Effects of Climate Variability on the Annual and Intra-annual Ring Formation of *Pinus merkusii* Growing in Central Thailand

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ARTICLE INFO	ABSTRACT

ABSTRACT

The research clarifies which climatic factors induce annual and intra-annual ring formation in merkus pine (*Pinus merkusii*) growing in the low lying plains of central Thailand and reconstructs the past climate by using climate modelling derived from climate-growth response. Not only are climate variations longer than a century in central Thailand explained, but the study also explores for the first time the variability in climate using the formation of intra-annual rings in Thai merkus pines. The tree-ring analysis of wood core samples indicated that the pine stand was more than 150 years old with the oldest tree being 191 years old. The annual variation in tree growth significantly correlated with local climate variables, the number of rainy days in each year ($r=0.520$, $p<0.01$) and the extreme maximum temperature in April ($r=-0.377$, $p<0.01$). The regional climate of the Equatorial Southern Oscillation in March (EQ_SOI_{March}) also highly correlated with the pine growth ($r=0.360$, $p<0.01$). The climate reconstruction indicated a declining trend in the number of rainy days during the 20th century and a decline in the number of rainy days was observed during the first and second decades of the 21st century, respectively, while the past climate reconstruction of maximum temperature in April and EQ SOI_{March} indicated a decline during the previous century and an increase in this century. A multiple regression analysis indicated that the extreme maximum temperature, which declined at the beginning of the wet season and increased around the transitional period of the late rainy and the cold seasons, influenced the formation of intra-annual rings ($r^2=40.5\%$, $p<0.05$). It can be summarized that the number of rainy days increasing in each year associated with the declining temperature at the beginning of the wet season indicated a rapid growth in *P. merkusii*, while the anomalous temperature declining at the beginning and increasing at the end of the wet season was the main factor inducing the intra-annual ring formation. Therefore the activity of forest and planation management, especially in the watering at the beginning of the wet season when anomalous increased temperature occurred, shall be specified in the forest management plan in order to increase annual pine growth and wood formation.

1. INTRODUCTION

Climate change has recently impacted human life and natural systems worldwide. Natural disasters related to climate systems have continuously increased since 1950 with a trend of warmer temperatures. IPCC (2014) suggested that during the period from 1880 to 2012, the global temperature rose by 0.85 °C (0.65 to 1.06 °C) and the sea level since the mid-19th century rose by 0.19 m (0.17 to 0.21 m.) and has been higher than the mean rate during the previous two millennia. In general, climate trends based on short records do not reflect precise long-term fluctuations (IPCC, 2014). As an example, consider the warmer period of 1998-2012, during which the rise in temperature was 0.05 °C (-0.05 to 0.15 °C per decade), which is smaller than the rise of 0.12 °C (0.08 to 0.14 °C per decade) calculated since

1951. It could be assumed that the recorded meteorological data is not enough to accurately predict the climatic trend in the future. Therefore, the understanding of the past climate system is necessitated and can be combined with the recorded meteorological data to construct a climate model in order to forecast the precise climate trend in the future.

Several climate proxies such as ice cores, sub-fossil pollen, boreholes, corals, sediments, and carbonate speleothems are used to reconstruct the past climate conditions. Tree-rings are another climate proxy generally used to reconstruct climatic patterns in many regions of temperate and tropical zones. In Southeast Asia, teak (*Tectona grandis* L.f.) in Java was first used for tree-ring analysis to investigate the climate related growth by Berlage (1931) and other dendrochronologists (e.g., DeBoer, 1951; Jacoby and D'Arrigo, 1990; D'Arrigo et al., 1994; D'Arrigo et al., 2006; Bijaksana et al., 2007). Apart from the initial studies in Indonesia, other countries in this region such as Myanmar, Laos PDR and Thailand also undertook teak ring analysis to investigate climate-growth response and past climate reconstruction (Pumijumnong et al., 1995a; Pumijumnong et al., 1995b; Pumijumnong and Park, 1999; Pumijumnong and Park, 2001; Buckley et al., 2007b; D'Arrigo et al., 2011; Lumyai et al., 2017).

