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ORIGINAL PAPER

Climate variability over the past 100 years in Myanmar derived from tree-ring stable oxygen isotope variations in Teak

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Abstract

We present a 100-year oxygen isotope record from teak tree-ring cellulose ($\delta^{18}O$), originating from a site in southern Myanmar that preserves the isotopic ratios of the regional wet season's rainfall. Tree-ring $\delta^{18}O$ correlates strongly with regional rainfall during the months of May to October ($r = -0.353$, $p < 0.01$). We found the tree-ring $\delta^{18}O$ had clear signals of the June to September Indian Summer Monsoon (ISM) over the years 1948–1998 ($r = -0.53$, $p < 0.01$). The $\delta^{18}O$ has a significant and negative correlation with the minimum temperature in September and has a significant positive correlation with maximum temperature in November and December. The study found that $\delta^{18}O$ has a significant positive correlation with the difference between the maximum temperature and the minimum temperature (DTR) in August to October. Based on our results, it can be concluded that tree-ring $\delta^{18}O$ in teak in southern Myanmar is controlled by the amount of rainfall during the monsoon season and the temperature in the November and December. Spatial correlation and spectral analyses revealed a strong impact of the El Niño-Southern Oscillation (ENSO) on tree-ring $\delta^{18}O$ of teak. In addition, tree-ring $\delta^{18}O$ also captures the signal of the Indian Ocean Dipole (IOD).

Keywords Teak · Myanmar · Oxygen Isotopes · Climate variability · ENSO

1 Introduction

The Asian Summer Monsoon (ASM) has a great influence on people's livelihoods in Southeast Asia. The main occupation of the people living in this area is mostly agricultural (Loo et al. 2015). Most of the farming is still reliant on rainfall (Lar et al. 2018a). Therefore, any variation in the ASM, such as the period of rainfall, rain density, and the end of the rainy season, will affect agricultural production and directly affect the income of the population and the livelihood of the people (Lar et al. 2018b; Zin et al. 2019). In addition, the amount of greenhouse gases released into the atmosphere has increased, steadily affecting global warming and causing more extreme climate fluctuations (Slagle 2014). The study of the variation of the ASM has increased (Latif et al. 2017; Ha et al. 2018). But the study of climate in Myanmar is quite limited (Sen Roy and Kaur 2000; Sen Roy and Sen Roy 2011).

Myanmar is a country in Southeast Asia that is influenced by the ASM, and it is prone to be impacted by cyclones. The country has been affected by climate change such as the occurrence of cyclone Nagis in the year 2008. The months of April, May, and October to December are considered to be cyclone months, according to historical records. In the last four decades alone, several major cyclones have severely affected Myanmar (Calkins and Win 2013; Besset et al. 2017). Climate monitoring stations in Myanmar are relatively few and recently established, making the study of ASM extremely limited.

There are very few studies about weather in Myanmar. For example, Sen Roy and Kaur (2000) used rainfall data in Myanmar during June to September (JJAS) from 33 stations

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from 1947 to 1978. They classified the characteristics of rain in Myanmar into five zones, namely north of Myanmar, west Myanmar, central Myanmar, east Myanmar, and south Myanmar, in which each zone has average rainfall during June to September of 556.26, 764.54, 172.72, 226.06, and 711.2 mm, respectively. The amount of precipitation is very high on the west coast, in the north and south of Myanmar; in the middle and the east, it was found that the amount of rainfall was relatively low and classified as arid areas due to the influence of high ridges that separates the winds of the monsoon. Recently, Sein et al. (2018) observed trends and changes in temperature and precipitation extreme indices over Myanmar; the trends of the maximum and minimum temperature show significant warming trends across Myanmar, days and nights are becoming hotter for the entire of Myanmar, along with a slightly higher increasing trend in wetter regions.

As there is a lack of climate data from the Meteorological Department in Myanmar, information from nature proxies in remote areas may be a substitute. One such proxy is teak tree-ring width. Myanmar teak ring width has been studied by several authors (Pumijumnong et al. 2001; Kyaw 2003; D'Arrigo et al. 2011; D'Arrigo et al. 2013; D'Arrigo and Ummenhofer 2014; Hlaing et al. 2014). There are some studies using teak in India (Ram et al. 2008; Borgaonkar et al. 2010; Sengupta et al. 2017), Thailand (Pumijumnong et al. 1995; Buckley et al. 2007; Pumijumnong 2012; Buajan et al. 2016; Muangsong et al. 2019; Preechamart et al. 2018), and Indonesia (Poussart et al. 2004; D'Arrigo et al. 2008; Schollaen et al. 2015). The results of the study of the teak ring width in previous past years have been enough to infer that there is potential to study weather variability.

At present, isotopes of oxygen from tree-ring cellulose are an effective tool for analyzing moisture sources (Baker et al. 2016). Isotope composition of cellulose in the tree-ring are widely used to study climate variability (Anderson et al. 2002). The use of oxygen isotopes in the tree-ring cellulose to study the variability of the climate in the past has been prevalent in the temperate zone (e.g., McCarroll and Loader 2004; Sternberg 2008; Leavitt 2010; Loader et al. 2015). And at present, the using of oxygen isotopes in studying the variability of weather conditions has increased in tropical regions (e.g., Evans and Schrag 2004; Poussart et al. 2004; Managave et al. 2011; Schollaen et al. 2013; Xu et al. 2013; Xu et al. 2015; Muangsong et al. 2016; Muangsong et al. 2019; Xu et al. 2018a, b). This research is the first study analyze tree-ring stable oxygen isotope variations from teak cellulose in Myanmar. The objectives of this research are (1) to analyze the oxygen isotopes present in Myanmar teak, and (2) to analyze climatic factors (rainfall, temperature) that control the oxygen isotopes of teak. This research will be useful in understanding the hydrological cycle in Myanmar and the possibility of expanding the network of teak oxygen isotope sampled locations.

2 Materials and methods

2.1 Study area and climatology

The study area is locating at the Moe Yungyi wildlife sanctuary (Fig. 1) 17.30–17.50 N and 96.30–96.60 E. Mixed deciduous forest is the main forest type in the area. The geology of the area is predominantly alluvial, and the soils are mostly sandy loams (http://www.eaaflyway.net/nominative-a-site.php#network). Climate data from the wildlife sanctuary during 2007–2017 showed that the average monthly rainfall during the rainy season (May–October) was 525.78 mm, with the highest rainfall month being August (706.30 mm) and the annual rainfall is 279.57 mm. The average monthly rainfall during the dry season (November–April) was 33.36 mm, with the most rainy month being January (13.30 mm). The average monthly temperature during the rainy season (May–October) is 28.43 °C and the average monthly temperature during the dry season (November–April) is 26.76 °C, and the annual temperature is 27.60 °C. April is the month with the highest average temperature of 30.9 °C. Due to the fact that the current climate data do not cover the period of the sampled trees, we used weather data CRU TS4.02 from the website https://climexp.knmi.nl (Fig. 2).

