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RESEARCH ARTICLE

Inter-annual and multi-decadal variability of monsoon season rainfall in central Thailand during the period 1804–1999, as inferred from tree ring oxygen isotopes

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Long-term records of precipitation in Thailand are necessary to evaluate the robustness of the relationship between El Niño–Southern Oscillation (ENSO) and rainfall. This study presents a tree ring-cellulose oxygen isotope ($\delta^{18}O$) record, based on *Pinus merkusii*, for the period 1804–1999 in Thailand. Response and spatial correlation analyses reveal that tree ring $\delta^{18}O$ is significantly correlated with regional monsoon season (May–October) precipitation. Tree ring $\delta^{18}O$, which explains 50.1% of the variability in regional precipitation, was employed to reconstruct monsoon season rainfall back to 1804. Relatively wet periods occurred in 1809–1821, 1876–1882, 1897–1908, and 1944–1975, while the periods 1825–1850, 1913–1925, and 1979–1997 were relatively dry. During the periods 1854–1930 and 1970–1999, inter-annual variability of precipitation was modulated by the ENSO. In contrast, the absence of this relationship between 1930 and 1970 might relate to the reduced variance of ENSO.

KEYWORDS
central Thailand, ENSO, monsoon season rainfall, tree ring oxygen isotopes

1 | INTRODUCTION

The global monsoon precipitation provides water resources to about two thirds of the world's population, and a better understanding of mechanism of monsoon changes will be of great societal importance (Liu *et al.*, 2009). In particular, almost 80% of the annual rainfall in Thailand occurs during the summer monsoon season (May–October), which has important implications for agriculture and the economy. For instance, 67% of the national rice crop originates in lowland areas that are dependent on monsoon precipitation (Office of Agricultural Economics (OAE), 2001), while monsoonal flooding in 2011 resulted in an estimated economic loss of US$30 billion and an insured loss of US $12 billion (Re, 2011). Such examples highlight the need for improved understanding of the causes and variability of monsoon season rainfall in Thailand. However, most previous monsoon studies have concentrated on the East Asian (Ding and Chan, 2005) and Indian (Goswami *et al.*, 2006; Kumar *et al.*, 2006) summer monsoons, with few focusing on Thailand (e.g., Singhrattna *et al.*, 2005). In their analysis of meteorological data for the period 1951–2001, Singhrattna *et al.* (2005) reported that August–October rainfall over central Thailand has been modulated by the El Niño–Southern Oscillation (ENSO) since 1980. However, because of the short nature of the meteorological data set, key questions remain about long-term changes in rainfall and climatic influences on past precipitation patterns. For instance, what was the impact of ENSO on monsoonal rainfall prior to 1950? Long-term, high-resolution precipitation records are crucial to addressing such questions and improving our understanding of monsoonal rainfall variability in Thailand.

Stable oxygen isotopes ($\delta^{18}O$) in speleothems from northwest Thailand are negatively correlated with the ratio of August–October to May–July rainfall. However, the correlation coefficient ($r = -0.3$) is insufficient for annually resolved paleoclimate reconstructions (Cai *et al.*, 2010). Similarly, elemental Ca in annually laminated lake sediments has been employed in Myanmar as a proxy for regional monsoonal rainfall, but again the correlation coefficient between Ca and precipitation ($r = -0.23$) is too weak to reconstruct annual paleo-precipitation (Sun *et al.*, 2015; 2016). Finally, while tree ring chronologies from teak trees in northwest Thailand show a positive correlation between ring width and the regional Palmer drought severity index (PDSI), none has passed the stringent calibration–verification tests required to develop statistically significant rainfall reconstructions (Buckley *et al.*, 2007). Thus, there remains a real need for a robust precipitation reconstruction.

Tree ring cellulose $\delta^{18}O$ is determined by both the $\delta^{18}O$ of precipitation and relative humidity (Roden *et al.*, 2000), each of which is highly correlated with monsoonal rainfall in Asia (Araguas-Araguas *et al.*, 1998). Previous studies have shown that tree ring $\delta^{18}O$ is an effective tool for reconstructing regional precipitation in monsoonal Asia including southeast and southwest China (Grießinger *et al.*, 2011; Xu *et al.*, 2013b; 2016), northwest Thailand (Xu *et al.*, 2015), and Bhutan (Sano *et al.*, 2013). In this study, we present a tree ring oxygen isotope chronology for the period 1804–1999 in Thailand, based on four *Pinus merkusii* trees, and discuss the factors potentially influencing regional rainfall.

2 | MATERIALS AND METHODS

2.1 | Sampling site

The study site (16.088°N, 98.865°E and 400–600 m a.s.l.) is located in the Umpang (UP) district, Tak province, in Thailand. General Merkus pine grows over a large altitudinal range, from 30 to over 1,800 m a.s.l., and on different types of soils. We used an increment borer (5-mm diameter) to collect two core samples at breast height from opposite sides of each tree, taking care to avoid both uphill and downhill sides and any severely fluted parts where the tree ring pattern might be distorted. We collected 40 cores from 20 trees in total. The cores were air dried at room temperature and their surfaces smoothed with a knife to enhance visibility of the tree ring borders. Ring widths were then measured at 0.01 mm resolution using a binocular microscope with a linear stage interfaced with a computer. Finally, we cross-dated samples in the laboratory by matching variations in ring width in all cores, thereby establishing the absolute growth year for each ring. We assessed the accuracy of our cross-dating using the COFECHA program (Holmes, 1983).

