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Decadal scale droughts over northwestern Thailand over the past 448 years: links to the tropical Pacific and Indian Ocean sectors

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Abstract A 448-year teak chronology from northwestern Thailand is used to assess past changes in the strength of the summer monsoon. The chronology is based on 30 living trees that extend from 1604 to 2005, and a 47-stump chronology that spans from 1558 to 1903. We used methods of cross dating and chronology building that address problems specifically found in teak. The result is a robust chronology with strong signal strength back to 1600 AD, and with variability retained at the multi-decadal scale. Variability in annual growth in teak from this area is dependent on rainfall and soil moisture availability at both the beginning and end of the monsoon season as confirmed by comparisons with temperature, rainfall and PDSI data. These correlation analyses confirm that our record is a proxy for summer monsoon strength and/or duration, and highlight the importance of soil moisture availability in the seasons of transition. The chronology reveals two prominent periods of decadal-scale drought in the early and mid 1700s that correspond to persistently warm sea surface temperature anomalies in the tropical Pacific as derived from Galapagos Island coral records. Speleothem data from central India also indicate protracted periods of drought for the 1700s. While these broad-scale eighteenth-century persistent droughts may be related to protracted El Niño-like conditions in the tropical Pacific, regional climate forcing over the Indian Ocean and western Pacific sectors appears to be a strong contributor as well. Spectral analyses reveal power in the ENSO range of variability from 2.2 to 4 years, and at the multi-decadal scale at 48.5 years.

1 Introduction

The role of the tropics in climatic change scenarios is generating much recent interest (e.g., Cane and Evans 2000; Deser et al. 2006; Meehl and Arblaster 2002; Meehl et al. 2006; Seager et al. 2005; Trenberth and Stepaniak 2003). The potential impact of hydrologic change in monsoon Asia is especially significant, since more than half of the world's population depends on monsoon rainfall. Changes that may alter the strength, timing or distribution of the monsoon can result in drought or floods, crop failure and famine, and changes in the hydrologic regimes of several of the most populous regions of Asia. Therefore the ability to accurately predict changes in

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future monsoon variability would have great societal relevance. However, such predictive capability requires a longer and more complete perspective on the range of possibilities occurring naturally in the climate system, and this is most efficiently achieved through a paleoclimate perspective from proxy records like tree-rings, corals, ice cores and speleothems. Conducting paleoclimate research in the terrestrial tropics has historically been fraught with difficulties, particularly with regards to tree rings (e.g., Jacoby 1989; Vetter and Wimmer 1999; Worbes 1995, 2002). In this paper, we present a 448-year tree-ring width record from teak trees from northwestern Thailand (Fig. 1). This is the longest tree-ring chronology yet produced from mainland Southeast Asia and one of the longest and best replicated from the global tropics. The chronology is based on a highly replicated collection of tree core samples from living trees, and cross sections and cores from stumps that remain from past logging.

2 Materials and methods

2.1 Tree-ring data

The Mae Hong Son (MHS) regional teak chronology (Fig. 2a) spans the time period from 1558 to 2005. The chronology is comprised of ring-width measurements from core samples from 30 living trees (21 from managed re-growth "plantations", around 90 years old, and 9 relict living trees that extend back as far as 1604), and cores and sections from 47 stumps of trees logged around the turn of the twentieth century. The mean segment length for our chronology is 160.6 years, a value that sets the ceiling for low-frequency variability retention. The mean series intercorrelation (a measure of the agreement within and between trees) is 0.424, while the mean sensitivity (a measure of the degree of change from 1 year to the next) is 0.271. The best-fit model for autocorrelation is an AR1, and the average mean measurement value for the entire chronology is 1.829 mm.