2.2 Tree-ring material

The teak samples used for this study were collected at Moe Yungyi wildlife sanctuary in 1999. We have been allowed to collect teak samples in Myanmar through the approval of Kuaw Tint, Director General, Forest Department, Mehm Ko Ko Gyi, former Coordinator of TEAKNET (Asia Pacific Region), Saw Eh Dah, Coordinator, Forest Department, Yangon/Myanmar, for cooperation during the sampling expedition in March 1999. The total number of collected trees by using increment borer is 20 trees, 2 samples per tree, and 40 samples in total. Ring width series of the samples used in this study were measured and cross-dated in an earlier study (Pumijumnong et al. 2001), indicating that the last tree rings were formed in 1998. The criteria for selecting the trees for stable isotope analysis were as follows: (1) cross dating was successful and age determination was correct and (2) all annual ring boundaries were clearly visible.

2.3 Cellulose extraction and stable isotope analysis

In this study, six teak specimens with relatively high correlations were selected (Table S1). The extraction of α-cellulose from each ring is a very time-consuming process. In this study, we applied a technique developed by Kagawa et al. (2015), which can extract α-cellulose directly from wood samples and still maintain the structure of the wood anatomy. Samples were sliced by low speed diamond saw microtome into

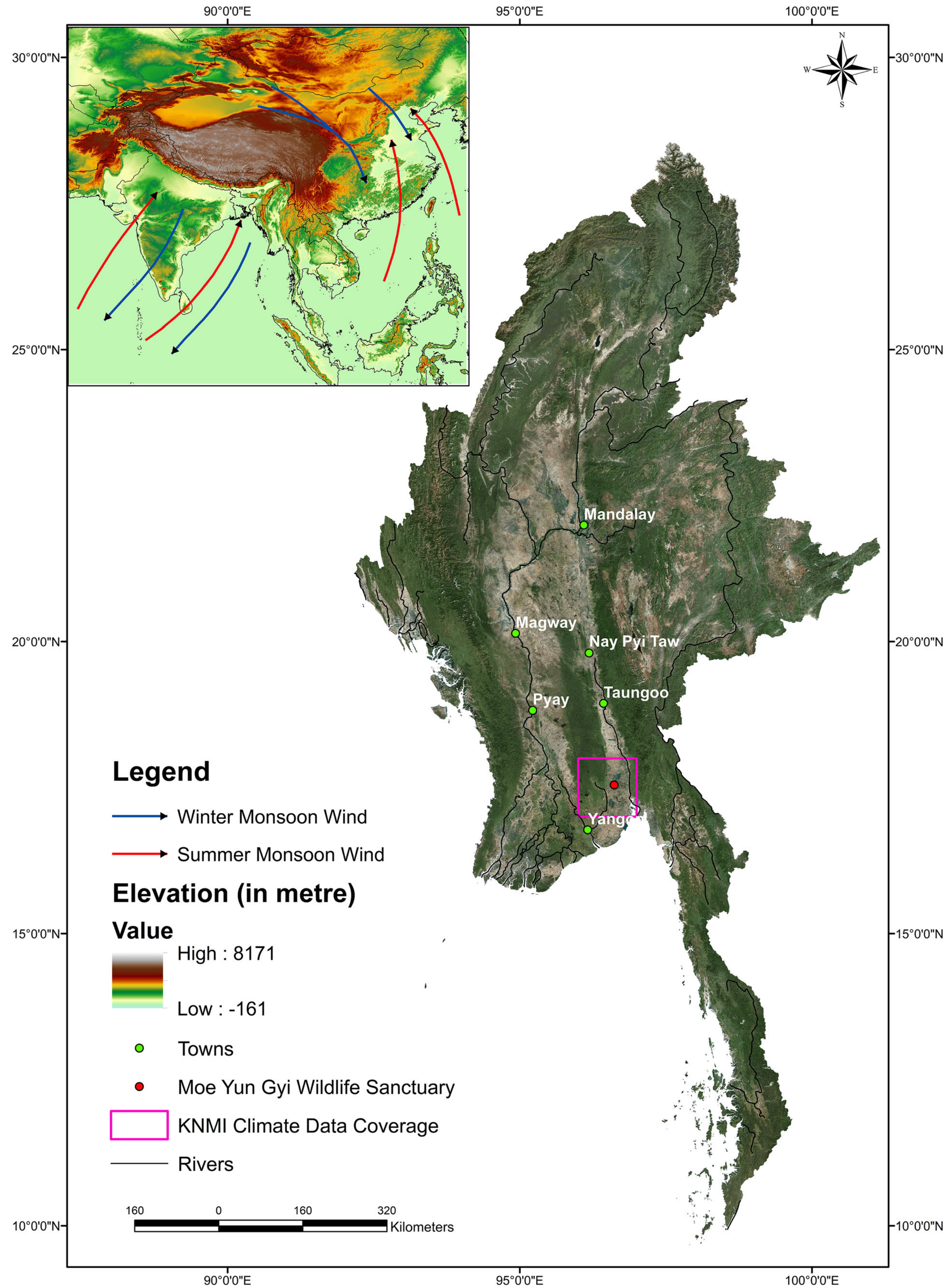


Fig. 1 Study sites. The dark pink circle represents Moe Yun Gyi Wildlife Sanctuary, green circle are towns, square pink is KNMI climate data coverage, dark lines represent rivers, and the map on the top left corner shows the direction of the monsoon

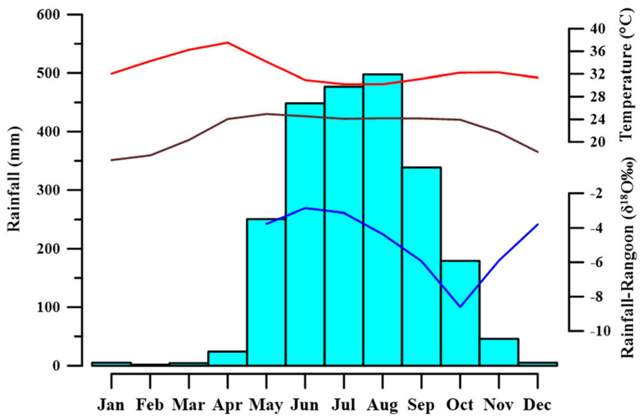


Fig. 2 Climate diagram CRU T4.02 grid data at 17–18° N, 96–97° E, from 1901 to 2018. The blue bar is the mean monthly rainfall (mm), red line is the maximum temperature (°C), brown line is the minimum temperature (°C), and the blue line is the rainfall $\delta^{18}O$ at Rangoon station (GNID-data)