2.2 | Cellulose extraction and isotope measurements

Previous studies showed that four trees were sufficient to build robust tree ring oxygen isotopes chronologies in monsoonal Asia (Shi *et al.*, 2011; Xu *et al.*, 2013a; 2015). The selection of wood samples for isotopic analysis was based on the following criteria: (1) trees contained as many rings as possible; (2) ring width of trees had a high correlation with master chronology; and (3) the rings were not too narrow in order to produce enough cellulose samples for measurement. Therefore, four trees (sample numbers UPML2b, 3b, 10a, and 16b) with relatively wide rings were selected for isotopic analysis. To extract α-cellulose, we used the modified plate method (Xu *et al.*, 2011; 2013b) adapted from the chemical treatment procedure of the Jayme-Wise method (Green, 1963; Loader *et al.*, 1997). Subsequently, we wrapped 120–250 μg samples of cellulose in silver foil and measured $^{18}O/^{16}O$ ratios on an isotope ratio mass spectrometer (Delta V Advantage, Thermo Scientific) interfaced with a pyrolysis-type high-temperature conversion elemental analyzer (TC/EA, 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 tree samples during measurement. Oxygen isotope results are presented in δ notation as the per mil (‰) deviation from Vienna Standard Mean Ocean Water (VSMOW): $\delta^{18}O = [(R_{sample}/R_{standard}) - 1] \times 1{,}000$, where R_{sample} and $R_{standard}$ are the $^{18}O/^{16}O$ ratios of the sample and standard, respectively. The analytical uncertainties for repeated measurements of Merck cellulose were ±0.19‰ ($n = 96$). The oxygen isotope data of 16 rings (Nos. 2b-1863, 2b-1979, 3b-

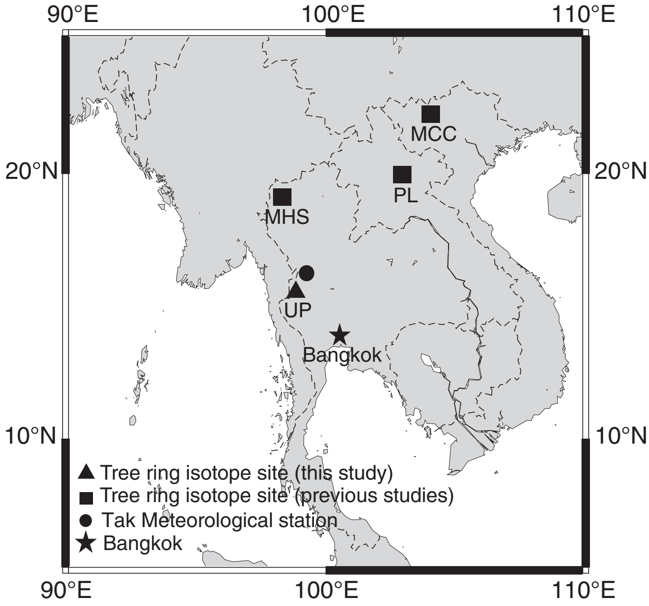

FIGURE 1 Map of the study area

1836, 3b-1844, 3b-1871, 3b-1874, 3b-1976, 10a-1824, 16b-1852-1853, 16b-1860-1863, 16b-1926-1927) are not available due to either the loss of several rings during the chemical treatment or the loss of cellulose samples during the oxygen isotopic measurement. The number of all rings from four trees is 710, and the percentage of missing data is 2.3%.

2.3 | Climate and statistical analyses

The rainy season in central Thailand occurs between May and October as a result both of the southwest monsoon and migration of the intertropical convergence zone (Singhrattna *et al.*, 2005). Long-term (1955–1999) observational data from the Tak meteorological station (black circle in Figure 1) show that the average temperature is 27.6 °C and mean annual precipitation is 1038.1 mm, 87.6% of which falls during the rainy season (Figure 2). For our study, we used gridded precipitation from CRU TS4.0 (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.00/) and GPCC V7 (ftp://ftp.dwd.de/pub/data/gpcc/html/fulldata_v7_doi_download.html) and temperature data sets (14°–17°N, 99°–103°E) with a resolution of 0.5 × 0.5° to represent the regional climate of central Thailand. May–October precipitation in central Thailand data set from Climatic Research Unit (CRU) and Global Precipitation Climate Centre (GPCC) are highly correlated during the common period of 1901–2013 ($r = 0.91$, $n = 113$, $p < .0001$), and there are no significant differences in mean and standard deviation of regional May–October precipitation from CRU and GPCC. In addition, May–October precipitation from CRU and GPCC do not show any significant trends during the period of 1901–2013. May–October rainfall contributes 86.4% of the total annual precipitation in this region. To evaluate the relationship between tree ring $\delta^{18}O$ and the $\delta^{18}O$ of rainfall, we used precipitation $\delta^{18}O$ values for Bangkok obtained from the Global Network of Isotopes in Precipitation (GNIP). We then employed the Royal Netherlands Meteorological Institute Climate Explorer (http://www.knmi.nl/) to examine spatial correlations between tree-ring cellulose $\delta^{18}O$ and precipitation (CRU TS4)/sea surface temperature (SST) values obtained from the National Climatic Data Center v4 data set (Huang *et al.*, 2014) and to do wavelet analysis in order to identify period characteristics of tree ring $\delta^{18}O$ record. Finally, to assess the validity of the linear regression model, we split the samples into two sub-periods (1901–1950 and 1951–1999) and conducted calibration and verification for each separately. The statistical tests include Pearson's correlation coefficients (r), explained variance (r^2), reduction of error (RE), and coefficient of efficiency (CE; Cook *et al.*, 1999). RE and CE as the rigorous statistics are widely used to test the validity of regression model in dendroclimatology. Both RE > 0 and CE > 0 indicate reconstruction skill in excess of climatology, which means the regression model is robust (Cook *et al.*, 1999).

