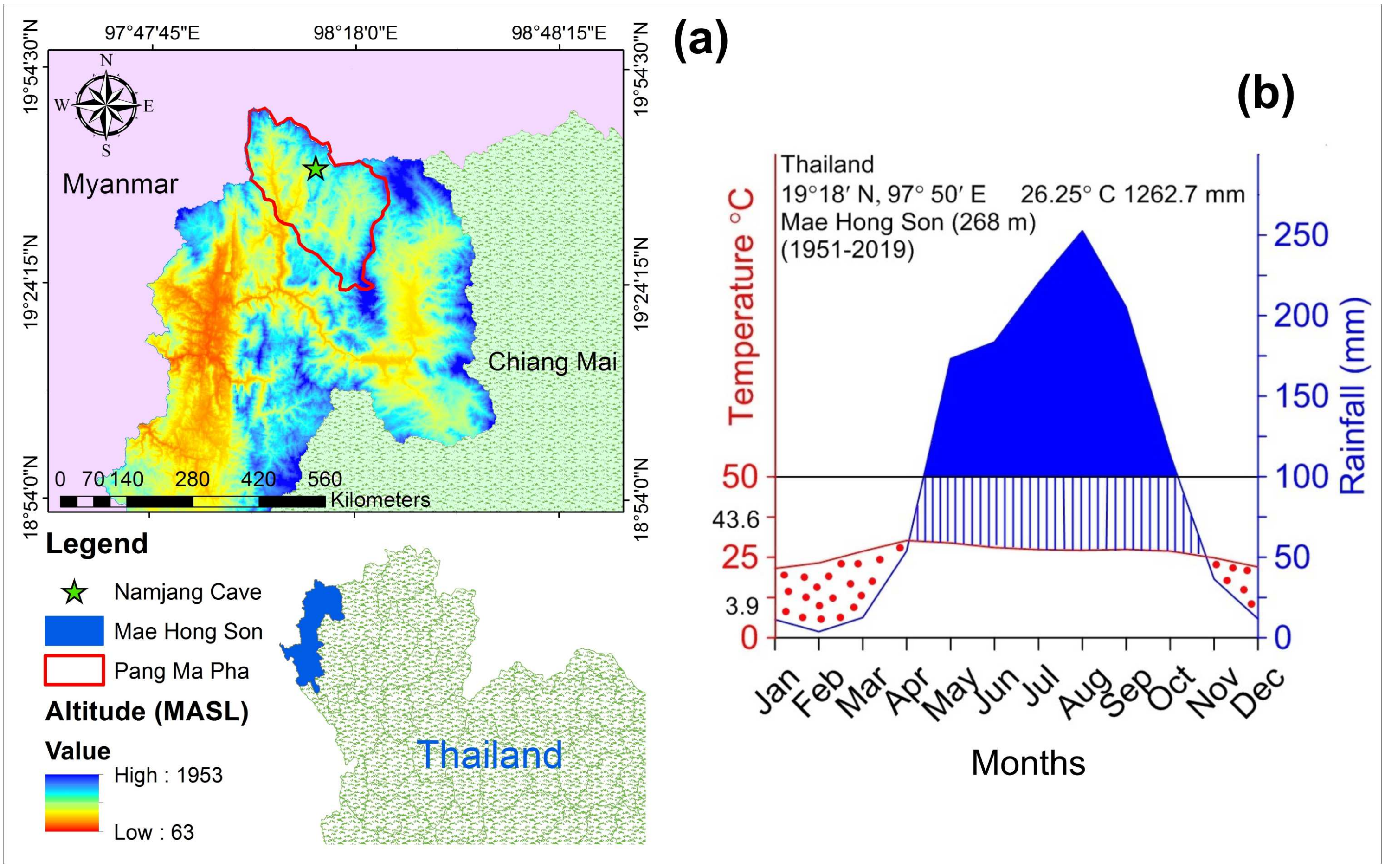

Figure 1

(a) Location of the study site: the star indicates the location of Namjang Cave, the red line is the boundary of the Pang Mapha district and the blue area is Mae Hong Son Province. (b) Climate diagram for the Mae Hong Son meteorological station; the blue line represents a rainfall curve, and the red line represents the temperature. The red dotted area indicates relatively dry period, blue stripe area indicates relatively humid period and blue solid area indicates mean monthly rainfall > 100 mm. Values on the left axis are the maximum temperature of the warmest month and the minimum temperature of the coldest month. The upper right corner of the diagram shows the annual average temperature and annual total precipitation. The period of the climate data is 1951–2019 AD. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