The possibility of tropical tree-ring analysis in this region is not only limited to teak trees. Studies in Laos PDR and Thailand found the feasibility of using *Pinus kesiya* and *P. merkusii*, especially growing in the highlands and on the slopes in the north and northeastern regions, for investigating the climate-growth response and the past climate reconstruction (Pumijumnong and Eckstein, 2011; Pumijumnong and Wanyaphet, 2006; Buckley et al., 1995; Buckley et al., 2007a; Duangsathaporn and Palakit, 2013). Once the relationships between climate and tree-ring formation were understood, the past climate was also reconstructed. Climate not only induces annual ring width variations, but it also induces the formation of intra-annual rings in several tree species in both tropical and temperate zones (Palakit et al., 2012; Vieira et al., 2010; De Luis et al., 2011; Olivar et al., 2012). Although it is clear that the formation of intra-annual rings can be directly induced by climate factors, especially precipitation and temperature (De Micco et al., 2016), the patterns or periods of climate response varies for each tree species. Therefore, in this study, the climate inducing annual and intra-annual ring occurrences in Thai mountain pine was studied in order to understand the climate-growth relationship and its adaptation to the changing climate.

This research (i) identifies the relationship between climate and annual ring widths of *P. merkusii* located in the Suphan Buri province, central Thailand; (ii) reconstructs the past climate by using climate modelling derived from climate-growth response; and (iii) clarifies which factors induce the formation of intra-annual rings. A pine stand, near the margin of the natural range, was selected following the principle of the ecological amplitude for dendrochronology which states that the growth of marginal trees is highly limited by climate and reflects the climate-growth responses greater than trees growing near the center of its geographical distribution (Fritts, 1976).