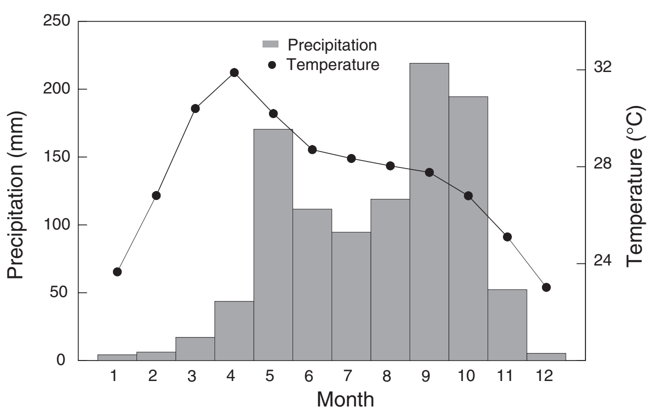

FIGURE 2 Monthly mean temperature and precipitation at the Tak Meteorological Station for the period 1955–1999

3 | RESULTS AND DISCUSSION

3.1 | Inter-tree variations in cellulose $\delta^{18}O$

Figure 3a shows the individual tree ring cellulose $\delta^{18}O$ time series for each of the four cores. Mean $\delta^{18}O$ values (standard deviations) for samples 2b, 3b, 10a, and 16b are 24.94‰ (0.89‰), 24.94‰ (0.89‰), 24.68‰ (0.86‰), and 24.89‰ (0.86‰), respectively, over the common period 1847–1997. For both the mean and standard deviation, there are no significant differences in $\delta^{18}O$ among the four trees. For the period 1828–1999, the four trees have a mean cellulose $\delta^{18}O$ of 24.99‰, which is comparable to that of *P. merkusii* (25.31‰) in northern Thailand (MHS site; Xu *et al.*, 2015; Figure 1) during the same period.

In total, four tree ring $\delta^{18}O$ time series are highly correlated with each other (Table 1).

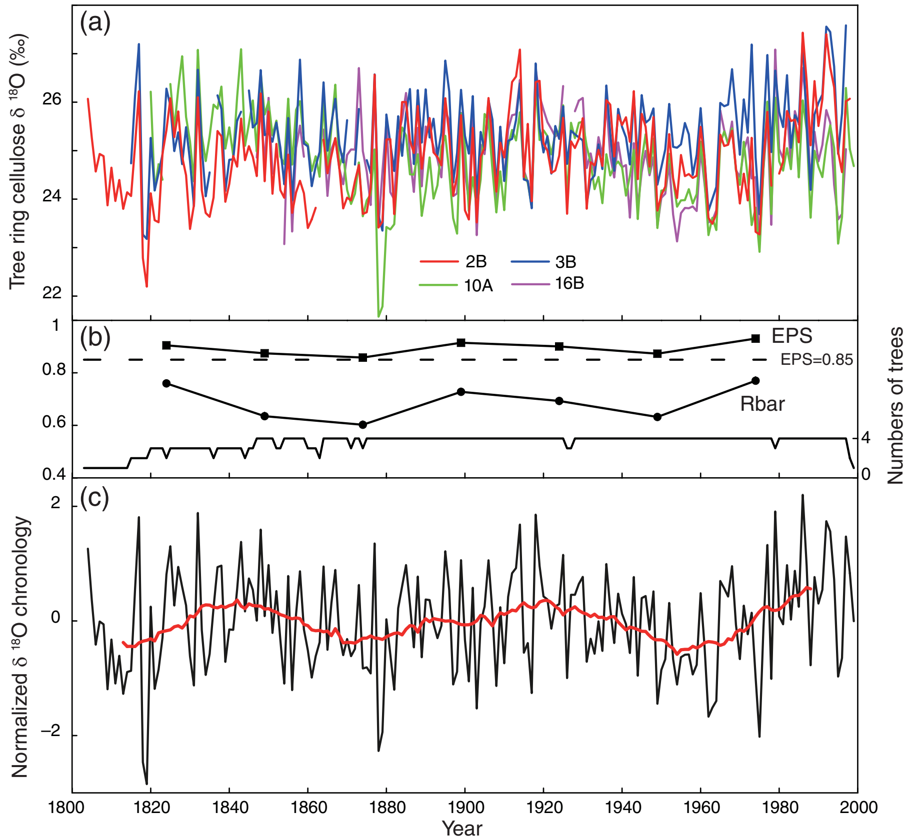

FIGURE 3 (a) Tree ring δ^{18}O series from the four trees analysed in this study; (b) EPS, Rbar statistics, and sample depth; and (c) annual normalized and 21-year running average δ^{18}O chronologies obtained in this study [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Correlation coefficients among tree ring oxygen isotope series

r	2b	3b	10a
3b	0.753*		
10a	0.484*	0.546*	
16b	0.694*	0.645*	0.695*

*$p < .01$.

As shown in Figure 3b, the mean correlation coefficient is 0.64 and the mean inter-series correlations (Rbar) among the cores range from 0.6 to 0.77, which is higher than the ring width correlations (0.37) in our study site. The expressed population signal (EPS) ranges from 0.86 to 0.93 (Figure 3b), based on a 50-year window between 1804 and 1999. As these EPS values are >0.85, we conclude that our tree ring δ^{18}O chronology based on four trees accurately represent the mean variance of the population and thus yield a relatively noise-free signal (Wigley *et al.*, 1984). A recent study in northern Thailand demonstrated that age-related effects on tree ring δ^{18}O are negligible for *P. merkusii* (Xu *et al.*, 2015); consequently, we do not consider age effects in the present study.

To give the same weight to each core, the four δ^{18}O time series were individually normalized based on the common period 1847–1997, and four series were averaged to produce the final δ^{18}O chronology (UP δ^{18}O chronology) for the entire period (Figure 3c). The first-order autocorrelation of the UP δ^{18}O chronology is 0.16. The UP δ^{18}O chronology from *P. merkusii* trees is positively correlated with the MHS δ^{18}O chronology obtained from *P. merkusii* in northwest Thailand (MHS site in Figure 1; Xu *et al.*, 2015) ($r = 0.61$, $p < .01$, $n = 172$).