cross-section laths of 1 mm (longitudinal length) × 12 mm (tangential) × less than 83 mm (radial), packing the 1 mm thick between the two Polytetrafluoroethylene (PTFE) sheets and loosely by cotton string. A modified chemical protocol, based on standard protocols for extracting α-cellulose which are 3 steps: (1) mixed 1:1 between toluene-ethanol, (2) mixed the sodium chloride solution ($NaClO_2$) and acetic acid (CH_3COOH) to remove lignin, and (3) removal of hemicellulose by washing with sodium hydroxide (NaOH) (Leavitt and Danzer 1993; Loader et al. 1997). When the chemical process is finished. Samples were dry at 70 °C in a drying oven. Put the dried 1 mm thick of cellulose plate onto a "Photo-binder" with an adherent black surface and transparent plastic film. The cellulose ring curve will be cut for oxygen isotope weight approximately 100–250 μg under the microscope using a design knife. Warp the cellulose fragment with silver foil. Cellulose $\delta^{18}O$ was measured with a pyrolysis-type elemental analyzer (TCEA-IRMS, Thermo Scientific, Bremen, Germany) at the Research Institute for Humanity and Nature, Japan. Cellulose $\delta^{18}O$ values were calculated against Merck cellulose (Laboratory working standard), which was inserted every eight samples. Oxygen isotope results are presented in δ notation as the per mil (‰) deviation from Vienna Standard Mean Ocean Water (VSMOW): $\delta^{18}O = [(R_{sample}/R_{standard}) - 1] \times 1000$, where $R_{samples}$ and $R_{standard}$ are the $^{18}O/^{16}O$ of the sample and standard, respectively.

2.4 Statistical analysis

For evaluating coherence of the data, we calculated the mean inter-series correlation (Rbar) (Cook and Kairiukstis 1990) and the expressed population signal, or EPS (Wigley et al. 1984), which indicates how well the tree-ring $\delta^{18}O$ estimates a theoretically infinite population. To determine the impact of the different climatic factors on $\delta^{18}O$, we computed simple correlations between $\delta^{18}O$ and monthly means of climate data. Climate data (temperature, rainfall) from the CRU TS4.2 (https://climexp.knmi.nl) gridded temperature/precipitation data, with a resolution 0.5° × 0.5°° were used for correlation analyses. The Moisture Index (*Im*) value of the study site was calculated using the Thornthwaite (1948) annual moisture index (Gregory and David 1992). This can be expressed by the following equation: $Im = 100 \times [(P/PE) - 1]$, where P = annual rainfall in millimeters and PE = annual potential evapotranspiration, which is based on the Hamon potential evapotranspiration equation (Gregory and David 1992) as follows: $PE = (0.05949–0.1189*TC)*365$, where PE is in millimeters per year and TC = annual mean temperature in degree Celsius. Then, we also compared the tree-ring $\delta^{18}O$ and tested the similarity with various climatic indices: the Indian Monsoon (IM) Index = U850(40E–80E, 5N–15N)-U850(70E–90E, 20N–30N), the Western North Pacific Monsoon (WNPM) Index = U850(100E–130E, 5N–15N)–U850(110E–140E, 20N–30N), and the Webster and Yang Monsoon (WYM) Index = U850(40–110E, EQ–20N)–U200(40–110E, EQ–20N), all of which were accessed from http://iprc.soest.hawaii.edu/users/ykaji/monsoon/definition.html.

We analyzed the influence of different monsoon indices on our $\delta^{18}O$ series during the main ASM season (June–September) over the common period of 1948–1998. Furthermore, similarities with the Multivariate ENSO index, Niño 3.4, Niño 4 (https://www.esrl.noaa.gov/psd/enso/mei.ext/table.ext.html), and the IOD model were investigated. Furthermore, we employed the Royal Netherlands Meteorological Institute Climate Explorer (https://climexp.knmi.nl) to examine spatial correlations between $\delta^{18}O$ and precipitation and sea surface temperatures (SSTs). To extract cyclical variations in our records, we performed a spectral analysis on our $\delta^{18}O$ series using the REDFIT program for unevenly spaced time series (Schulz and Mudelsee 2002).

3 Results

3.1 Teak oxygen isotope chronology

The lengths of the individual tree-ring $\delta^{18}O$ were 98, 69, 75, 100, 93, and 58 years, respectively. Most of the individual tree-ring $\delta^{18}O$ series showed significant intercorrelations, which allowed their averaging to the mean regional site chronology (Table S1). Figure 3 shows the annually resolved $\delta^{18}O$ mean values of tree-ring cellulose from six trees for the period AD 1898–1998 along with its running EPS and Rbar statistics, through the use of 30-year windows, with a 15-year lag (Fig. 3). The Rbar statistic for these data spans a range of 0.41–0.73, and EPS is in the range of 0.8–0.89. For our $\delta^{18}O$ series, the EPS attained a generally accepted threshold value of 0.85, which is used to infer that a time series actually represents a

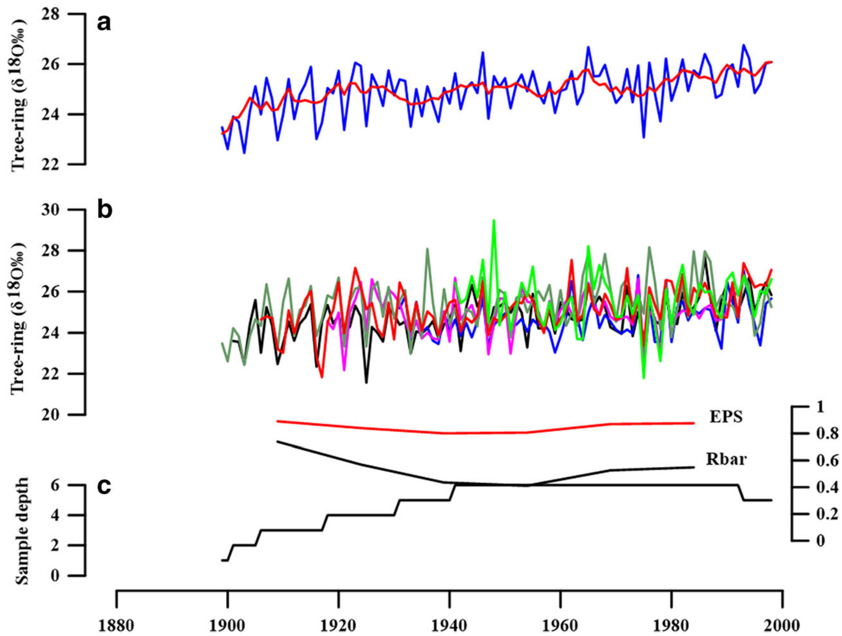


Fig. 3 Tree-ring $\delta^{18}O$ and 11-year mean value running average (**a**); tree-ring $\delta^{18}O$ series of six trees (**b**). The running EPS (red line) and Rbar statistics used 30-year windows, lagged 15 years (dark line) and sample depth (**c**)

common regional signal (Wigley et al. 1984) but fell below this criterion in some periods (AD 1940–1950), as sample sizes diminished. The $\delta^{18}O$ values ranged between 21.56 and 29.47‰, and the long-term average was 24.94‰.