2. METHODOLOGY

2.1 Study area and climate data

The study area is a natural pine (*Pinus merkusii*) stand located at the Phu Toei National Park in Suphan Buri province, central Thailand (Figure 1). *P. merkusii* can be found alongside other dry dipterocarp trees such as *Dipterocarpus obtusifolius*, *Shorea obtuse* and *S. siamensis*, at an elevation of 500-800 m above mean sea level. These dipterocarp trees and *P. merkusii* are the dominant species accounting for 41.92% and 31.68% of crown cover, respectively. The climate data in A.D. 1953-2016, measured by the Suphan Buri Meteorological Station included temperature, rainfall, and relative humidity and was divided into 2 seasons as dry (Nov-Apr) and wet (May-Oct). The dry season, when the mean monthly temperature and rainfall were 27.68 ºC and 29.13 mm, respectively, could be further divided into cold (Nov-Feb: The mean temperature was 26.36 ºC) and hot (Mar-Apr: The mean temperature was 30.33 ºC) periods. The wet season, when the mean monthly temperature and rainfall were 25.50 ºC and 156.31 mm, respectively, could be further divided into 3 periods of early (May-Jun), mid (July-Aug), and late (Sep-Oct) rainy seasons with the mean monthly rainfall for 119, 120 and 230 mm, respectively. The amount of rainfall decreased during the mid-rainy season and rapidly increased during the late rainy season (Figure 1).
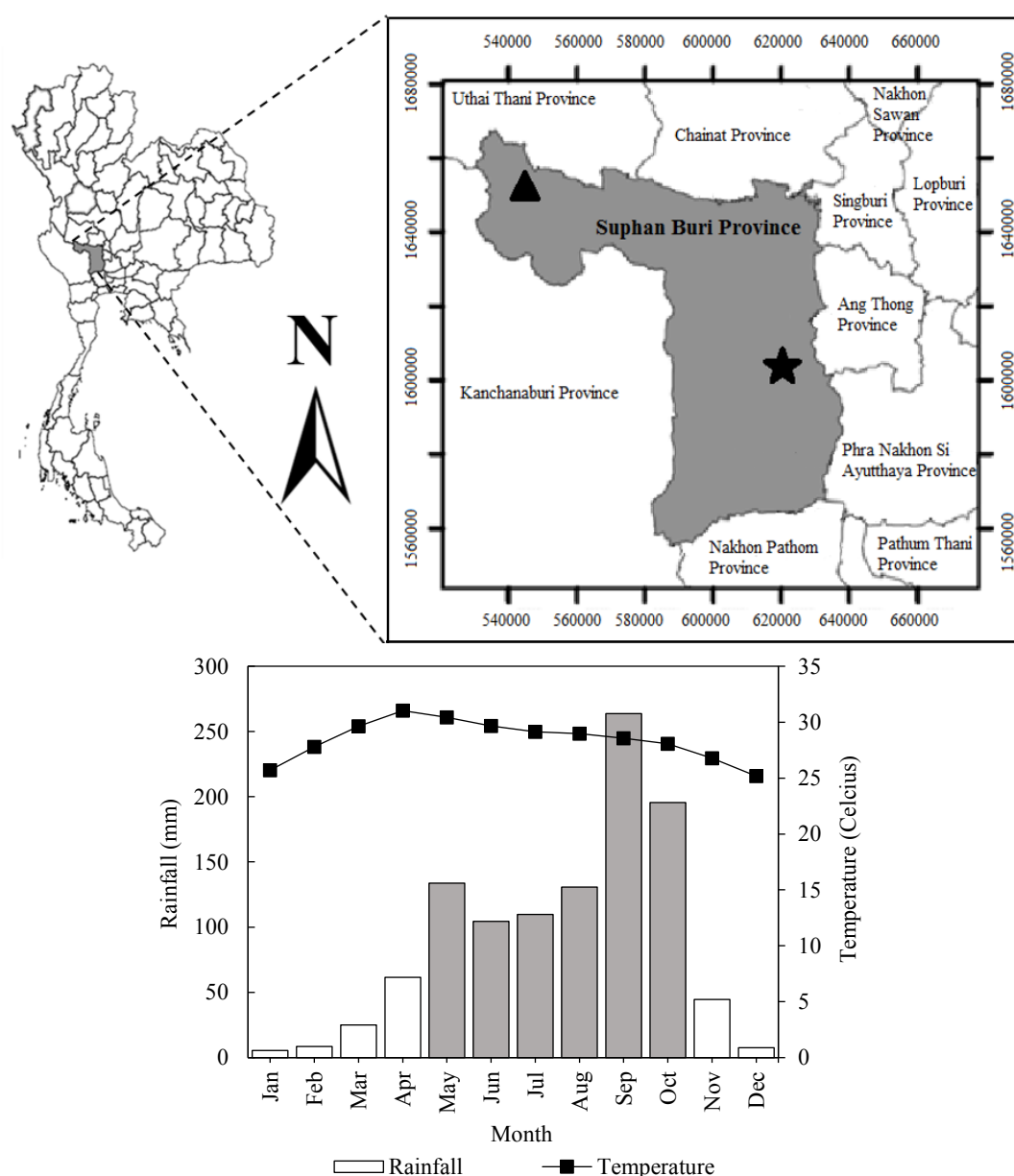
Figure 1. Location of the study site (triangle and star symbols indicate the study site and the Suphan Buri Meteorological station, respectively) and the average monthly climate data obtained from the Suphan Buri Meteorological Station in A.D. 1953-2016 (Gray columns indicate the wet season).

2.2 Wood core collection and annual ring measurement

At a breast height of 1.3 m, a total of 24 wood cores were collected from healthy pine trees using an incremental borer with a 40 cm long and 0.5 cm diameter drill bit, in order to avoid the effect of buttress and injury to the tree base. Following the standard method of dendrochronology (Stokes and Smiley, 1996), after drying at room temperature, all the wood cores were fixed on wood support using a soluble glue and adhesive tape and carefully polished by using several grades of sandpapers to obtain clean and smooth wood surfaces to expose the ring boundaries.