3.2 | Climatic implications of tree ring δ^{18}O and precipitation reconstruction

Figure 4 depicts correlations between the UP δ^{18}O chronology and regional climatic parameters. For the period 1955–1999, the UP δ^{18}O chronology shows negative correlations with local precipitation during the months of April, May, July, September, and October, with a rainy season correlation coefficient of −0.37. UP δ^{18}O chronology is negatively correlated with May–October precipitation from CRU ($r = -0.71$, $n = 99$, $p < .001$) in central Thailand between 1901 and 1999 (Figure 4b). Similarly, UP δ^{18}O chronology has negative correlations with May–October precipitation from GPCC (data not shown). On local and regional scales, the UP δ^{18}O chronology shows no significant correlation with temperature. Spatial correlations between the UP δ^{18}O chronology and May–October precipitation (Figure 5) show that the tree ring δ^{18}O reflects rainy season precipitation in central Thailand. In addition, 31-year running correlation analysis is utilized to evaluate the temporal correlation during the period of 1901–1999 between tree ring δ^{18}O and

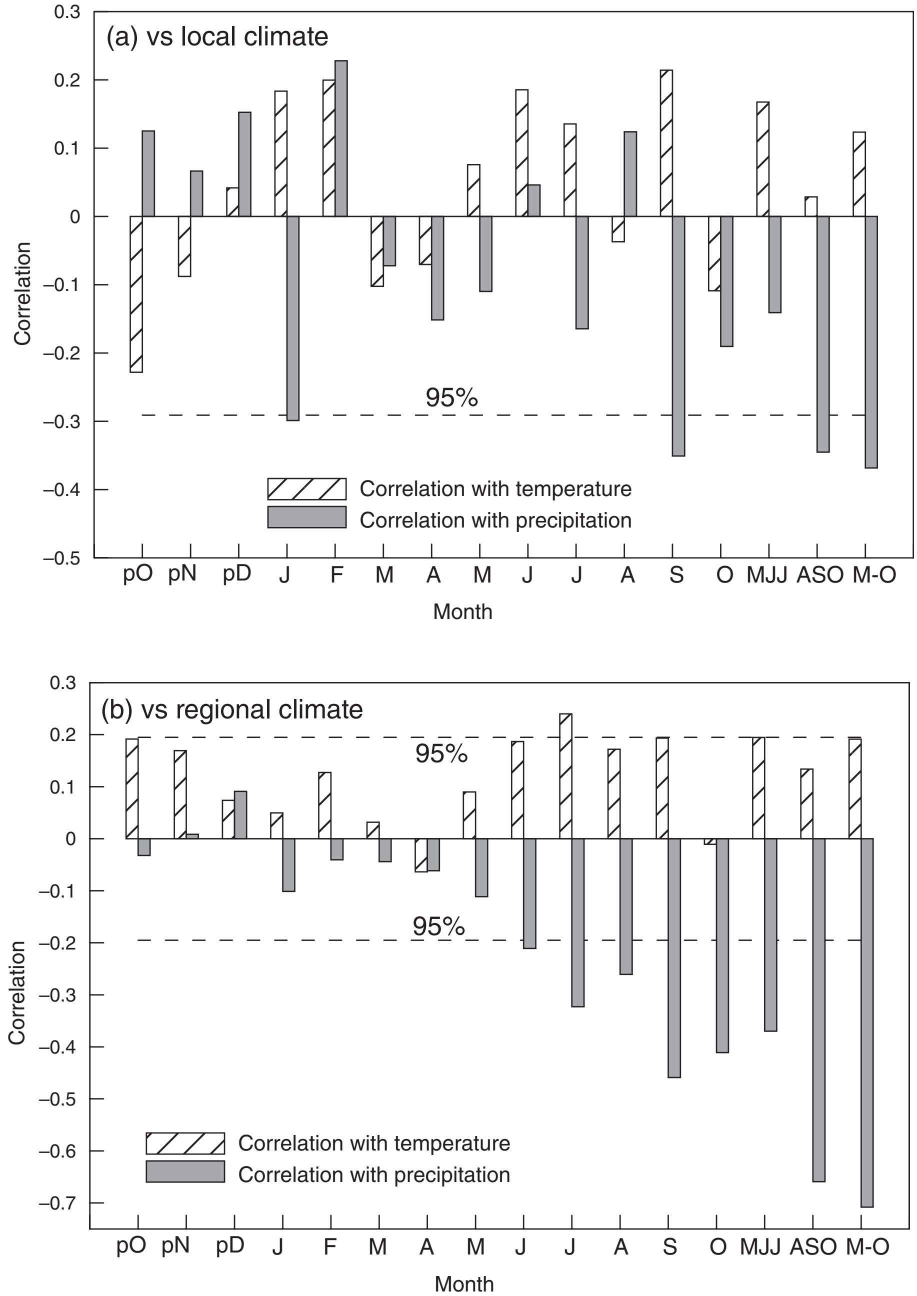

FIGURE 4 Correlations between the tree ring $\delta^{18}O$ chronology and (a) observed temperature/precipitation data from the Tak Meteorological Station for 1955–1999, and (b) the CRU TS4 data set from central Thailand for 1901–1999

regional precipitation (Figure S1, Supporting Information). The stable correlations between them indicate tree ring $\delta^{18}O$ is a promising proxy for precipitation reconstruction (Figure S1). Besides, this relationship has been reported elsewhere in monsoonal Asia, such as northern Laos (Xu *et al*., 2013a), northern Thailand (Zhu *et al*., 2012; Xu *et al*., 2015), northern Vietnam (Sano *et al*., 2012), southeast and southwest China (Grießinger *et al*., 2011; Xu *et al*., 2013b; 2016; 2017), Bhutan (Sano *et al*., 2013), and northwest India (Sano *et al*., 2017).