3.2 Relationships between tree-ring $\delta^{18}O$ and climate data

3.2.1 Tree-ring $\delta^{18}O$ and climate data

The mean $\delta^{18}O$ was significantly and negatively correlated with CRUT4.02 rainfall in May ($r = -0.219$, $p < 0.05$), July ($r = -0.301$, $p < 0.01$); September ($r = -0.279$, $p < 0.01$); May and October (MO) ($r = -0.353$, $p < 0.01$); May, June, and July (MJJ) ($r = -0.311$, $p < 0.01$); and June, July, August, and September (JJAS) ($r = -0.275$, $p < 0.01$). These results suggest that moisture source availability in wet season dominated the $\delta^{18}O$ signal in tree-ring cellulose of teak. The $\delta^{18}O$ had a significant negative correlation with the minimum temperature in September ($r = -0.251$, $p < 0.05$) and August, September, and October (ASO) ($r = -0.246$, $p < 0.05$) and a significant positive correlation with the maximum temperature in November ($r = 0.319$, $p < 0.01$) and December ($r = 0.239$, $p < 0.01$). DTR is the difference between the maximum temperature and the minimum temperature. The study found that $\delta^{18}O$ has a significant positive correlation with DTR in June ($r = 0.237$, $p < 0.05$), September ($r = 0.297$, $p < 0.01$), October ($r = 0.2$, $p < 0.05$), MO ($r = 0.309$, $p < 0.01$), MJJ ($r = 0.208$, $p < 0.05$), JJA ($r = 0.245$, $p < 0.05$), JJAS ($r = 0.291$, $p < 0.01$), and the highest month in ASO ($r = 0.327$, $p < 0.01$) (Fig. 4).

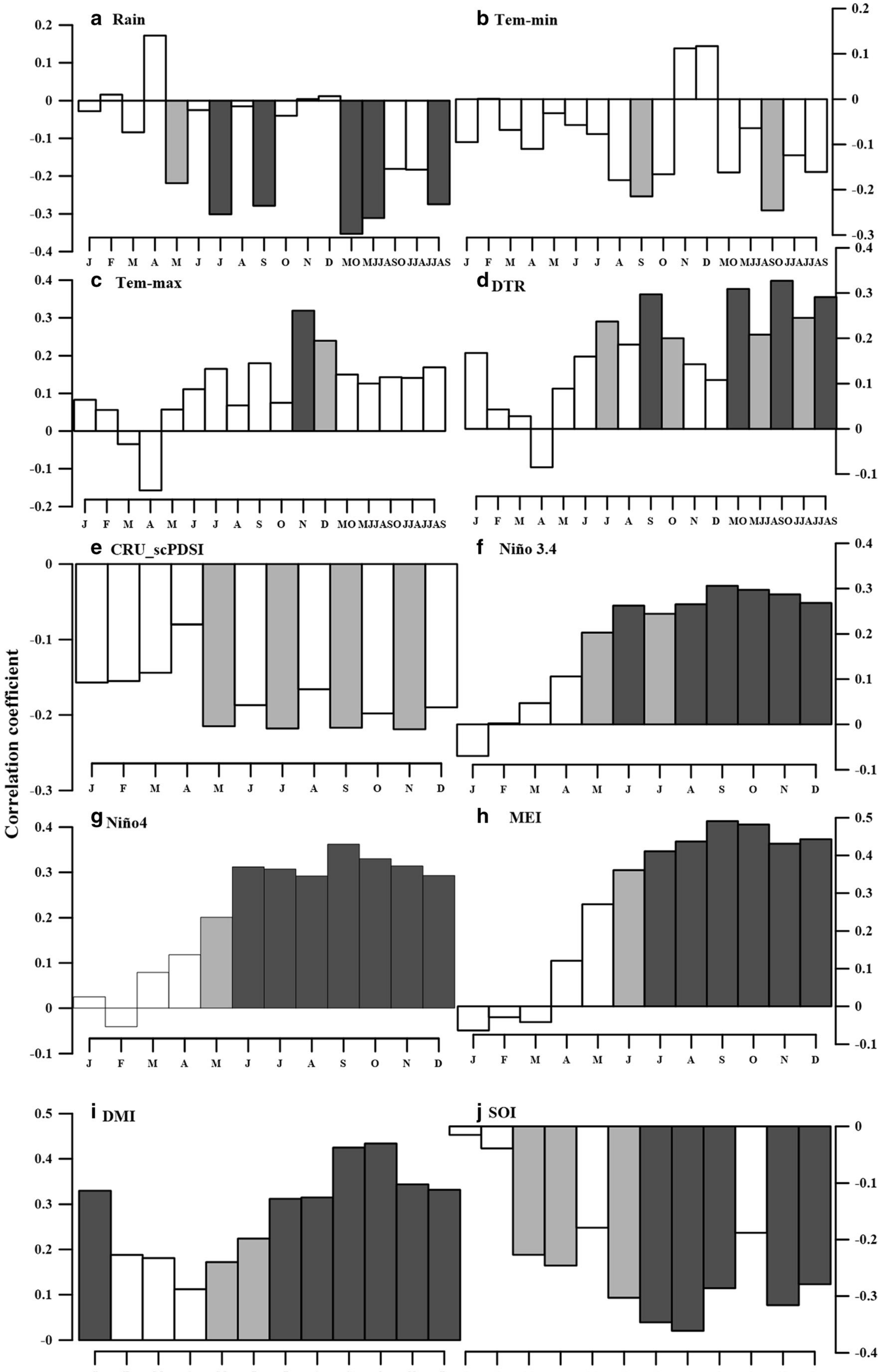
In general, when the amount of rainfall is high (low), the relative humidity in the air is also high (low) and the temperature decreases (increases), causing the tree-ring $\delta^{18}O$ to be high (low). We found that Myanmar teak $\delta^{18}O$ showed significant negative correlation with CRU_scPDSI in May ($r = -0.215$, $p < 0.05$), July ($r = -0.218$, $p < 0.05$), September ($r = -0.219$, $p < 0.05$), and November ($r = -0.219$, $p < 0.05$). We found that the relationship between tree-ring $\delta^{18}O$ and the moisture index (*Im*) has a significant negative correlation in May ($r = -0.219$, $p < 0.05$), July ($r = -0.29$, $p < 0.01$), and September ($r = -0.279$, $p < 0.01$). Due to the fact that the $\delta^{18}O$ data in the rainwater from the Rangoon Station is very limited, we did not find a significant correlation between Myanmar teak tree-ring $\delta^{18}O$ and $\delta^{18}O$ from the rainwater, only the $\delta^{18}O$ in the rainwater values shown in the graph as shown in Fig. 2.

3.2.2 Tree-ring δ18O and monsoon indices

The negative significant correlations occurred for the rain in June ($r = -0.393$, $p < 0.05$), August ($r = -0.435$, $p < 0.01$), September ($r = -0.297$, $p < 0.05$), JJA ($r = -0.417$, $p < 0.01$), and the highest in JJAS ($r = -0.53$, $p < 0.01$), which could be interpreted as a declining influence of the ISM. The strongest influence of the Webster and Yang Monsoon Index (WYM) (1948–1998) was in August ($r = -0.287$, $p < 0.5$) and September ($r = -0.33$, $p < 0.05$). There was no relationship between $\delta^{18}O$ and the northwest Pacific monsoon (NWPM).