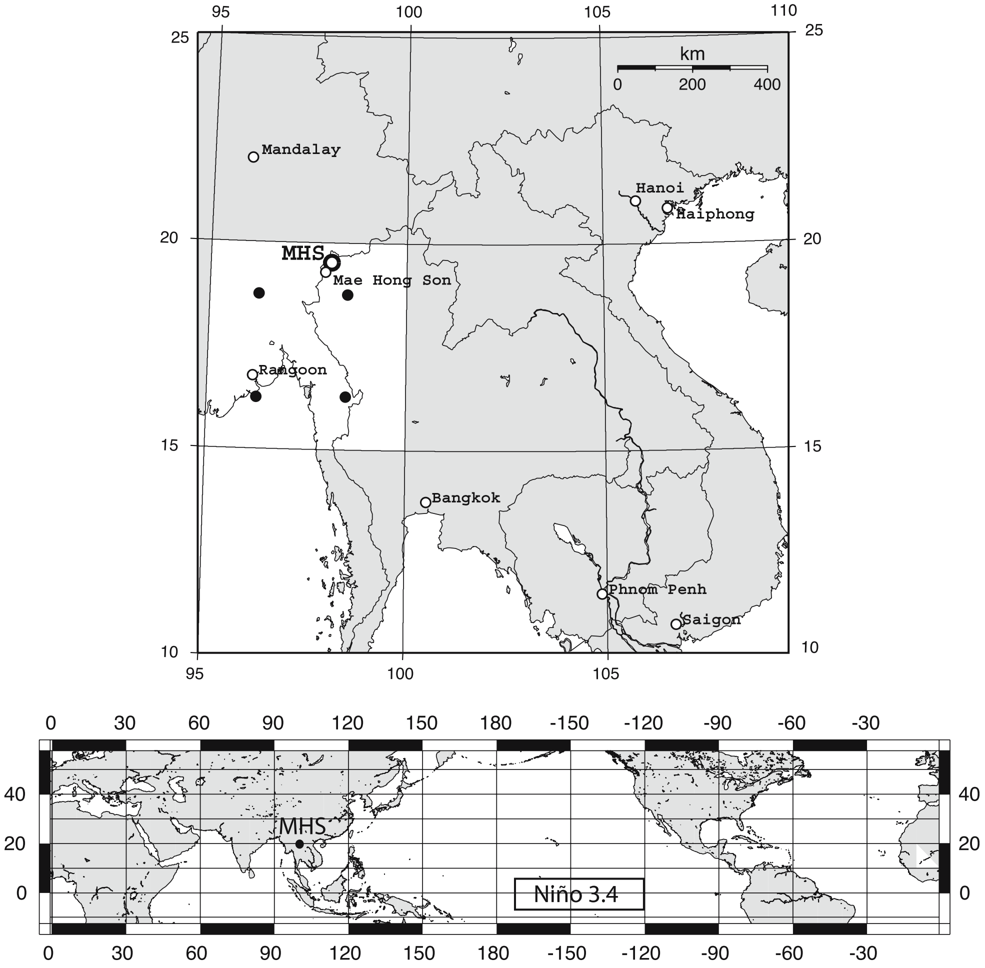


Fig. 1 Map of the study region showing North Thailand and the locations of the MHS teak site and the Mae Hong Son instrumental station. The *white shaded area* delineates the area of the four-gridbox variance-adjusted average of the Dai et al. (2004) PDSI data