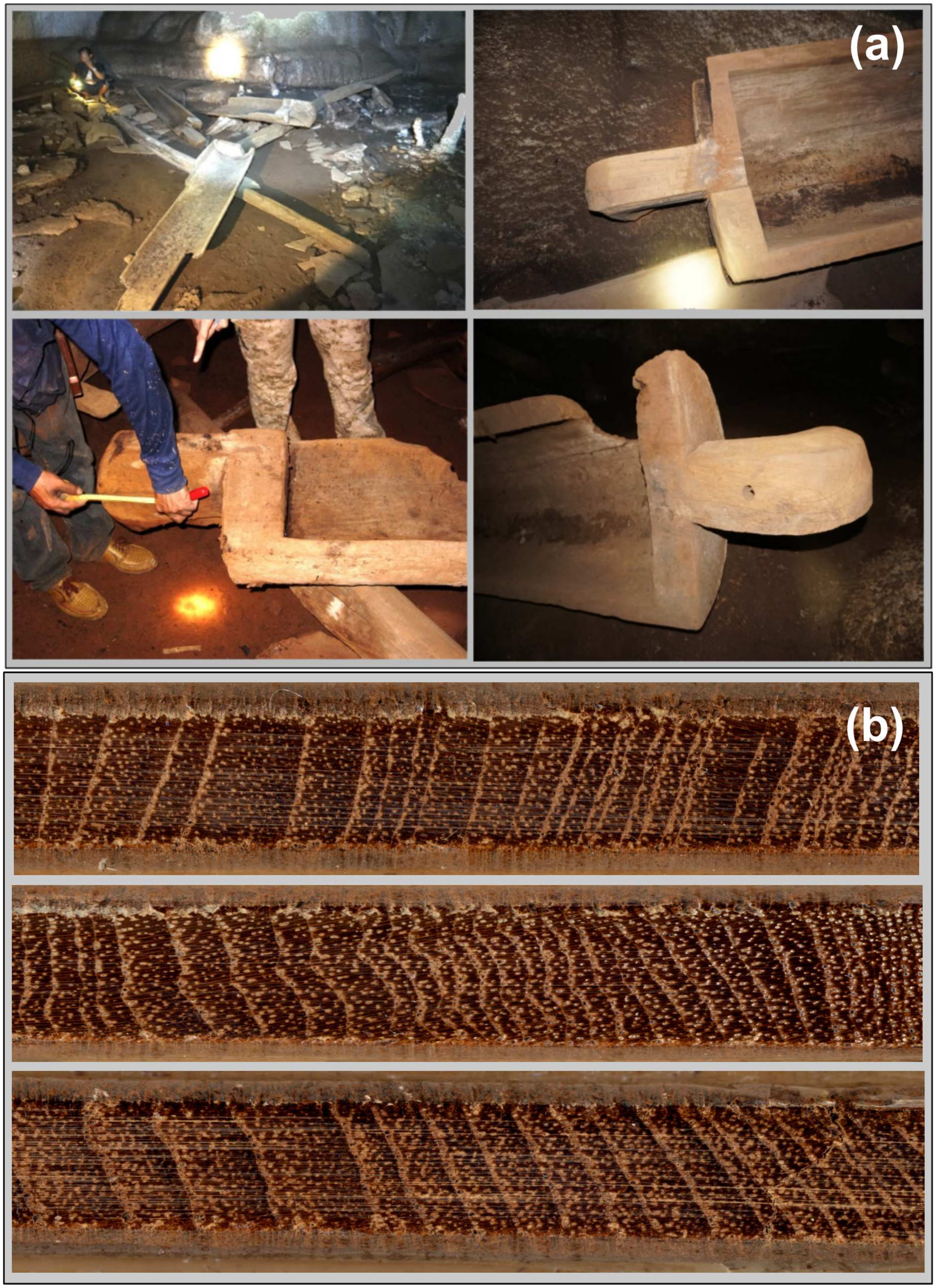

Figure 2

(a) The characteristics of log coffins inside Namjang Cave, Pang Mapha District, Mae Hong Son Province, northwestern of Thailand; (b) The log coffin core samples after polishing.