3.3 Correlation between tree-ring $\delta^{18}O$ and sea surface temperature globally

We found significantly positive relationships between $\delta^{18}O$ and the Multivariation ENSO Index (MEI) from


a Rain
b Tem-min
c Tem-max
d DTR
e CRU_scPDSI
f Niño 3.4
g Niño4
h MEI
i DMI
j SOI
Correlation coefficient
J F M A M J J A S O N D MO MJJASO JJA JJAS
J F M A M J J A S O N D

◀ **Fig. 4** Correlation between tree-ring $\delta^{18}O$ and precipitation (**a**), temperature minimum (**b**), temperature maximum (**c**), DTR (Tmax–Tmin) (**d**), CRU-scPDSI (**e**), (precipitation, temperature minimum and maximum, DTR, and CRU-scPDSI) obtained from the CRU TS4.02 during the period 1901–2017, Niño 3.4 (**f**), and Niño 4 (**g**). Multivariate ENSO index (MEI) (**h**), Dipole Mode index (DMI) (**i**), and SOI (**j**) obtained from the (https://rda.ucar.edu/dataset/ds299.0) Black bars indicate correlations significant at the 99% level of confidence; light black bars indicate correlations significant at the 95% confidence level

June to December, and September (r = 0.491, p < 0.01). The same relationship was found between $\delta^{18}O$ and Niño 3.4, and Niño 4, where the relationship of tree-ring $\delta^{18}O$ to Niño 4 is higher than that of Niño 3, with the relationship starting from May to December, with September having the highest relationship (r = 0.362, p < 0.01). We also calculated the relationship between $\delta^{18}O$ and Southern Oscillation Index (SOI). Correlations were significantly negative from March to December, except for May, with the highest correlation in August (r = − 0.361, p < 0.01). The relationship between temperature variations on both sides of the Indian Ocean (Dipole Mode index [DMI] or IOD and the Indian Summer Monsoon (ISM)) has been intensively studied (Saji et al. 1999; Ashok et al. 2001; Ashok and Saji 2007). Correlations between $\delta^{18}O$ and DMI over the entire period (1870–1998) revealed significant positive relation from January to December, except for February to May, with October being the month that had the highest correlation (r = 0.434, p < 0.01) (Fig. 4).

3.4 Spectral analyses

The spectral analysis revealed significant peaks (p < 0.01) at years 2.3 and 2.4 (Fig. 5) for cyclicity. It should be acknowledged that short cycles of 2–7 years corresponded to the typical ENSO frequency band (Fig. 5).

4 Discussion

4.1 Teak oxygen isotope chronology characteristics

We constructed a 100-year long teak oxygen isotope chronology that cover the period of AD 1898–1998 including data from six individual living teak trees from Moe Yun Gyi wildlife sanctuary in southern Myanmar. The year mean tree-ring $\delta^{18}O$ values ranged between 21.56‰ and 29.47‰, and the long-term average was 24.94‰. Comparing the average values of Myanmar and India tree-ring $\delta^{18}O$, the $\delta^{18}O$ values in Myanmar teak are lower than those of the Indian teak (Managave et al. 2011). It indicates that the source of moisture and factors that control tree-ring $\delta^{18}O$ of the two countries might be different. Muangsong et al. (2019) examined the tree-ring $\delta^{18}O$ of teak from northwestern Thailand; and the mean $\delta^{18}O$ value is 23.6‰, ranging from 14.1 to 33‰, which is a wider range than teak from Myanmar. Indonesia teak tree-ring $\delta^{18}O$ ranged from 23 to 28.5‰ (Hisamochi et al. 2018), which is a narrower range than teak from Myanmar. The average annual $\delta^{18}O$ value of Java teak from central Java (Poussart et al. 2004) was 26‰ and 25.8‰, which was higher than for Myanmar teak. Tree-ring $\delta^{18}O$ values are mainly controlled by the isotopic composition of atmospheric precipitation and plant physiological responses to moisture stress levels (McCarroll and Loader 2004) or by a combination of both. Despite large rainfall amount variations across the entire Southeast Asia (i.e., heterogeneous distribution of rainfall regimes), similar intraseasonal rainfall $\delta^{18}O$ pattern was clearly observed for both Bangkok, Thailand, and Rangoon, Myanmar, meteorological stations (Cai et al. 2010; Muangsong et al. 2016; Wei et al. 2018) with a clear decreasing trend (i.e., more negative $\delta^{18}O$ values) of approximately − 3‰ during the late rainy season compared to the early rainy season (Fig. 2). This consistent intraseasonal pattern is associated with different two moisture regimes originating from the Indian Ocean (the Bay of Bengal) during the early rainy season and the Pacific Ocean (the South China Sea) during the late rainy season (Cai et al. 2010; Muangsong et al. 2016; Wei et al. 2018). Tree-ring $\delta^{18}O$ values in this region are modified not only by total (or annual) rainfall but also monthly and seasonally rainfall isotopic signatures. Consequently, the distinctive variations in monthly and/or seasonally input of rainwater isotopic signals, which in turn relate to different moisture sources, can therefore determine tree-ring $\delta^{18}O$ in this region as well as can result in different tree-ring $\delta^{18}O$ values from even the same or nearby locations (Buajan et al. 2016; Muangsong et al. 2019). Further important process modifying tree-ring $\delta^{18}O$ is an isotope fractionation occurs in leaves via

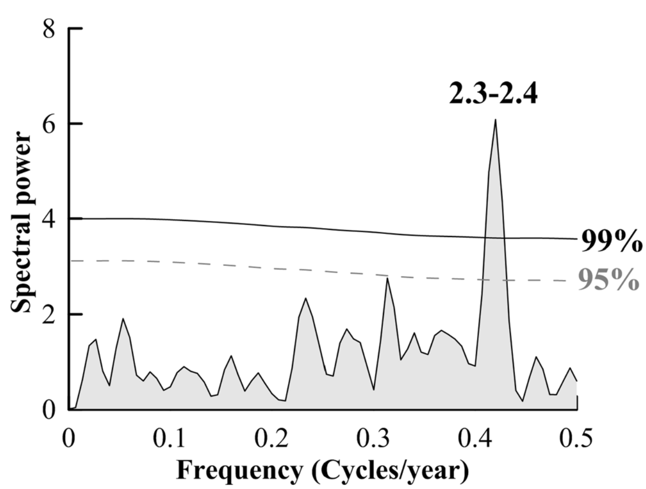


Fig. 5 Spectral analysis of tree-ring $\delta^{18}O$ values. The solid line indicates 99% confidence levels, the dotted line 95% confidence levels

evapotranspiration procession, resulting in isotopic enrichment of leaf water (McCarroll and Loader 2004). Therefore, an important environmental factor that regulates oxygen isotope in the wood is the oxygen isotope in rainwater and/or atmospheric humidity which the relative intensity of these two signals will vary (Gessler et al. 2014).