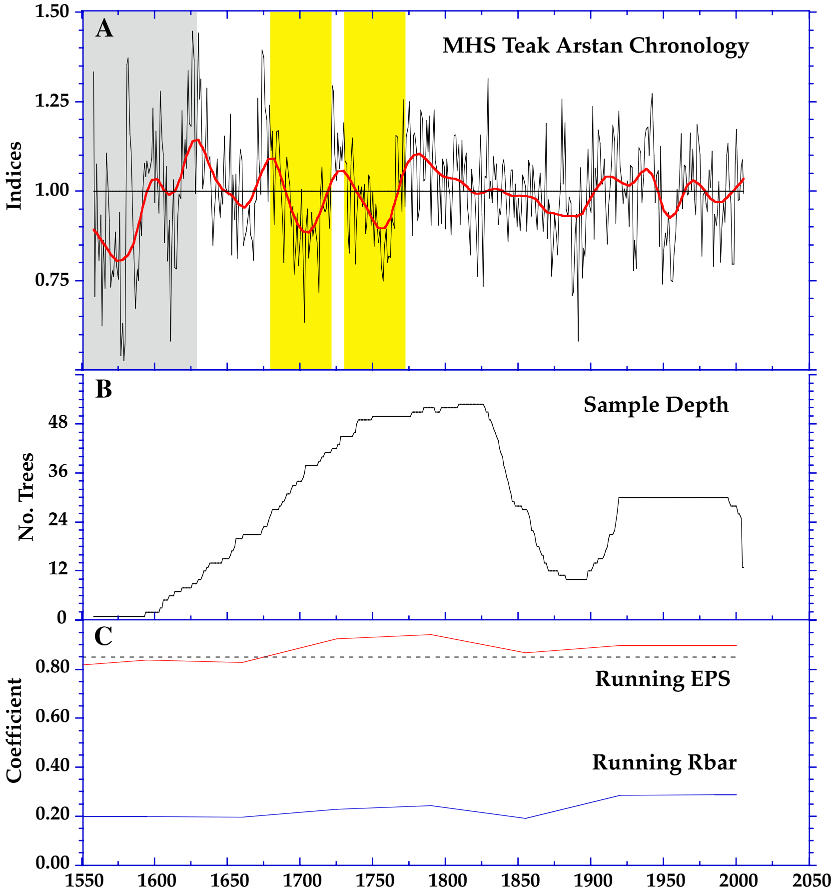


Fig. 2 Plots of (**a**) the MHS composite teak chronology (**b**) sample depth through time, and (**c**) running EPS and Rbar statistics. The *yellow-shaded areas* indicate time periods of sustained below average growth anomalies in the chronology linked to SST anomalies in the tropical Pacific, while the *grey shaded area* denotes the period of low sample depth and less reliability in the estimation of mean annual growth

There are inherent difficulties encountered when cross dating teak, mainly related to within-tree noise generated by poor circuit uniformity. We countered these problems by measuring as many as seven radii per stem, when possible, to build individual-tree chronologies that reduce the effects of within-tree noise and enhance the common signal between trees (Palakit 2004). We standardized the individual-tree chronologies using methods aimed at retaining multi-decadal-to-centennial low-frequency variance potentially due to climate in the final regional teak chronology. First, we employed a two-step procedure described by Cook and Peters (1997) that stabilizes the variance using a power transformation based on the local mean and standard deviation, and reduces potential end-fitting bias by calculating the residuals from the expected growth curve, rather than the ratios. In producing the individual-tree chronologies we retained the variance-stabilized unstandardized raw ring width chronologies and then employed standardization to each tree's time series. Teak, for the most part, do not exhibit negative exponential growth trend when grown in natural stands, exemplified as they are by multiple endogenous disturbance pulses. Therefore, we standardized our series individually, using interactive detrending and alternative methods of standardization including varying stiffness cubic smoothing splines when necessary (Cook and Peters 1981), and the Friedman super smoother (Friedman 1984), a data adaptive smoothing technique designed to retain low-frequency variance. Of the 77 tree time series, we employed the Friedman super smoother (alpha value set to 9) for 53 trees, and varying stiffness smoothing splines on 18 others (150-year stiffness for 8 trees, 200-year for 6 trees, and 300, 100, 50, and 142-year stiffness for 1 tree each). The remaining six trees were standardized with a straight line of horizontal slope. We computed the bi-weight robust mean for calculating the mean value function and then temporally stabilized the variance of the chronologies using techniques outlined in Osborn et al. (1997) to reduce the effects of changing sample size. With regards to the final chronology, the high level of replication (Fig. 2b) coupled with measures of chronology signal strength (Fig. 2c), indicate that the MHS chronology is a robust estimate of yearly growth changes for at least the past 400 years, with variance retained at the multi-decadal scale.

2.2 Climate data

Monthly rainfall and temperature records from northwestern Thailand were obtained from the Thai Meteorological Department in Bangkok, in order to statistically model the climatic signal in the MHS chronology. We used the record from Mae Hong Son that is closest to the area of the study site. The rainfall data span from 1911 to present while temperature dates back only to 1951. The average monthly climate at Mae Hong Son is plotted in Fig. 3, indicating the predominance of monsoon rains from May to September, with the peak of more than 250 mm reached in August. Mean monthly temperatures range from about 22–30°C with maximum temperature reached in April just before the onset of the monsoon. The cool season coincides with the early dry season from November to February, with increasing warmth by March when the monsoon begins to build anew.