The patterns of variations in annual ring width and the calendar year, during which each annual ring was formed, were examined and matched with sample cores using the technique of cross-matching by observing under a stereo microscope with a magnification of 10x-40x. During cross-matching, intra-annual rings were identified and their frequencies during each year were marked. The annual ring width was measured by using the Velmex Tree-Ring Measurement System (Velmex Inc., New York, USA), consisting of 3 components of a unislide linear stage, 0.001 mm resolution linear encoder, and an encoder readout.

2.3 Data analysis

The accuracy of the annual ring measurement and cross-matching was then verified using the software COFECHA (Holmes, 1983). The software used the technique of segmented time series correlation to assess the quality of the measurement (Grissino-Mayer, 2001). The statistical value of annual ring width series including the intercorrelation, autocorrelation and mean sensitivity coefficients derived from the software COFECHA were then informed. All the annual ring-width series were transformed to annual ring width indices as a ratio of the measured annual ring width and the expected growth in order to eliminate the age effect and maximize the climatic signal using the double detrending technique. By using the ARSTAN software with autoregressive modelling (Cook and Peters, 1981), the first detrending was done using a negative exponential curve or straight line with a negative slope, followed by a second detrending using a 66 years spline curve, which was fitted to each ring-width series. All the indices were averaged to obtain a master chronology by using the arithmetic mean with a mean value of 1. The index with the lowest autocorrelation coefficient and the highest mean sensitivity was selected. To indicate an acceptable sample size and common variance, the expressed population signal (EPS) was also calculated (Borgaonkar et al., 2010; Cook et al., 1990; Wigley et al., 1984).

In order to investigate the significant climate-growth relationship, the correlation coefficient (r) and the coefficient of determination (r^2) were calculated by using the statistics of simple correlation and regression analysis, respectively. The local climate data of monthly rainfall (total rainfall, number of rainy day and maximum rainfall), monthly temperature (extreme maximum temperature, extreme minimum temperature, mean maximum temperature, mean minimum temperature and mean temperature) and relative humidity were defined as the predictors (independent variables) and the constructed ring width index was defined as the predictand (dependent variable). The regional climate data of the Equatorial Southern Oscillation Index (EQ_SOI) and the Equatorial Sea Surface Temperature (EQ_SST), obtained from https://www.esrl.noaa.gov/psd/data/climateindices/, were other important predictors selected for investigating the relationship with the ring width index.

2.4 Climate reconstruction

The past climate reconstruction was performed by using the patterns of climate-growth response derived from the above statistical analysis. The resemblance between instrumental and reconstructed climate was compared to indicate the efficiency of the past climate modeling using several statistics such as Pearson product-moment correlation (Rp), sign-product test (ST), reduction of error test (RE), T-value, means, and standard deviation (SD). The Verify Calibration Model (VFY) software, under the Dendrochronology Program Library (DPL), was used for calculating these statistics.

2.5 Climate factors affecting intra-annual ring formation

The frequencies of intra-annual rings, which were marked during each calendar year, were converted into a percentage and termed as false ring frequency (Fn). Osborn et al. (1997) proposed an equation to stabilize the intra-annual ring frequencies and eliminate bias by changing the sample depth (n) as:

$$f = Fn^{0.5}$$

Where, f is the stabilized intra-annual ring frequency and Fn is the percentage of intra-annual ring frequency. The stabilized intra-annual ring frequency was then related to the local and regional climatic data by using the statistical analysis of linear correlation and multiple regression in order to determine climate factors inducing the intra-annual ring formation.

3. RESULTS AND DISCUSSION
3.1 Annual ring width data

A total of 16 samples were successfully cross-dated from 24 samples of collected wood cores while the anomalous growth patterns of 8 samples could not be cross-matched and cross-dated with other samples. The oldest sampled tree had been growing for longer than 191 years, as indicated by the annual ring samples collected at a height of 1.3 m. These illustrated a growing period during A.D. 1825-2015, while the growing period of the youngest tree was 147 years during A.D. 1869-2015. Although the average ring width was only 1.67 mm/year, Pumijumnong and Eckstein (2011) reported that the mean growth rate of merkus pine (*Pinus merkusii*) distributed in Thailand grew at 1.28 mm/year indicating that their growth was faster than merkus pines in other sites of Thailand,

while the average growth of khasi pine (2.15 mm/year) was higher than that of merkus pine.