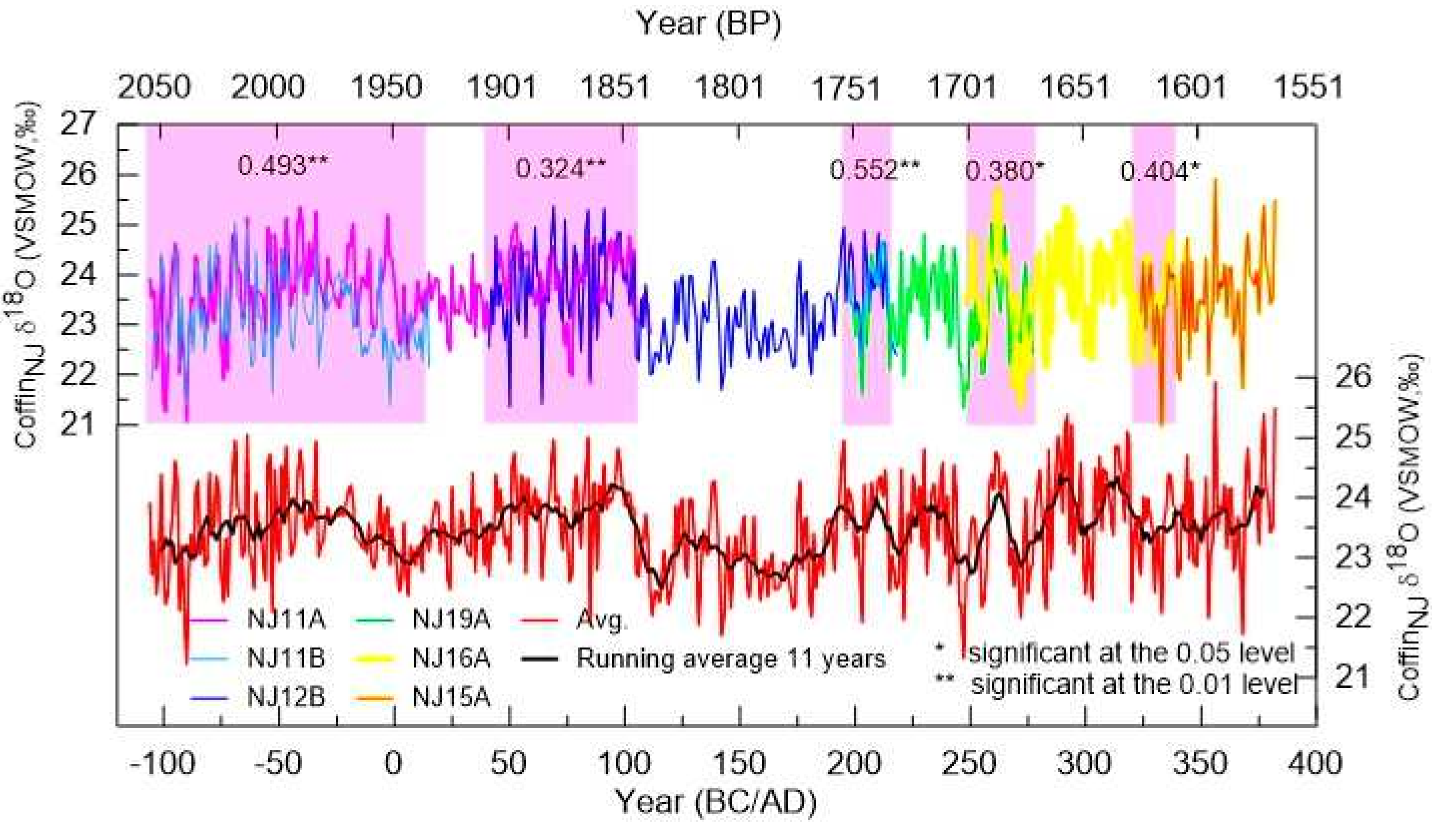

Figure 3

CoffinNJ δ18O series variation and cross-dating position according to the C-14 dating data of each Namjang log coffin sample. The pink shaded area indicates the overlap periods, and correlation coefficients (r) are shown at the top of each overlap period.