In addition to the statistical relationship between tree ring $\delta^{18}O$ and precipitation, there are links between them based on precipitation and tree ring $\delta^{18}O$ fractionation theory (Araguas-Araguas *et al*., 1998; Roden *et al*., 2000). Tree ring cellulose $\delta^{18}O$ is controlled by $\delta^{18}O$ of rainfall and relative humidity, both of which are related to monsoon season precipitation in Asia monsoonal area. The negative relationship between rainfall and precipitation $\delta^{18}O$, known as the "amount effect," has been documented throughout Southeast Asia (Araguas-Araguas *et al*., 1998) and is particularly apparent in Bangkok during the rainy season (Ichiyanagi and Yamanaka, 2005; He *et al*., 2006). In the present study area, for example, tree ring $\delta^{18}O$ for the period 1970–1999 varied in step with the $\delta^{18}O$ of May–October precipitation in Bangkok (Figure 6). Specifically, higher rainfall amounts lead to a depletion of $\delta^{18}O$ in precipitation,

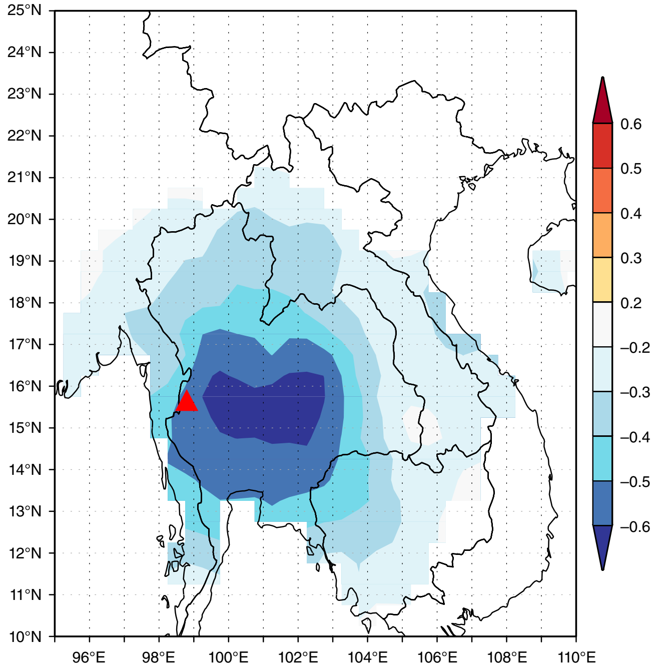

FIGURE 5 Spatial correlations between $\delta^{18}O$ and May–October precipitation, obtained from the CRU TS4 data set for the period 1901–1999 [Colour figure can be viewed at wileyonlinelibrary.com]

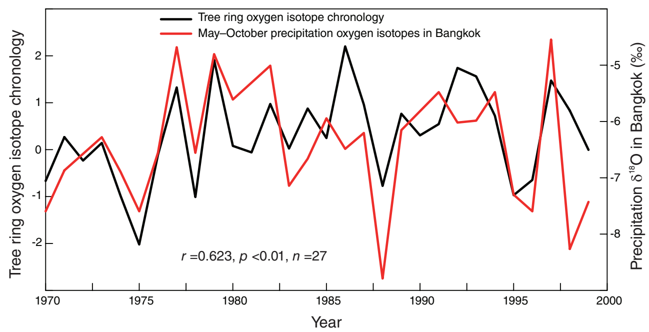

FIGURE 6 Time series of tree ring $\delta^{18}O$ chronology and May–October precipitation $\delta^{18}O$ in Bangkok for the period 1970–1999 [Colour figure can be viewed at wileyonlinelibrary.com]

and this signal is incorporated into tree ring $\delta^{18}O$ during cellulose synthesis (Roden *et al.*, 2000; Vuille *et al.*, 2003). Furthermore, the rainout processes over neighbouring regions that directly influence the $\delta^{18}O$ of rainfall in our study area also serve to enhance the relationship between local precipitation $\delta^{18}O$ and that of adjacent areas (Kurita *et al.*, 2009). More intense or prolonged rainfall in surrounding or upstream areas can also result in a depletion of local precipitation $\delta^{18}O$, thereby lowering tree ring $\delta^{18}O$. Rainy season precipitation in monsoonal Asia generally exhibits a strong relationship with relative humidity, which is a further controlling factor for tree ring $\delta^{18}O$. Specifically, elevated relative humidity associated with higher rainfall leads to the relative depletion of leaf water $\delta^{18}O$, soil water $\delta^{18}O$, and therefore tree ring $\delta^{18}O$ by dampening both evapotranspiration from trees and evaporation from the soil.

May–October is the growing season for pine in Thailand (Pumijumnong and Wanyaphet, 2006), and tree ring $\delta^{18}O$ exhibits highest correlations with May–October precipitation in central Thailand (Figure 5b). May–October precipitation is selected as the target for reconstruction. Based on the linear relationship between tree ring oxygen isotopes and regional May–October precipitation, transfer function that relates tree ring $\delta^{18}O$ (the predictors) to regional May–October precipitation (the predictand) is developed:

$$\mathrm{Pre} = -98.97^{*}\mathrm{O} + 1083.01 \left(R^2 = 0.501,\ n = 99,\ p < .001\right),$$

where Pre represents regional May–October precipitation and O is the normalized tree ring $\delta^{18}O$ chronology. The linear regression model explains 50.1% of the actual variance in May–October precipitation. We used the split calibration–verification test to assess the validity of the reconstructed mode (Table 2). For both sub-periods, r and R^2 are significant ($p < .01$), and RE and CE are positive, suggesting the model is valid.