The statistical values of annual ring width series intercorrelation, autocorrelation, and mean sensitivity were 0.633, 0.603, and 0.266, respectively. These values indicated the similarity of pine growing pattern suitable for studying climate-growth relationship, although the autocorrelation was quite high (Fritts, 1976). The annual growth pattern and growth rate of the merkus pine indicated an average growth of 1.61 mm in the first 46 years in A.D. 1825-1870 followed by an increasing trend of 2.19 mm during the next 50 years in A.D. 1871-1920. Tree growth declined to 1.37 mm for 30 years in A.D. 1921-1950 and declined to 1.01 mm for the next 40 years in A.D. 1951-1990. Pine growth rate was re-stimulated to 1.44 mm from A.D. 1991 to the present time as shown in Figure 2(a) and (b).

Using an autoregressive modeling, the constructed annual ring width index (Figure 2(c)) indicated that the autocorrelation reduced from 0.603 to -0.120, while the mean sensitivity increased from 0.266 to 0.293. EPS indicated that the acceptable sample sizes in all the segments ranged between 0.85-0.97, which was higher than the critical value of 0.85 (Figure 2(d)). The mean sensitivity of these merkus pines was higher than that reported by Pumijumnong and Eckstein (2011), who stated that the mean sensitivity of this species in Thailand was about 0.26 and varied between 0.22-0.33, while the mean sensitivity of khasi pine in Thailand was 0.32 and varying within a range of 0.28-0.37. The reduced growth during A.D. 1951-1990 (Figure 2(a)) was induced by environmental factors and was similar to other studies in several sites of Thailand and Lao PDR followed by an increased growth trend until the current period (Buckley et al., 2007a; Duangsathaporn and Palakit, 2013).
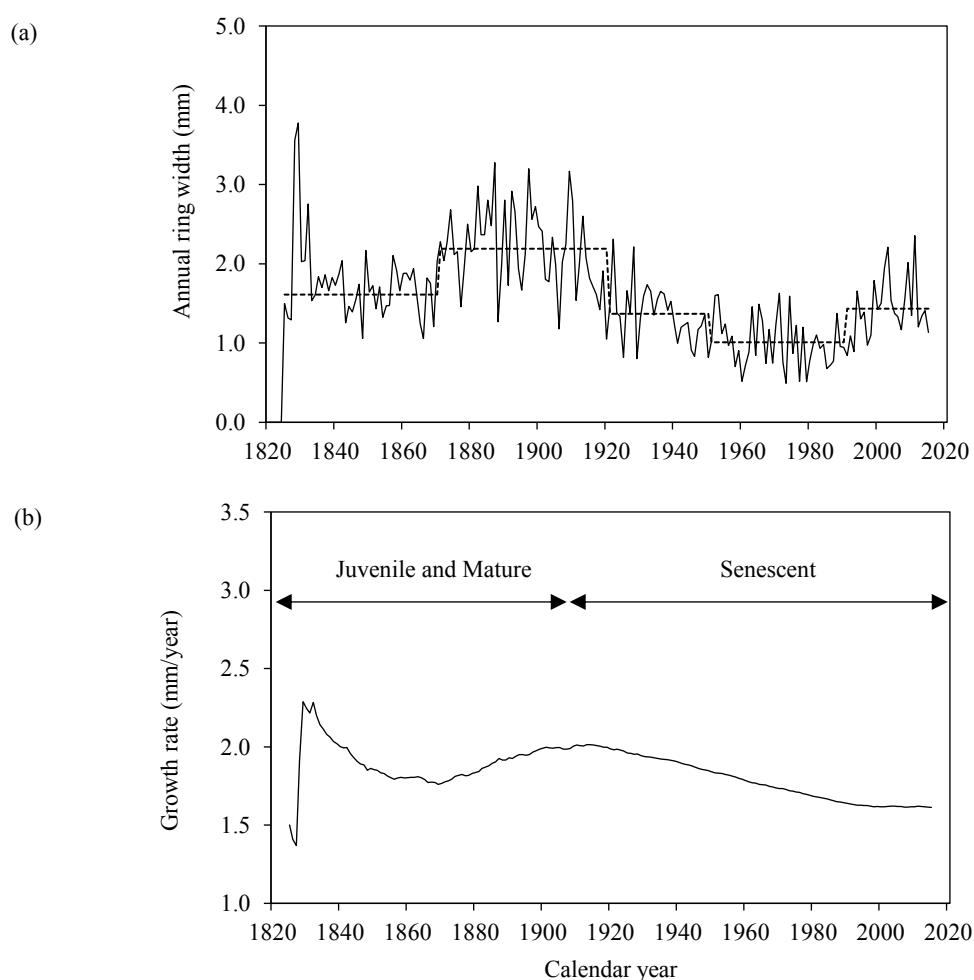