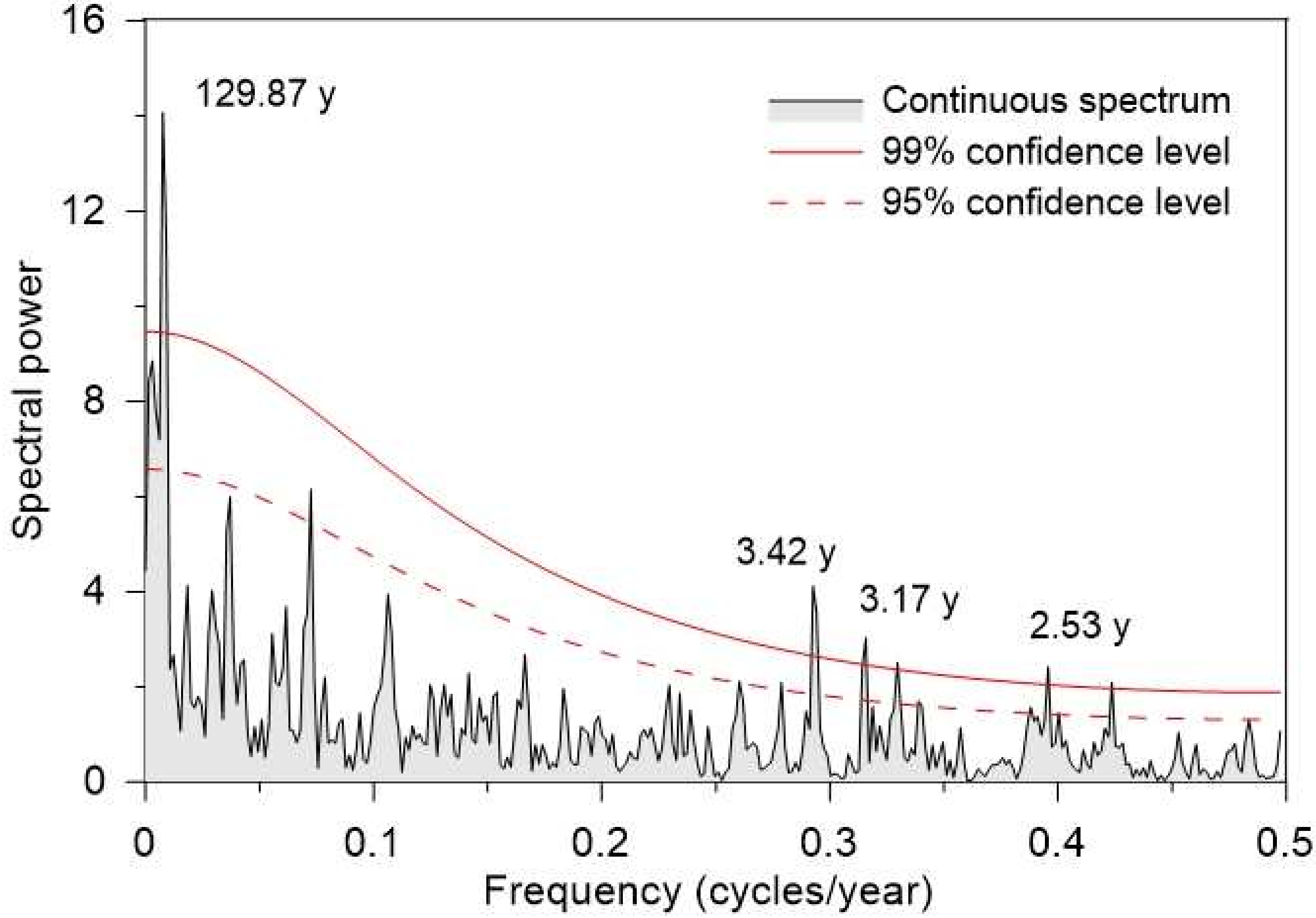

Figure 4

Spectral analysis of the CoffinNJ δ18O series using REDFIT (Schulz and Mudelsee 2002). The gray area indicates the power spectrum of the δ18O value. The red lines and red dashed line represent the 99% and 95% confidence levels, respectively, relative to the red-noise spectrum. The confidence levels were estimated using a Monte Carlo simulation. Significant peaks are labeled for each period.