Using the regression model, we reconstructed annual rainy season precipitation for the period 1804–1999 (Figure 7). Overall, our reconstruction aligns well with observed precipitation data (Figure 7a). For instance, our data suggest that rainy season precipitation in central Thailand declined after 1950 but increased again after 1980, a pattern that is similar to trends in the observed data set (Singhrattna *et al.*, 2005). In addition, our May–October precipitation reconstruction shows significant correlation ($r = 0.384$) with regional June–August PDSI by Cook *et al.* (2010) during the common period of 1804–1999. The mean value and standard deviation (σ) of the reconstructed series are 1084.44 and 80.34 mm, respectively. We defined extremely wet (dry) years as those with precipitation greater (less) than the mean + σ (mean − σ). According to these criteria, we identified 33 extremely wet years and the same number of dry years in the 196-year series. The reconstructed series were further smoothed using a 21-year moving window to highlight the fluctuations at decadal timescales. Wet periods, during which precipitation exceeded the mean, occurred in 1809–1821, 1876–1882, 1897–1908, and 1944–1975. Dry periods occurred in 1825–1850, 1913–1925, and 1979–1997.

TABLE 2 Calibration and verification statistics for the common period of 1901–1999

Calibration period	*r*	R^2	Verification period	RE	CE
Full period (1901–1999)	−0.708	0.501			
Early half (1901–1950)	−0.649	0.421	Late half (1981–2011)	0.554	0.421
Late half (1951–1999)	−0.769	0.592	Early half (1951–1980)	0.410	0.383

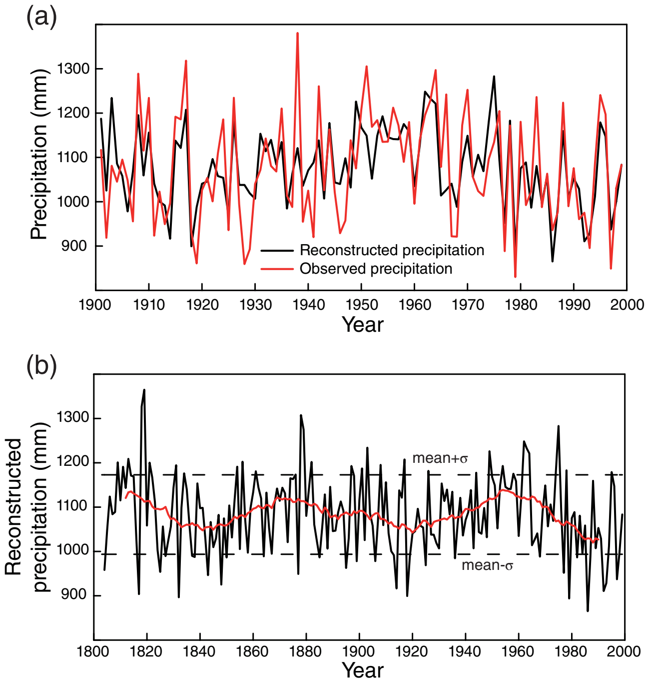

FIGURE 7 (a) Reconstructed (black) and actual (red) precipitation from 1901 to 1999; and (b) reconstructed precipitation during the period 1804–1999 [Colour figure can be viewed at wileyonlinelibrary.com]

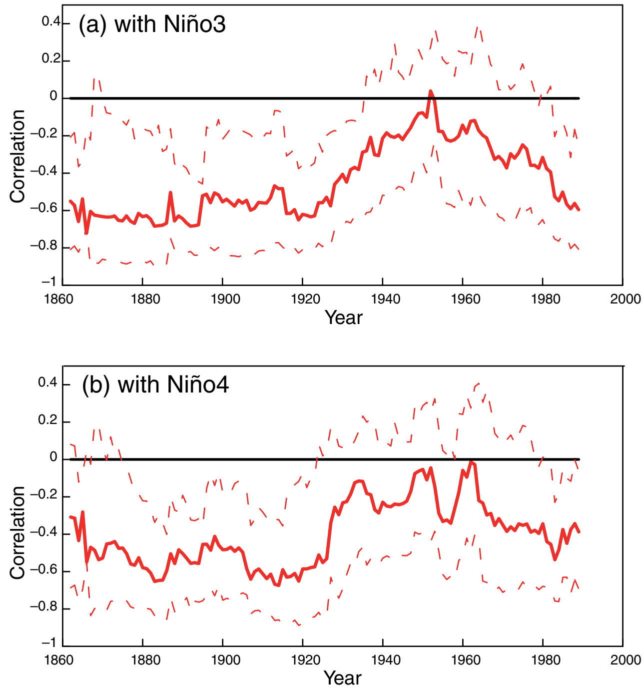

FIGURE 9 Twenty-one-year running correlations between reconstructed precipitation and the EP and CP ENSO indices [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Inter-annual variations in monsoon season rainfall in central Thailand

Wavelet analysis indicates that reconstructed rainy season rainfall in central Thailand exhibits high-frequency quasi-periodicities (2–7 years) at >90% confidence during the period of 1804–1999 except for 1920–1960 (Figure 8). The inter-annual variability in rainfall is similar to that during ENSO events (2–7 years), suggesting a possible relationship between them (Torrence and Webster, 1999). The canonical ENSO (EP El Niño), which is characterized by unusually warm SSTs in the eastern equatorial Pacific, has a pronounced impact on regional summer precipitation over central Thailand (Singhrattna *et al*., 2005). Similarly, recent intensification of the central Pacific El Niño (CP El Niño), or El Niño Modoki (Ashok *et al*., 2007; Kao and Yu, 2009), during which warm SST anomalies dominate the central Pacific and cold SST anomalies occur to the west and east of the warm anomalies, influences climate in Thailand (Feng *et al*., 2010; Xu *et al*., 2015).