Figure 2. Annual ring width data of merkus pines at the Phu Toei National Park: a) average annual ring widths with mean (dash line) in each segments; b) growth rates; c) annual ring width index (dash line) with a 5 year moving average (thick line); and d) Expressed Population Signal (EPS: thick line) with the critical value of 0.85 (dash line).
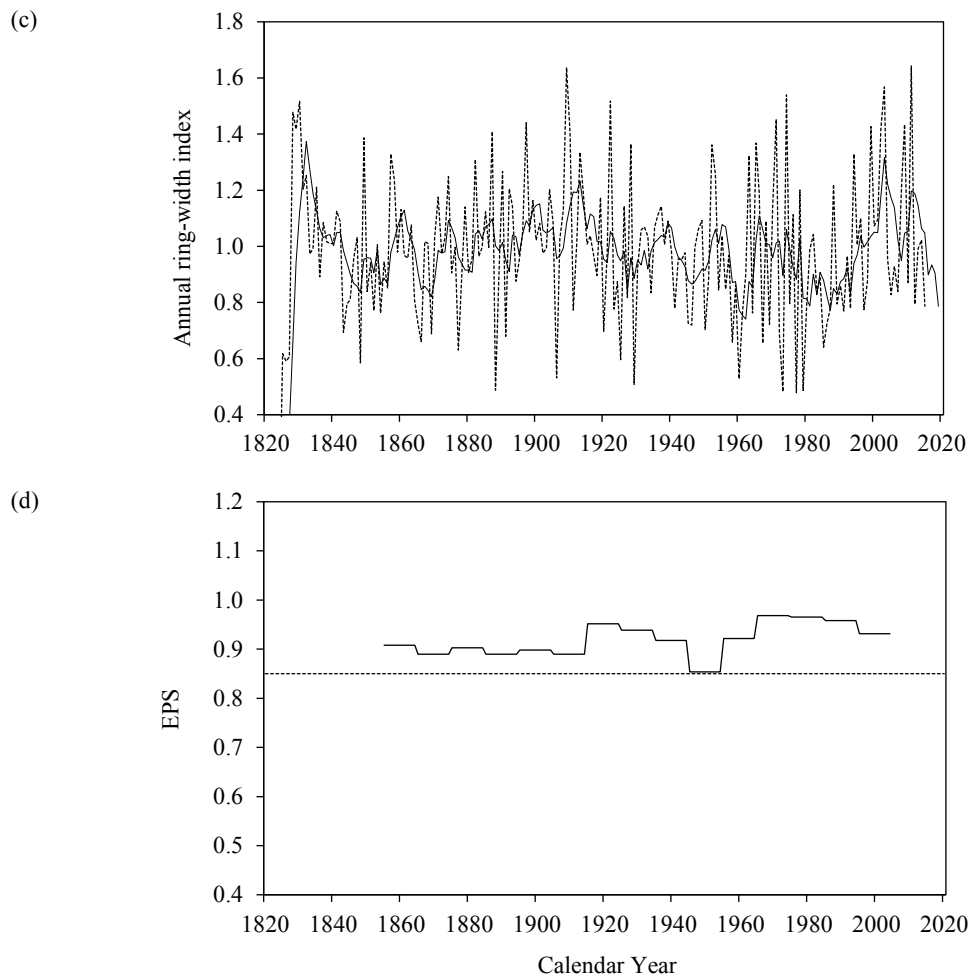
(c)