4.2 Possible mechanisms for the climate signal in $\delta^{18}O$

Myanmar tree-ring $\delta^{18}O$ exhibits a stable inverse relationship with the amount of rainfall in May ($r = -0.219$, $p < 0.5$), July ($r = -0.301$, $p < 0.01$), and September ($r = -0.279$, $p < 0.01$), probably as a result of the well-known “amount-effect” (Dansgaard 1964). However, more research on the relationship of $\delta^{18}O$ in rainfall and the amount of rain falling in the regions influenced by the Asian monsoon showed it was controlled by convective activity and terrain (Shen and Poulsen 2019; Kumar et al. 2010). Therefore, our results show that the rainfall in the rainy season is not every month that has a significant negative effect on tree-ring $\delta^{18}O$. Tan (2014) explained that the southwest monsoon (SWM) drives long-distance transport of water vapor from Indian Ocean to the Monsoon regions of China and along this pathway increasing rain leads to more negative $\delta^{18}O$ in rainfall via Rayleigh distillation process. This process is expected to occur at our study area. The minimum temperature in September has a significant negative correlation ($r = -0.251$, $p < 0.05$) with the oxygen isotope, whereas the temperature in November ($r = 0.319$, $p < 0.01$) and December ($r = 0.239$, $p < 0.01$) were positively correlated with the tree-ring $\delta^{18}O$ (Fig. 6).

We have divided the teak tree-ring $\delta^{18}O$ into two periods, 1989–1947 and 1948–1998 to find a relationship with CRU TS4.03 precipitation. We found that teak tree-ring $\delta^{18}O$ in the second half have a significant negative relationship with rainfall throughout the rainy season (May to October) up to $r = -0.360$ ($p < 0.009$, $n = 51$), while the first period had a negative relationship but not insignificant (May to October, $r = -0.287$, $p < 0.050$, $n = 47$). It may explain that the monsoon that provides moisture to Myanmar has changed dramatically (Fig. 7). Supporting events related to the violence of the monsoon in the last 3 decades, according to Zin and Rutten (2017) studied the changes in rainfall in Myanmar during 1967 to 2015 and found that the monsoon duration and withdraw days have been shifted significantly. Furthermore, it was noticed that monsoon withdraw dates have shift to be early. An increase in the intensity of the monsoon in the short time has been reported by the Myanmar Department of Meteorology and Hydrology. This is consistent with the study of Wang et al. (2013) found that post-1979 increase in both premonsoon month of May and tropical cycle intensity that is caused by regional warming. The monsoon trough over the Bay of Bengal does not only affect the frequency of tropical cyclones but directly affects the increasing number of cyclones heading to Myanmar.

Because relative humidity data from the atmosphere is not available to analyze, we hypothesize that when the rainfall amount is high and the temperature lower, resulting in high atmospheric moisture, causing the enrichment in the $\delta^{18}O$ levels of leaf water (Roden et al. 2000). In general, teak cambium begins to be active during the beginning of the rainy season or the transition between dry season and rainy season, and the early

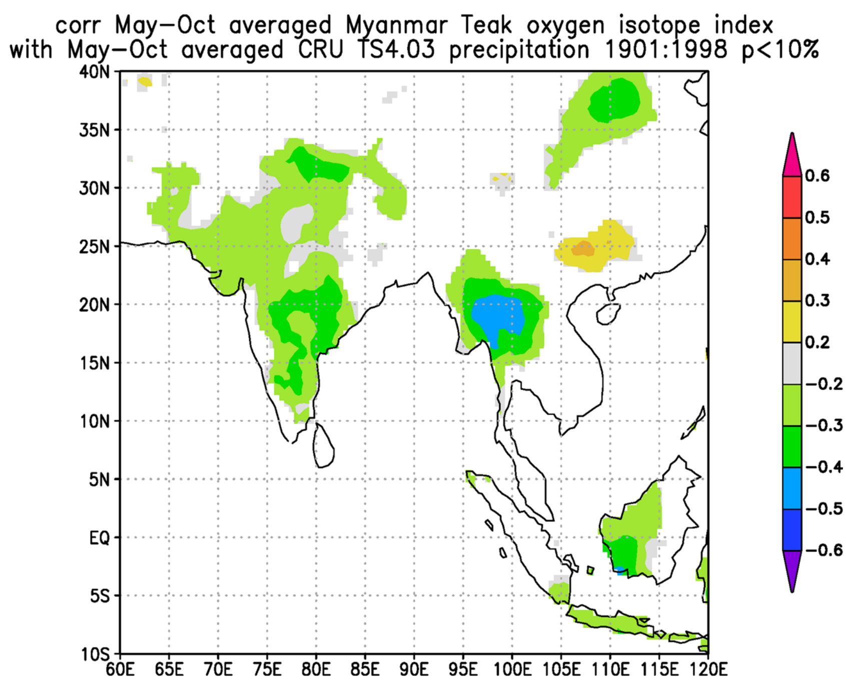


Fig. 6 Correlation pattern of Myanmar Teak $\delta^{18}O$ vs. CRU TS4.03, May–October precipitation

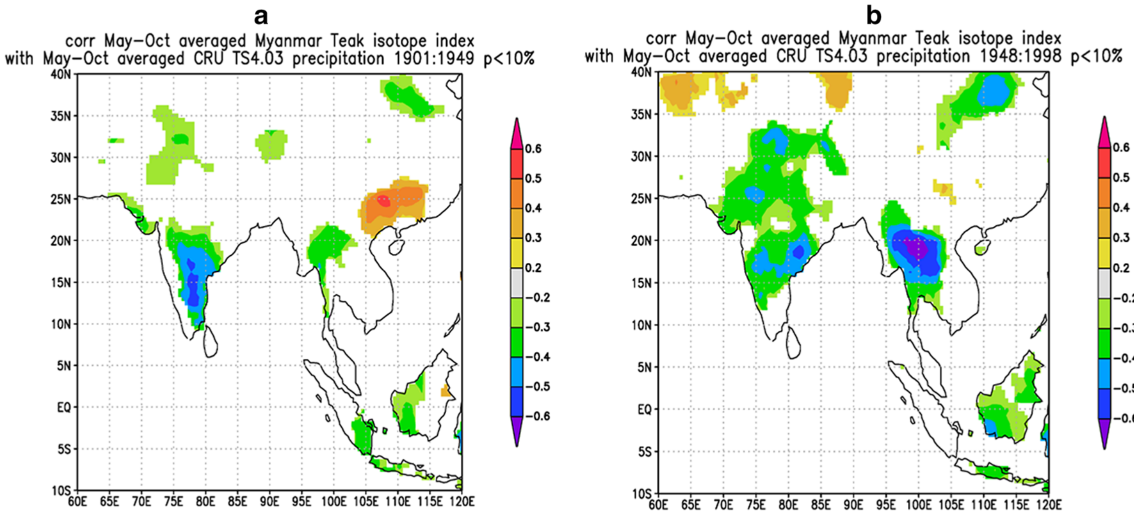


Fig. 7 Correlation pattern of Myanmar Teak $\delta^{18}O$ vs. CRU TS4.03, May–October precipitation 1898–1947 (**a**) and 1948–1998 (**b**)

wood builds up rapidly in the first half of the rainy season and the latewood is finished during the end of the rainy season (Pumijumnong et al. 1995). Most teak trees stand without leaves during the dry season. Schollaen et al. (2013) studied two Java teak tree from a lowland rainforest in the eastern part of Java and found that the younger teak $\delta^{18}O$ had a positive correlation with dry season rainfall (May–October) and negative correlation with the November–February rainy season rainfall; we did not find the relationship between Myanmar $\delta^{18}O$ and rainfall during the dry season. This is probably due to the Javanese teak may receive moisture almost every direction (Java is an Island), and during the dry season, there is still some rain but in the dry season in Myanmar, the amount of the rain is very low.