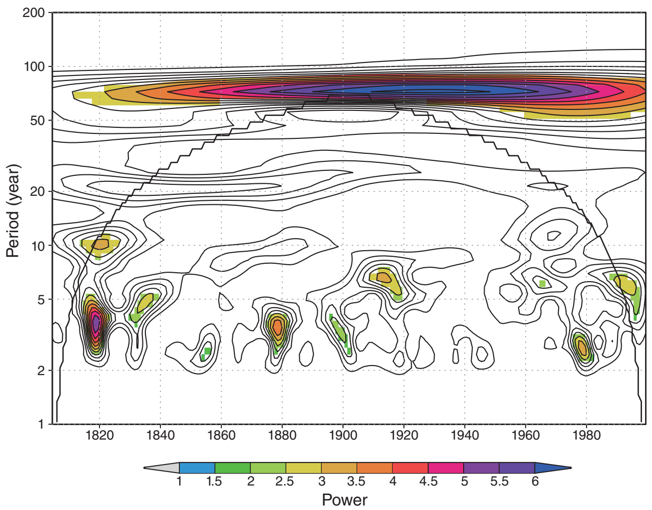

FIGURE 8 Wavelet analysis for the reconstructed precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

For both the South Asian and East Asian summer monsoons, the ENSO–monsoon relationship is non-stationary (Kumar *et al*., 1999; Ding and Chan, 2005). To investigate the relationship between monsoonal precipitation in central Thailand and the two ENSO types, we employed the Niño3 and Niño4 indices as proxies for EP ENSO and CP ENSO (after Yeh *et al*., 2009), respectively, and extracted the high-frequency (<8 years) precipitation signal. Figure 9 shows the 21-year running correlations between precipitation and ENSO in the study area. Monsoonal rainfall exhibits significant correlations with the Niño3 and Niño4 indices for the periods 1860–1930 and 1970–1999, but not between 1930 and 1970. Moreover, we note that the response of monsoon precipitation to the two different ENSO types is similar during the common period. Figure 10 also depicts spatial correlations between precipitation and SST during the different periods. For instance, between 1854 and 1930, rainfall exhibits a significant negative correlation with central and eastern Pacific SST, and positive correlations with western Pacific SST (Figure 10a), forming the familiar ENSO