(d)

Calendar Year

Figure 2. Annual ring width data of merkus pines at the Phu Toei National Park: a) average annual ring widths with mean (dash line) in each segments; b) growth rates; c) annual ring width index (dash line) with a 5 year moving average (thick line); and d) Expressed Population Signal (EPS: thick line) with the critical value of 0.85 (dash line) (cont.).

3.2 The Relationship between climate and annual ring width index

By using the simple correlation analysis, rainfall data and relative humidity were significantly related to the variations in the annual ring width index (Figure 3), suggesting they are factors inducing tree growth. Monthly rainfall in February, March, and April were significantly correlated with the index as indicated by a correlation coefficient (r)=0.255, 0.298, and 0.262, respectively (p<0.05). The number of rainy days in February, May, July and annual rainy days were significantly related with the annual ring width index as indicated by r=0.344, 0.341, 0.366 and 0.520, respectively (p<0.01). The number of rainy days in March, April, and October were also significantly related to the annual ring width index as indicated by r=0.319, 0.321, and 0.283, respectively (p<0.05). The maximum rainfall in July and the relative humidity in May and August were significantly related to the annual ring width index as

indicated by r=-0.288, 0.254, and 0.256, respectively (p<0.05).

The variation of temperature was also illustrated the significant correlation with the pine index (Figure 4). The extreme maximum temperature in April was significantly correlated with the index as indicated by r=-0.377 (p<0.01). At p<0.05, the extreme maximum temperature in February and June was significantly correlated with the index for r=-0.305, and -0.266, respectively, while the extreme minimum temperature and mean minimum temperature were not significantly correlated with the growth. The pine index was significantly correlated with the mean maximum temperature in January (r=-0.300; p<0.05), February (r=-0.268; p<0.05), March (r=-0.325; p<0.01), May (r=-0.258; p<0.05) and June (-0.282; p<0.05). The mean temperature was another local climate variable which was significantly correlated with the index, with the mean temperature in May being significantly correlated with the index