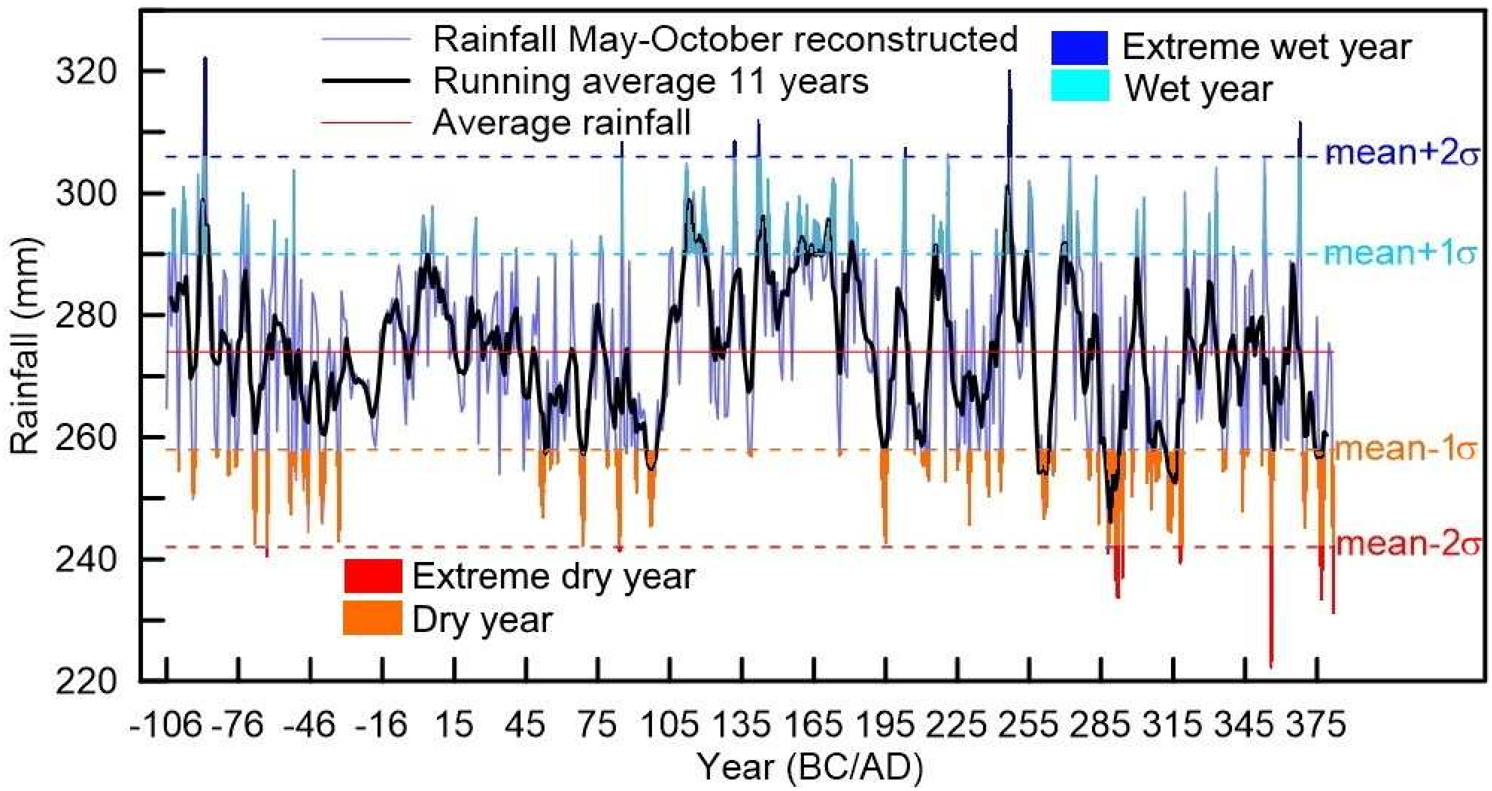

Figure 5

May to October rainfall (mm). The blue line is a reconstructed May to October rainfall (mm) calculated from the linear regression of 338 years of stable oxygen isotopes of living teak trees from Mae Hong Son: Rainfall May-October = 772.985+(-21.25) × δ18O (Pumijumnong et al. 2020a). The black line is the running average of 11 years. The horizontal red and dotted colored lines indicate an average rainfall of 274 and dry/wet (the mean ± 1σ) and extreme dry/wet events (the mean ± 2σ), respectively. σ indicate a standard deviation value.