We also compared the MHS record with the updated 2.5° × 2.5° gridded global monthly Palmer Drought Severity Index (PDSI) data from Dai et al. (2004). PDSI is a metric of drought that takes into account temperature and precipitation and is considered to be a proxy for soil moisture (Palmer 1965). For this purpose we calculated the mean and variance adjusted average of the four gridpoints surrounding the study site as shown in Fig. 1. We also used various indices related to El Niño (Kaplan et al. 1998) and the southern oscillation index (SOI) (Ropelewski and Jones 1987) to model large-scale forcing effects on the response of the local climate and teak growth. For this purpose, we utilized the KNMI Climate explorer (http://www.knmi.nl/) (van Oldenborgh and Burgers 2005) and we highlight relationships with the NCEP/NCAR Surface Temperature records, temperature at 700 mb height, and latent heat/relative humidity at the 500 mb height.

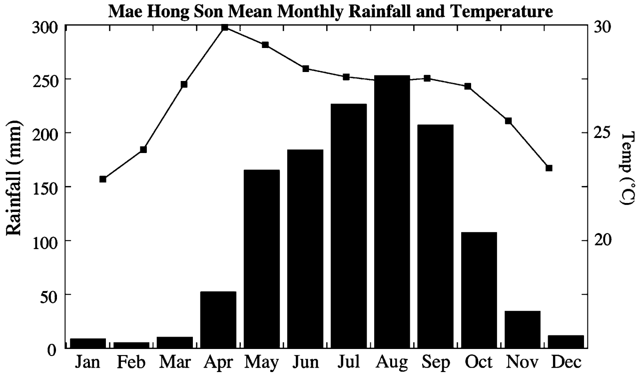


Fig. 3 Mean monthly rainfall from 1911–2003 (*black bars*) and temperature from 1951–2003 (*solid line*) for Mae Hong Son in northwestern Thailand

3 Results and discussion

3.1 A proxy record of monsoon strength

Figure 4 shows the monthly Pearson correlations of our teak record with Mae Hong Son rainfall and temperature, and the mean and variance adjusted average of the four PDSI grid points that surround the study area. For PDSI, our results show significant positive correlation (all levels of significance henceforth as

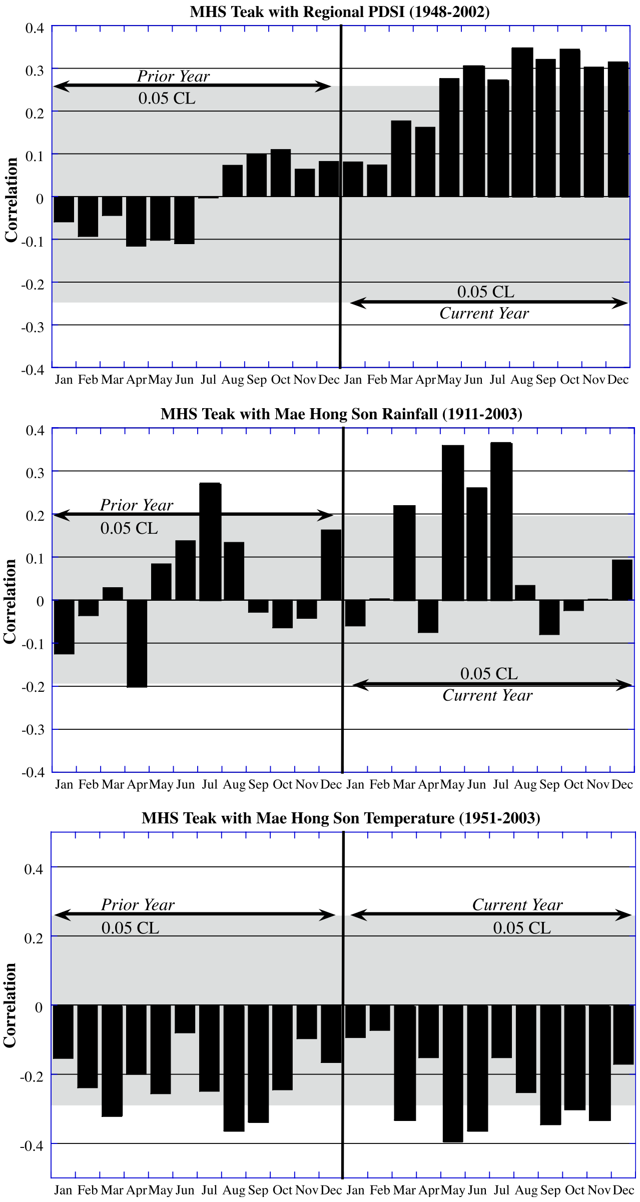


Fig. 4 Response plots for MHS teak chronology with; **a** monthly PDSI; **b** monthly total rainfall; **c** mean monthly temperature. The correlation functions are shown for a 2-year window with months of the prior year to the *left*. All portions that fall outside the *shaded area* are significant at the 95% level of confidence