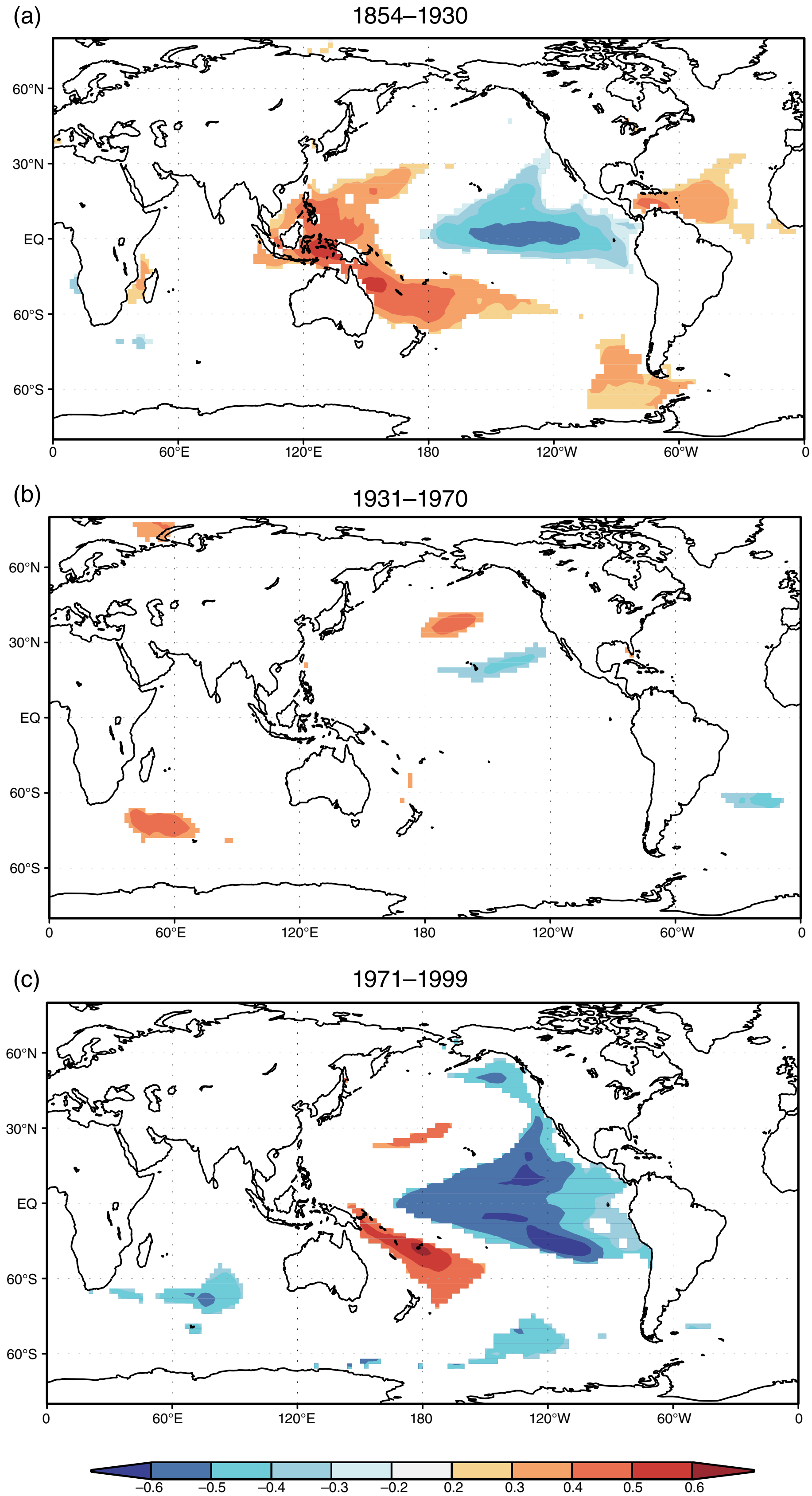

FIGURE 10 Spatial correlations between reconstructed precipitation and SSTs during the periods (a) 1854–1930, (b) 1931–1970, and (c) 1971–1999. Correlations that are not significant at the 95% level have been masked out [Colour figure can be viewed at wileyonlinelibrary.com]

horseshoe configuration. This relationship breaks down during the period 1931–1970 (Figure 10b), but resumes again after 1970 (Figure 10c).

According to both our reconstruction and observational record (Singhrattna *et al.*, 2005), the correlation between summer rainfall in central Thailand and the ENSO index strengthens in 1965, while the ENSO–monsoonal rainfall teleconnection becomes significant after 1980 (Figure 9). Singhrattna *et al*. (2005) reported that the increased ENSO signal in regional rainfall can be attributed to ENSO events in the eastern Pacific, which impact the location of the Walker circulation and therefore rainfall patterns in central Thailand. In contrast, the seven CP ENSO events since 1980 have had a significant negative impact on monsoonal rainfall in the present study area (Xu *et al*., 2015). Specifically, a negative correlation between rainfall and SST occurs between 160°E and 120°W in the central tropical Pacific, while a weak or zero correlation occurs in the eastern and/or western Pacific during the period 1971–1999 (Figure 10c). This configuration of SST–rainfall correlations is similar to that of CP ENSO (Kao and Yu, 2009). Moreover, since CP El Niño events are more effective at focusing drought-producing subsidence over India than are EP El Niño events (Kumar *et al*., 2006), our reconstructed monsoonal precipitation in central Thailand exhibits a close relationship ($r = 0.44$, $p < .001$) with All Indian Rainfall during the period 1871–1999. As the occurrence of CP ENSO events has increased since 1980 (Ashok *et al*., 2007; Kao and Yu, 2009), so has its influence on central Thailand monsoonal precipitation.

The influence of ENSO on monsoonal rainfall in central Thailand is not stable between 1930 and 1970. Previous studies have demonstrated the impact of weakened or absent ENSO variability on hydroclimate in the southern Himalayas between 1950 and 1970 (Sano *et al*., 2013), in southeast China between 1920 and 1960 (Xu *et al*., 2013b), and in southwest China between 1930 and 1980 (Liu *et al*., 2011). The 2–7-year variance of different ENSO index is reduced between 1920 and 1960, but higher during the periods 1875–1920 and 1960–1990 (Torrence and Webster, 1999). For the Indian summer monsoon, a strong relationship between ENSO and precipitation is associated with intervals of high variance, while intervals of low variance produce a weakened relationship (Torrence and Webster, 1999). In our reconstruction of monsoonal precipitation in central Thailand, the 2–7-year variance is relatively low during the periods 1840–1860 and 1930–1965 (data not shown), which coincide with the reduced ENSO variance between 1920 and 1960. A similar pattern is evident in Australian rainfall between 1921 and 1950 (Simmonds and Hope, 1997). Therefore, we suggest that the collapse of the ENSO–monsoon relationship evident in our reconstruction was driven by reduced ENSO variance. Moreover, while previous studies have argued that the ENSO–monsoon relationship is modulated by the Pacific decadal oscillation (PDO) (Sano *et al*., 2013; Sakashita *et al*., 2016) and that a clear relationship exists between equatorial and North Pacific SSTs (Deser and Blackmon, 1995), a causative mechanism linking the PDO and ENSO remains elusive.

Compared with the previous study by Singhrattna *et al*. (2005), our reconstruction shows that the influence of ENSO on monsoonal rainfall in central Thailand is evident not only after 1980 but also before 1930, and suggests this relationship may also have existed in the past. To evaluate the magnitude and spatial impact of ENSO on monsoonal Asia and examine how this relationship varies under different mean climate states, additional long-term, high-resolution precipitation records are required from subtropical and tropical areas.

4 | CONCLUSION

We established a 196-year tree ring cellulose $\delta^{18}O$ chronology for Thailand based on *P. merkusii*. Tree ring cellulose $\delta^{18}O$ showed significant correlations ($r = -0.71$, $p < .001$) with monsoon season regional precipitation during the period 1901–1999. Using regression modelling of tree ring $\delta^{18}O$ and regional rainfall, we produced the first statistical reconstruction of May–October rainfall in central Thailand for the period 1804–1999. Our record shows that extreme wet periods occurred in the periods 1809–1821, 1876–1882, 1897–1908, and 1944–1975, while extreme dry events occurred during 1825–1850, 1913–1925, and 1979–1997.

The monsoon season rainfall exhibits significant inter-annual variability. With the exception of the period 1930–1970, inter-annual changes between 1854 and 1999 are closely related to ENSO. However, this ENSO–rainfall teleconnection weakens during periods of low ENSO variability. The May–October precipitation reconstruction in central Thailand is helpful to understand history and influencing factors of flood/drought events, and such added understanding will be useful for water management practice in future. Continued efforts to develop a tree ring $\delta^{18}O$ network in Southeast Asia, South Asia, and East Asia will be vital to improve our understanding of the history and driving factors of Asian summer monsoon rainfall.

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Conflict of interests

The authors declare no potential conflict of interests.

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