The results of our study are consistent with Hisamochi et al (2018), who studied teak in Indonesia from four plantations, as well as teak in Thailand (Muangsong et al. 2019) and teak from southern India (Managave et al. 2011). It indicates that the amount of rainfall during the monsoon season (MO, $r = -0.353$, $p < 0.01$) and the temperature at the beginning of the dry season controls the tree-ring $\delta^{18}O$ of Myanmar teak. We found confirmation of this effect of the maximum temperature during the dry season (November and December, $r = 0.319$, $p < 0.01$ and $r = 0.239$, $p < 0.01$, respectively), with this relationship not being found in teak studied in other areas (Schollaen et al. 2013). Furthermore, the difference in the maximum and minimum temperature is very important in controlling the tree-ring $\delta^{18}O$ of Myanmar teak. Only during the rainy season, it was found that the second half of the rainy season had a higher ($r = 0.327$, $p < 0.01$) relationship than in the first half of the rainy season with the tree-ring $\delta^{18}O$ ($r = 0.208$, $p < 0.05$) (Fig. 8).

The possible mechanism by which maximum temperatures were positively and significantly correlated with tree-ring $\delta^{18}O$ is that warmer conditions enhance evaporation of the soil water, which increase $\delta^{18}O$ in the source water (Sano et al. 2017). It can be concluded that the amount of rainfall during the summer monsoon and the difference of the maximum and minimum temperatures are important factors in controlling the tree-ring $\delta^{18}O$; the results of this study indicate that tree-ring $\delta^{18}O$ can indicate the amount of rainfall during the summer monsoon as well as other climactic factors. Therefore, the study of teak tree-ring $\delta^{18}O$ in Myanmar from other areas will be useful in relation to model the variation on the summer monsoon.

It is well known that Myanmar is influenced by the cyclone, which is mostly formed in the Bay of Bengal (BoB). Chakraborty et al. (2016) has analyzed the oxygen isotope in rainfall at Andaman Island, BoB for 2 years, 2012 and 2013. The oxygen isotope variations are different. The $\delta^{18}O$ in rainfall is subjected to a varying degree of isotopic fractionation during heavy to severe cyclonic storms. Although our tree-ring $\delta^{18}O$ data do not compare with the $\delta^{18}O$ levels in the rainfall, it can be concluded that the severity of the rainfall in Myanmar is an important factor causing the variability of tree-ring $\delta^{18}O$. Since the topography may be a factor that causes variations in $\delta^{18}O$ in rainfall and in tree-ring $\delta^{18}O$, the study of tree-ring $\delta^{18}O$ at the monthly scale (sub-annual) should greatly benefit better understanding of the circulation of hydrological systems in Myanmar. It is very obvious that the terrain is a factor that prevents even rainfall distribution (Brienen et al. 2012).

4.3 Comparison with other tree-ring cellulose $\delta^{18}O$ records

Aside from teak having the potential to study dendrochronology, dendroclimatology in subtropical regions, there are other tree species such as *Pinus merkusii* (two needle leaf tree, PM) (Pumijumnong and Eckstein 2011), *Pinus kesiya* (three needle leaf tree, PK) (Pumijumnong and Wanyaphet 2006), and *Fokienia hodginsii* (Sano et al. 2009). These are trees with clear annual rings and have the potential to study climate in the past.

It is interesting to find a significant relationship between the Myanmar tree-ring $\delta^{18}O$ and PM tree-ring $\delta^{18}O$ at Mae

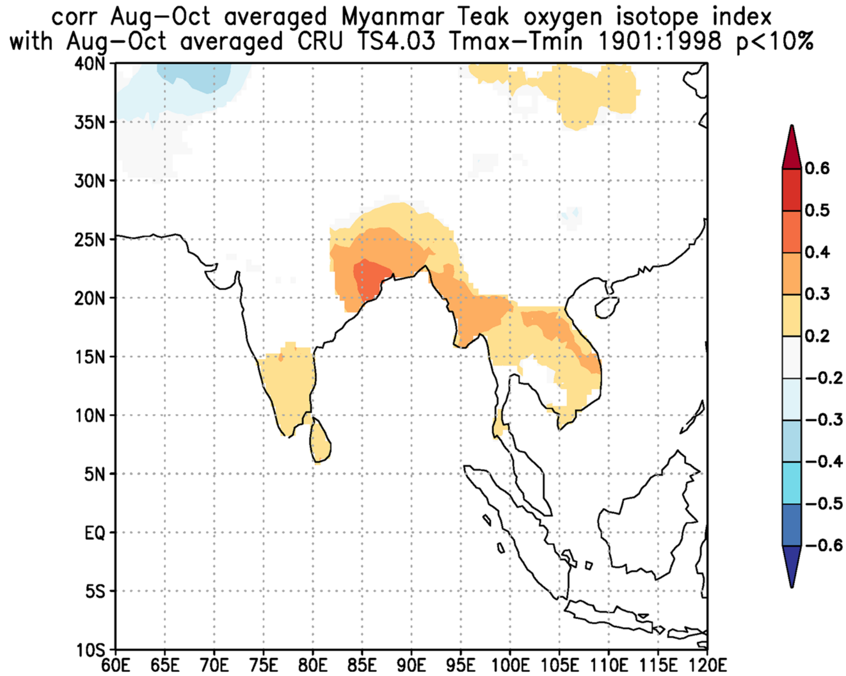


Fig. 8 Correlation pattern of Myanmar Teak $\delta^{18}O$ vs. CRU TS4.03, August–October DTR (the difference between temperature maxima and temperature minima)

Hong Son, Thailand, up to $r = 0.51$ ($p < 0001$, $n = 100$) (Xu et al. 2015) and the relationship with the PM tree-ring $\delta^{18}O$ at Umpang, Thailand, is $r = 0.337$ ($p < .001$, $n = 100$) (Xu et al. 2018a, 2018b). It may be possible to use the $\delta^{18}O$ values of both isotopes of tree to create $\delta^{18}O$ network in the future. The tree-ring $\delta^{18}O$ of *Pinus kesiya* growing in northern Thailand has a negative relationship with local amount of rainfall (August to October, $r = -0.44$, $p < .001$) and regional rainfall amount of rainfall (July to September, $r = -0.46$, $p < .001$) (Zhu et al. 2012), which is slightly different from Myanmar teak and *Pinus merkusii*, most of which have a relationship between $\delta^{18}O$ value and rainfall during the growing season (May to October). The relationship between *Fokienia hodginsii* tree-ring $\delta^{18}O$ and Myanmar tree-ring $\delta^{18}O$ is quite low $r = 0.192$ ($p < .055$, $n = 100$) (Xu et al. 2011, 2013), which is lower than the relation between the $\delta^{18}O$ values of Myanmar teak and pine trees (PM) in Thailand. Indicates that the climate controlled $\delta^{18}O$ values in Myanmar teak, and pine trees in Thailand are more similar than *Fokienia hodginsii* trees growing in northern Laos. And beyond, probably about that distance away how far away the trees will be influenced by similar weather conditions.