$P < 0.05$) for all the months of the monsoon, strongest in June, and the early post-monsoon dry season. This is a clear indication of the effects of soil moisture on teak growth, reflecting the adverse effects of dry conditions (i.e., PDSI < -1.0) as the season transitions from the monsoon to the dry season (Fig. 4a). Rainfall from May to July of the current year (Fig. 4b) is also significant indicating the importance of early rain (May) and general wetness through the early part of the monsoon. Current March and prior-year July rainfall also show positive correlations that are significant. For temperature (Fig. 4c) all of the months of the current and prior year are inversely correlated, with significant correlations for March, May–June and September–November of the current year, and March, August and September of the prior year. Since there is a general tendency for maximum temperature to increase as rainfall decreases, due to the radiative heat loading associated with cloud-free conditions, maximum temperature becomes increasingly limiting when the rains cease. For comparison purposes, we plot the twentieth century time series for the teak chronology, rainfall during the monsoon period, rainfall during the transition seasons before and after the monsoon, mean temperature for the pre-monsoon of April and May, and the monsoon season (JJAS), and the four-grid-point averaged PDSI (Fig. 5a–e). It should be noted that while the tree–growth–climate relationships described herein are statistically significant and credible, none proved sufficiently robust to pass the stringent calibration–verification tests to enable the development of statistical reconstruction.

Overall, our results are consistent with the findings of Yoshifuji et al. (2006), who demonstrated that annual variations in teak growth in central north Thailand are most strongly influenced by soil moisture deficit at the beginning and end of the wet season, with the greatest variability resulting from changes at the end of the season. In 3 years of monitoring (2001–2004), Yoshifuji et al. (2006) found that the canopy duration and transpiration period varied from 40 to 60 days, much larger than expected, with most of that variability coming at the end of the monsoon. Buckley et al. (2001) used dendrometer bands to monitor teak growth in northern Thailand and noted the importance of transitional season rainfall for growth. Pumijumnong et al. (1995) likewise noted that rainfall at the beginning of the monsoon was the most significant climate factor for teak growth across several sites in Thailand, and D'Arrigo et al. (2006) successfully used teak to reconstruct drought in Java, Indonesia over the past two centuries. We therefore interpret our long teak record as a proxy of soil moisture availability related to the strength, timing and/or duration of the annual monsoon, and negative growth departures are considered to be indications of drought.

The MHS record shows marked decadal variability over the past 400 years, with the most notable negative departures occurring in the early and mid eighteenth century (Fig. 2a). Other significant periods of reduced growth are indicated for the 1890s and the 1950s, however, both come during periods of potentially increased disturbance factors related to local land use (e.g., logging between the 1890s and 1903) and a time of overlap between senescent stump wood and regrowth trees. Positive growth is most notable in the 1630s to 1650s, and again in the late 1700s. We interpret these negative (positive) departures as periods of decreased (increased) soil moisture availability during the monsoon and the seasons of transition before and after.

3.2 A mechanism for drought in northwest Thailand

Rainfall in Thailand has been shown to have links to various manifestations of the ENSO phenomenon. For example Kripalani et al. (1995) and Kripalani and Kulkarni (1998) found that rainfall across north Thailand was correlated with Indian monsoon summer rainfall (IMSR), the Darwin pressure tendency (DPT) and the mean location of the sub tropical ridge (STR). Singhrattna et al. (2005) identified significant negative correlation for central Thailand rainfall with ENSO, but the relationship only becomes significant after about 1980 with little correlation before that time. This time dependence is the result of a shift in the location of one end of the Walker circulation to an area farther to the southeast over Southeast Asia and away from India. The authors hypothesized that the ENSO teleconnection in Thailand is dependent on the SST configuration in the tropical Pacific, with an eastern Pacific based El Niño pattern, as is the post-1980s situation, resulting in reduced rainfall over Thailand. For the instrumental period prior to the 1980s this influence was felt over India when the descending arm of the Walker circulation was farther to the west as identified by Krishna Kumar et al. (1999). These authors note that the effects of El Niño on monsoon rain in India has declined since the 1980s after a century of strong coincidence, the exact opposite of the trend for central Thailand and confirming the shift in the Walker circulation noted above.