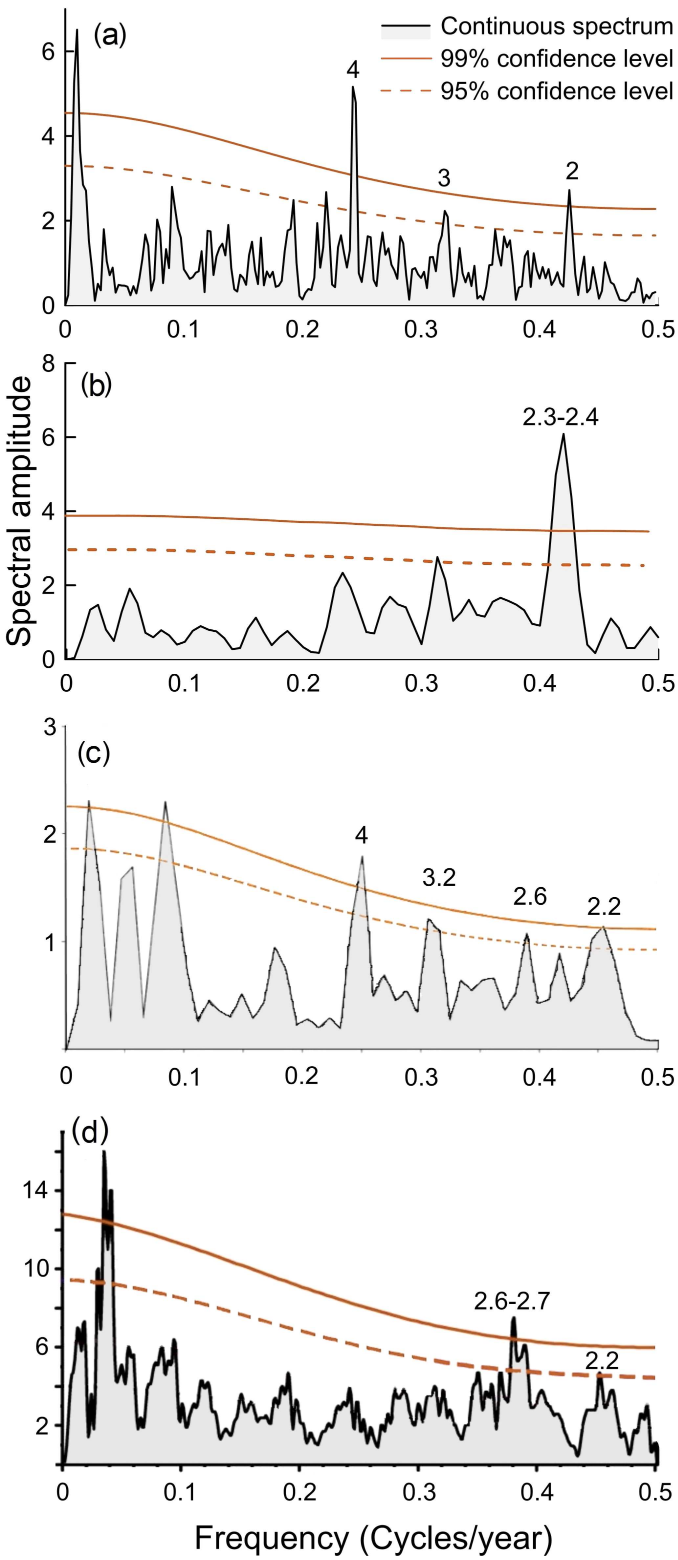

Figure 6

The spectral plot of (a) the δ18O cycles of living teak trees at Mae Hong Son (Pumijumnong et al. 2020a); (b) the oxygen isotopes of teak ring widths in Myanmar (Pumijumnong et al. 2020b); (c) the teak δ18O values in tree-ring cellulose from Indonesia (Schollaen et al. 2015) and (d) those, in southern Myanmar (Zaw et al. 2020).