4.4 Large-scale drivers of inter-annual to decadal variation in tree-ring oxygen isotopes

The El Niño–Southern oscillation is a major driver of global climate variability. ENSO is also interacting with other modes of climate variability, such as Indian summer monsoon rainfall (ISRM). The easterly trades and SST gradients across the equatorial Pacific undergo a regime change, with enhanced trades and a significant cooling (warming) over the tropical eastern (western) Pacific in the later period. Previous research showed that the relationship between the ISRM and the SST is variable (Malik et al. 2017; Achuthavarier et al. 2011). The strongest relationships were found on short timescales (interdecadal periodicity, 2–7 years), but with varying significance levels (Varikodena and Babu 2015).

Myanmar teak tree-ring $\delta^{18}O$ captures well the Niño 4 from May to December, with the highest values in September ($r = 0.362$, $p < 0.01$) and a significant negative relationship with SOI, with September being the highest month ($r = -0.361$, $p < 0.01$) (Fig. 9). Teak tree-ring $\delta^{18}O$ from southern India has a significant negative relationship with Niño 3 ($r = -0.27$, $p < 0.01$) and SOI ($r = -0.29$, $p < 0.01$) (Managave et al. 2011). Annual resolved $\delta^{18}O$ in Java teak has a negative relationship with SOI, when SOI is low (El Niño event) (Poussart et al. 2004, $r = -0.33$, $p = 0.02$). The results of this study are consistent with previous study. It suggests that when SOI is low (El Niño event), the $\delta^{18}O$ of teak cellulose increases in response to decreases in rainfall abundance and/or relative humidity.

Muangsong et al. (2019) found a significant positive relationship between tree-ring $\delta^{18}O$ of Thai teak from northwestern Thailand and Niño1–2, with the highest in JJA ($r = 0.57$, $p < 0.01$). The results of their study are different from our study results. It may be due to that the El Niño phenomenon affects the amount of rainfall differently in different areas.

Myanmar tree-ring $\delta^{18}O$ had a significant positive correlation with Indian Ocean Dipole (IOD). The IOD typically develops during the boreal summer (May–October), peaks in July–September, and then rapidly decays in November and December when the Australian summer monsoon starts (Lim and Hendon 2017).

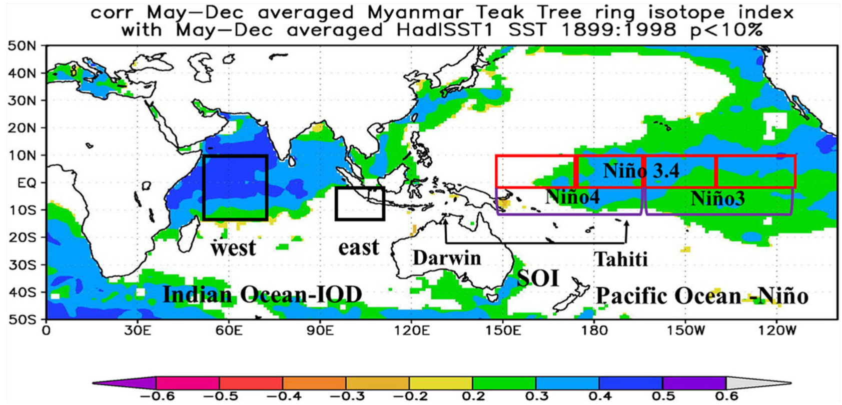


Fig. 9 Correlation between average Myanmar Teak $\delta^{18}O$ (May–December) and HadlSST (Niño 4) in the time period 1889–1998. The dark frames are West SSTA and East SSTA and the red frames are Niño 4, Niño 3.4, and Niño 3

Development of the IOD is often linked with the ENSO in the Pacific because of variations in the Walker Circulation, which has been explored by a number of studies (Pokhrel et al. 2012; Pervez and Henebry 2015). A positive IOD generally means there is more moisture than normal in the atmosphere over the West Indian Ocean and Arabian Sea. This changes the path of weather systems coming toward India, often resulting in more rainfall during Southwest Monsoons and generally a positive IOD, most of time overlapping the El Niño phase. A negative IOD typically adversely affects the Indian Southwest Monsoon rainfall, resulting in below-average rainfall over India.

Positive IOD phases (like the El Niño phase) occurred in 1961, 1963, 1972, 1982, 1983, 1994, and 1997 (Hong et al. 2008). Our tree-ring $\delta^{18}O$ value is greater than the mean (24.9‰) in 1961, 1972, 1982, and 1994. It indicated that probably there are other factors that are related to the appearance of IOD (such as El Niño) that affect precipitation. Recently, Wang et al. (2016) demonstrated the interaction between the IOD and ENSO associated with the ocean subsurface and found that the ENSO's impact on the IOD intensity is larger for the eastern pole than for the western pole and is stronger during a negative IOD event than during a positive event. The results reveal an asymmetry of the ENSO's influence between the positive and negative IOD phases.

D'Arrigo and Ummenhofer (2014) reanalyzed teak tree-ring width from the Maingtha Reserve, in the so-called "Dry Zone." They presented the Pacific Decadal Oscillation (PDO)'s impact on Myanmar's monsoon hydroclimate. Overall, the teak record and the PDO correlate most significantly and positively with each other during December–May, $r = 0.41$, $p < 0.002$, based on the annual tree-ring/PDO time series. Our teak tree-ring $\delta^{18}O$ showed a significant positive relationship with PDO only in August ($r = 0.23$, $p < 0.05$) (data not shown).

5 Conclusion

The 100-year teak tree-ring $\delta^{18}O$ profile has been developed from six individual teak trees from southern Myanmar. Teak tree-ring $\delta^{18}O$ is controlled both by the amount of rainfall in the summer monsoon (May to October) and the difference between the maximum temperature and the minimum temperature during the dry season, which corresponds to the negative relationship of tree-ring $\delta^{18}O$ and the moisture index during the monsoon season. ENSO has been influenced by teak tree-ring $\delta^{18}O$ as well as IDO and SOI but in the opposite direction. It is very highly suggested to further examine the intra-annual tree-ring $\delta^{18}O$ to gain more high resolution of summer monsoon and other climatic data and also examine teak samples growing throughout a wider distribution in Myanmar. It is highly possible to study past cyclones.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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