Coral records from the Galapagos Islands (Dunbar et al. 1994) indicate very warm SST anomalies during the 1700s that are consistent with protracted El Niño-

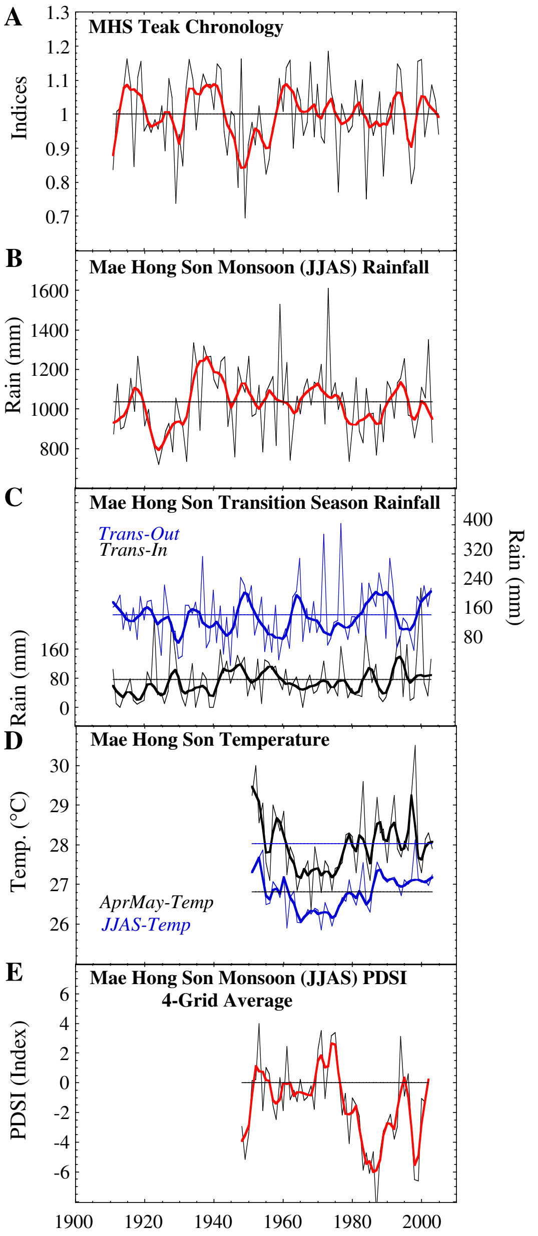


Fig. 5 Common period time series comparison for **a** MHS teak chronology, **b** Mae Hong Son monsoon season rainfall, **c** transition season rainfall, pre and post monsoon, **d** pre-monsoon (April–May) and monsoon (JJAS) mean temperature, and **e** PDSI for the four-grid average