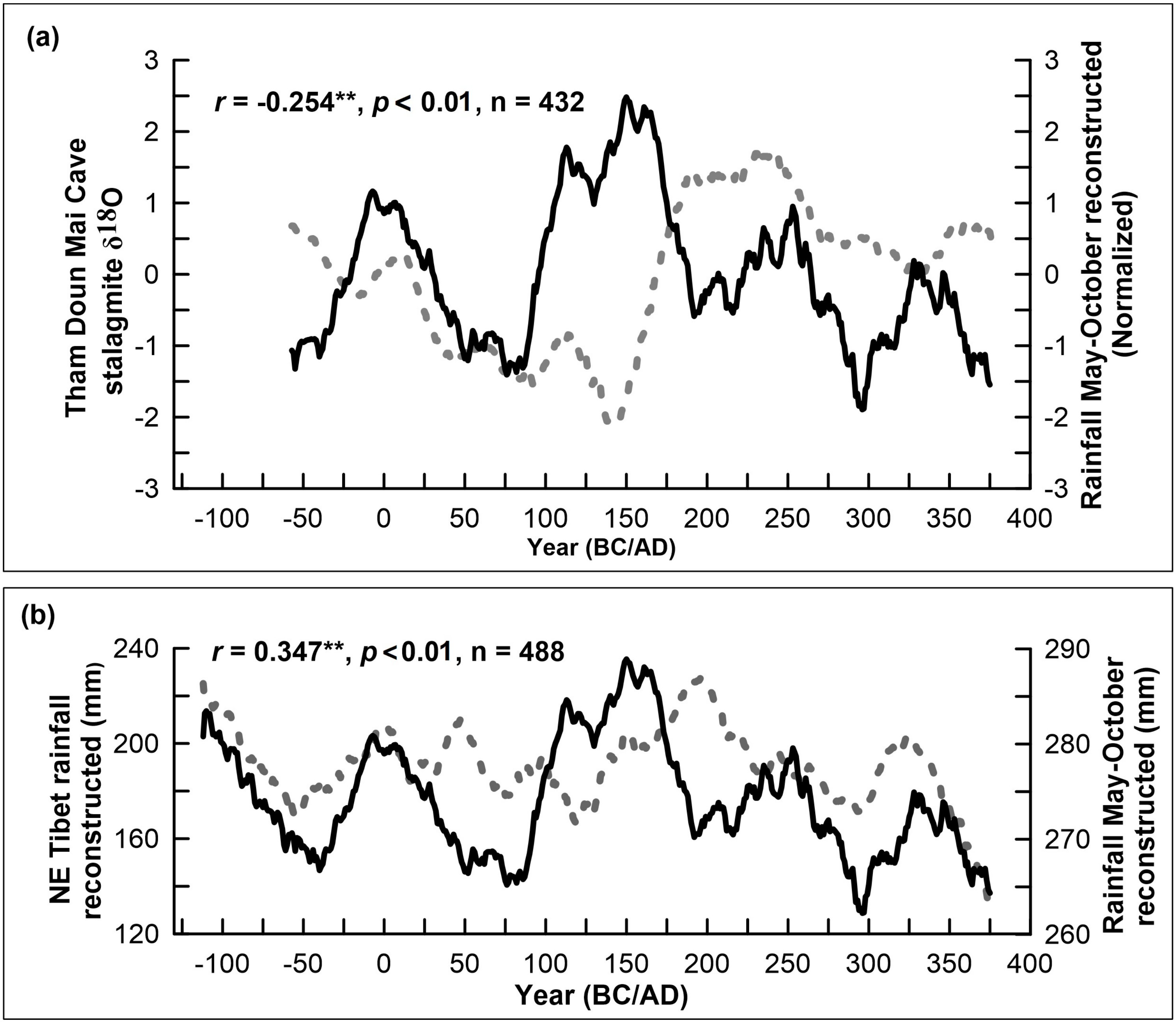

Figure 7

(a) The stalagmite δ18O values from Tham Doun Mai Cave, Laos (Wang et al. 2019) (dashed line), and May-October rainfall reconstructed from the CoffinNJ δ18O series (black line). (b) Northeastern Tibet reconstructed rainfall (Yang et al. 2014) (dashed line) and May–October rainfall reconstructed from the CoffinNJ δ18O series (black line). Both figures feature a 31-year running average. r represents Spearman's correlation coefficient, p indicates a statistically significant value, and n indicates the number of samples.