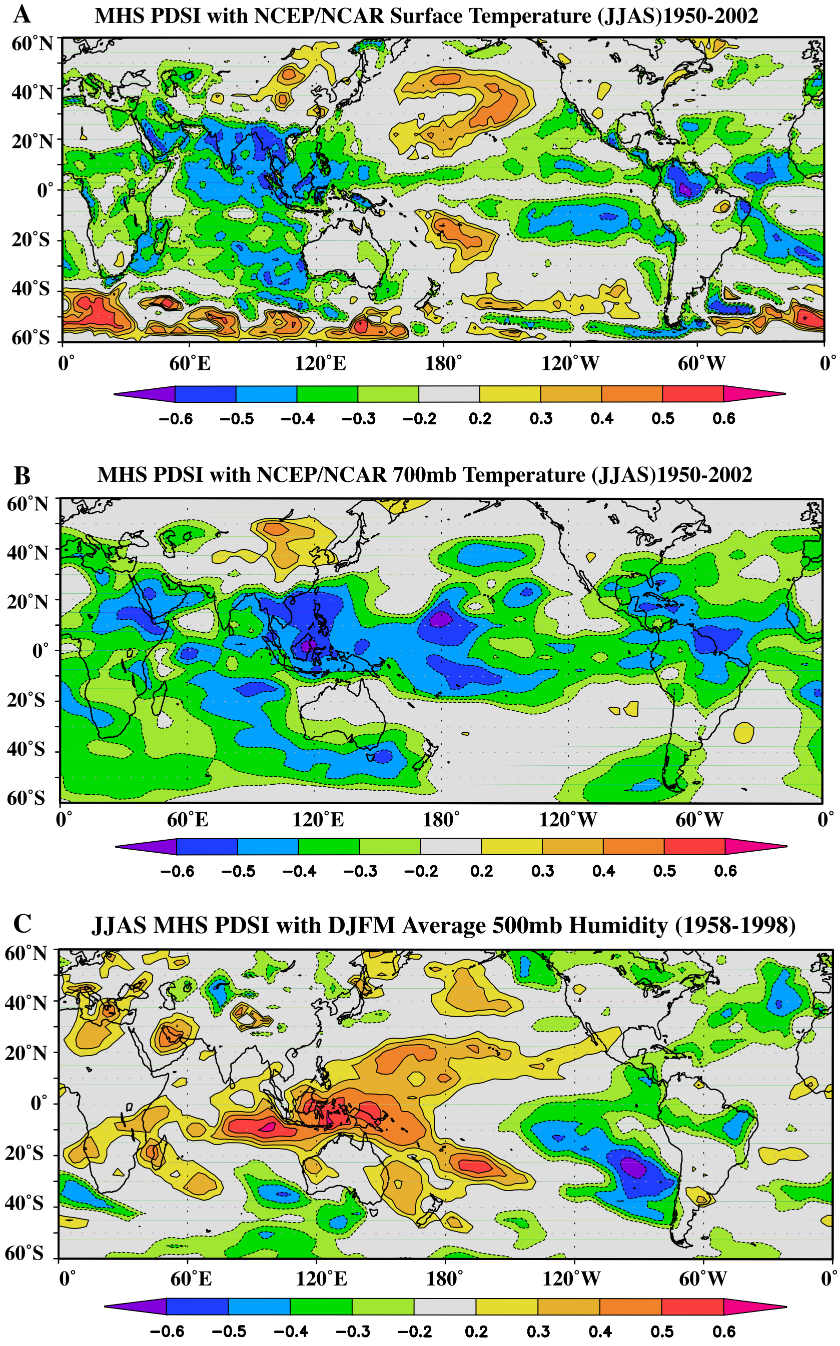
like warm conditions that would be expected to have downstream influences on climate. Their record, however, does not correspond exactly to the timing of the two distinct drought periods we see in the MHS teak record, but shows continuously warm conditions throughout the century. The authors note that warm excursions in the tropical Pacific do not always correspond to ENSO events, pointing out that the southern oscillation, El Niño and eastern Pacific warm events are not always in exact correspondence. As noted earlier, the effects of El Niño on rainfall in the region exhibits time dependence and it is likely that other factors contribute to the decadal droughts we see in northwest Thailand.

The 1700s droughts in northwestern Thailand are in basic agreement with speleothem records from Sinha et al. (2006) from Dandak cave in central India that indicate very similar decades-long periods of reconstructed drought in the 1700s, that are intriguingly close to what we see in the MHS record. In fact, their record indicates that persistent droughts throughout the Little Ice Age (LIA) period were the most severe for the past 1,500 years, with the worst droughts indicated for the 1500s. Our record shows growth reduction in the late 1500s, but the sample depth is currently insufficient to use this portion of the record with confidence. An increasing body of work, as noted by Cobb et al. (2003) and others defines the LIA period as being one of persistent El Niño like conditions in the tropical Pacific. The implication from our research is that the effects of El Niño-like warm SST anomalies can exert influence that extends across Southeast and South Asia simultaneously.

Seager et al. (2005) and Herweijer and Seager (2006) suggest that warm (cold) temperature anomalies in the tropical Pacific alone can be used to derive models to produce rainfall anomalies of wetness (drought) in the western Americas while simultaneously producing drought (wetness) in many parts of the tropics. When lasting for decades and longer, these departures may mark periods of persistent El Niño or La Niña states, respectively, in the tropical Pacific. This prospect becomes more intriguing as we generate more proxy data from these regions. While clearly ENSO is not the only factor contributing to the growth anomalies we see, an expanded network of chronologies combined with other proxy records, will likely increase the fidelity of this model.