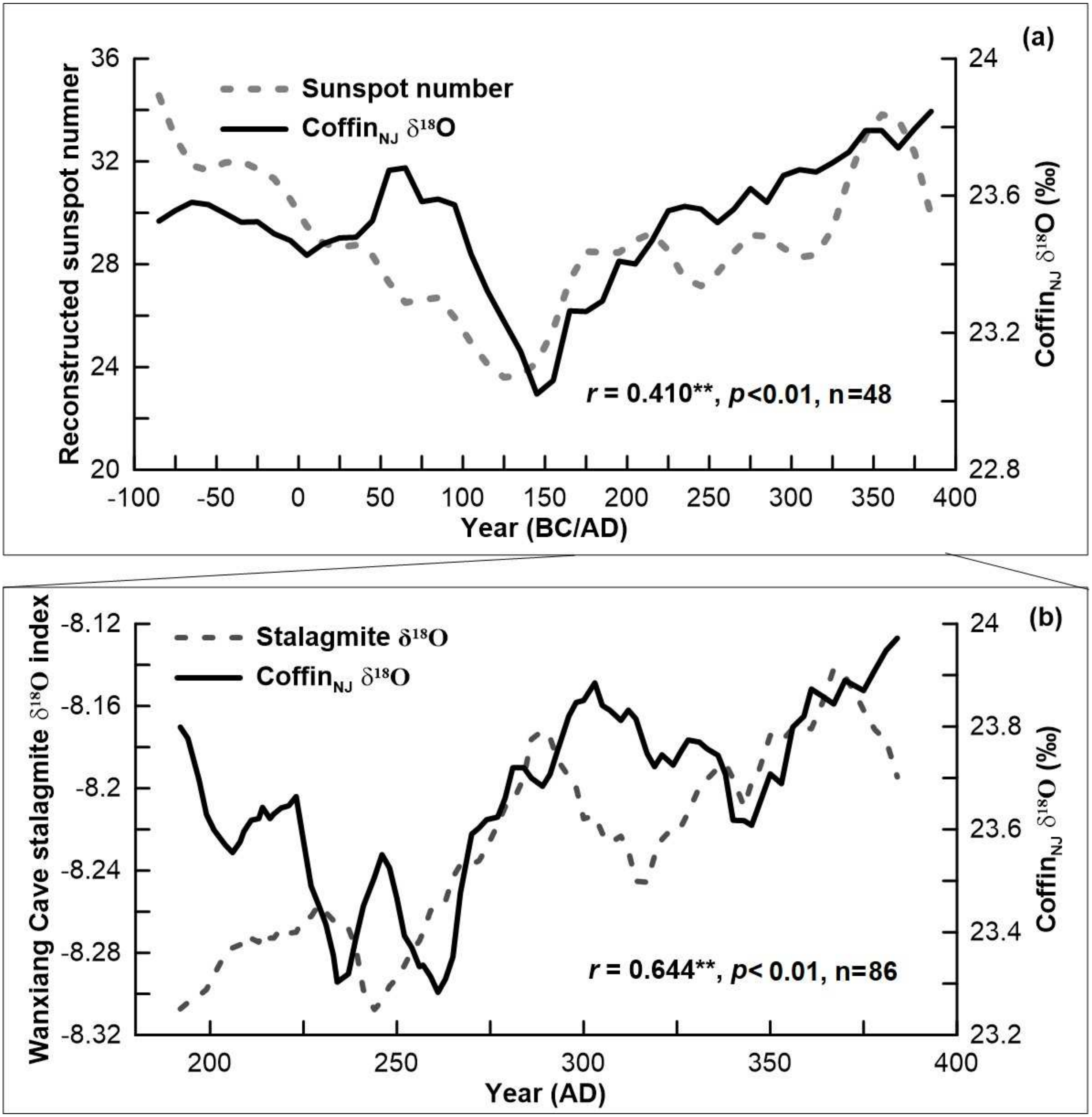

Figure 8

(a) An 11-year running average of the reconstructed sunspot number (Solanki et al. 2004) (dashed line) and the CoffinNJ δ18O record (black line). (b) A 21-year running average of the δ18O record of a stalagmite from Wanxiang Cave (Zhang et al. 2008) (dashed line) and the CoffinNJ δ18O record (black line). r represents Spearman’s correlation coefficient, p indicates a statistically significant value, and n indicates the number of samples.

Supplementary Files

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- SupplementaryMaterials.docx