We further tested the relationship between northwest Thailand climate and the tropical Pacific by comparing the PDSI average with global surface temperature fields, 700 mb temperature, and humidity at the 500 mb height (Fig. 6). The relationship with the tropical Pacific is clear, with cooler surface conditions in the eastern tropical Pacific correlating to positive values of PDSI (Fig. 6a). However, surface temperature in the Indian Ocean and over much of Indonesia is also strongly negatively correlated. Perhaps more telling is the relationship with temperature at the 700 mb height (Fig. 6b) that shows very strong negative correlation for the central Pacific and for the Warm Pool region over the Philippines, the South China Sea, Indonesia and Borneo. Comparison with humidity at the 500 mb height, reflective of latent heat flux, shows very strong positive correlation over the western Warm Pool region over the Indonesian archipelago and into the central Indian Ocean (Fig. 6c). These results all point to effects on climate and teak growth that involve more than just ENSO.

The cause of these decadal scale droughts over north Thailand is currently uncertain. A look at the spectral power of our MHS record (Fig. 7), derived from the Multi-Taper method, shows significant ($P < 0.001$) power in the range of ENSO variability spanning 2.2–4 years. There is also a strong peak around 48.5 years that reflects the decadal scale variance retained in this long record. Whether or not this is a direct reflection of low-frequency ENSO variance is unclear at this time. The previously noted issues of stationarity in the relationship between ENSO and rainfall in this region still need to be fully analyzed. It is quite clear, however, based on the analyses presented in this paper, that ENSO is not the only factor that influences climate in the study region, and further analyses are needed.

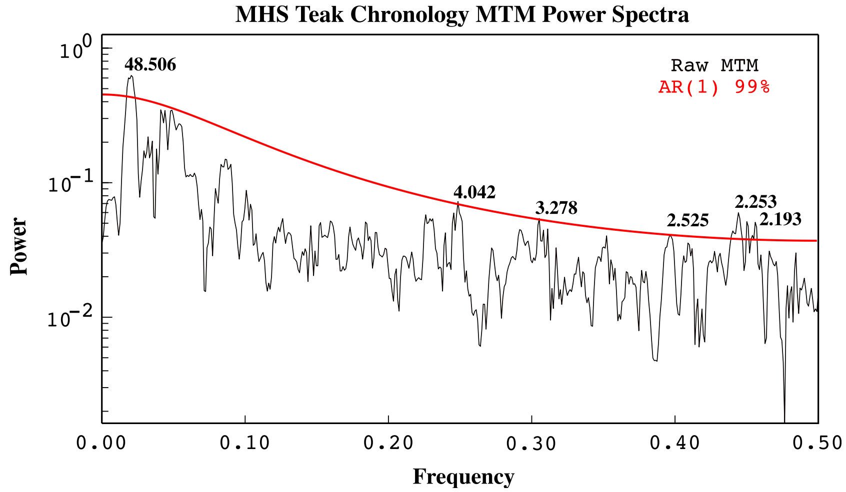

A MHS PDSI with NCEP/NCAR Surface Temperature (JJAS)1950-2002

B MHS PDSI with NCEP/NCAR 700mb Temperature (JJAS)1950-2002

C JJAS MHS PDSI with DJFM Average 500mb Humidity (1958-1998)

Fig. 6 Spatial Pearson correlation plots for regional PDSI with; **a** global surface temperature; **b** temperature at the 700 mb height; **c** humidity at the 500 mb height

Fig. 7 Multi-Taper method power spectra for the MHS teak chronology. Peaks above the *solid line* indicate significance at the 99% level of confidence



4 Summary

We have developed a 448-year proxy record of monsoon variability and strength over northwestern Thailand from a robustly estimated teak tree-ring chronology based on multiple tree samples from the region. It indicates the occurrence of two periods of greatly diminished rainfall in the 1700s. These decadal-scale droughts correspond to periods of anomalously warm SST in the central and eastern tropical Pacific, and to drought in central India as derived from speleothem records. We interpret these findings as further evidence, at least in part, for the long-term influence of ENSO on Asian monsoon variability, and suggest El Niño conditions as an important contributor to drought in this region. However, the possibility of changes in this relationship over time must be kept in mind, and correlations with the Warm Pool region and the Indian Ocean sector suggest there is more to this story than just ENSO. It is clear that other factors are influencing growth, and more study into the physiological response to climate for teak is needed. Further research using an expanded multi-species tree-ring network, combined with other proxy records, will shed more light on the variability of climate in Southeast Asia, and how it relates to the dynamics of monsoon variability on decades to longer timescales.

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