as indicated by r=0.323 (p<0.01). The index was also significantly related to the monthly temperature in March, April and June (r=-0.278, -0.257, -0.276, respectively; p<0.05).
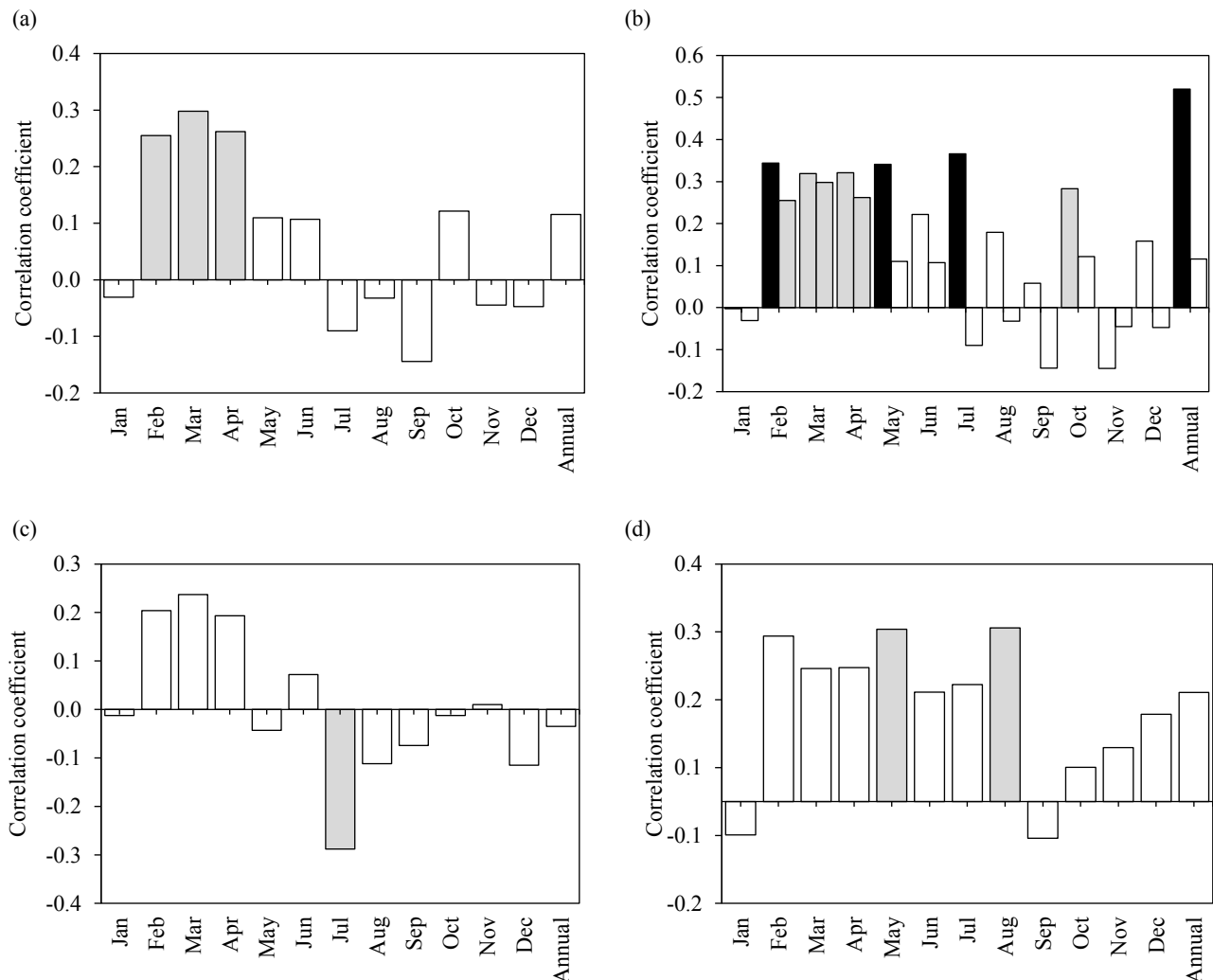
(a)

(b)

(c)

(d)

Figure 3. Correlation coefficient between annual ring width index and climate data of rainfall (a), number of rainy days (b), maximum rainfall (c) and relative humidity (d). Gray and black bars indicate the significant (p<0.05) and highly significant (p<0.01) correlation between variables.

Although merkus pines growing at Phu Toei National Park were significantly related to several local climate data, rainfall and temperature at the transition period of the hot (Mar-Apr) and the beginning of the wet (May-Jun) seasons were the main factors inducing pine growth. This observation is similar to the study of Pumijumnong and Eckstein (2011), who found a significant correlation of rainfall and temperature during pre-monsoon (Mar-May) with the merkus pine growing in northern Thailand, while Buckley et al. (2007a) reported a significant correlation of monsoon climate with merkus pine growth in Lao PDR. Lumyai et al. (2008) also indicated the post-monsoon temperature in October as being a key factor affecting the growth of merkus pine in central Thailand. Not only the responses to merkus pine growth, but the pre-monsoon climate was also significantly correlated with the growth of khasi pines in Thailand and India (Chaudhary and Bhattacharyya, 2002; Pumijumnong and Eckstein, 2011), indicating the importance of the pre-monsoon climate on tree growth in Thailand and other countries.
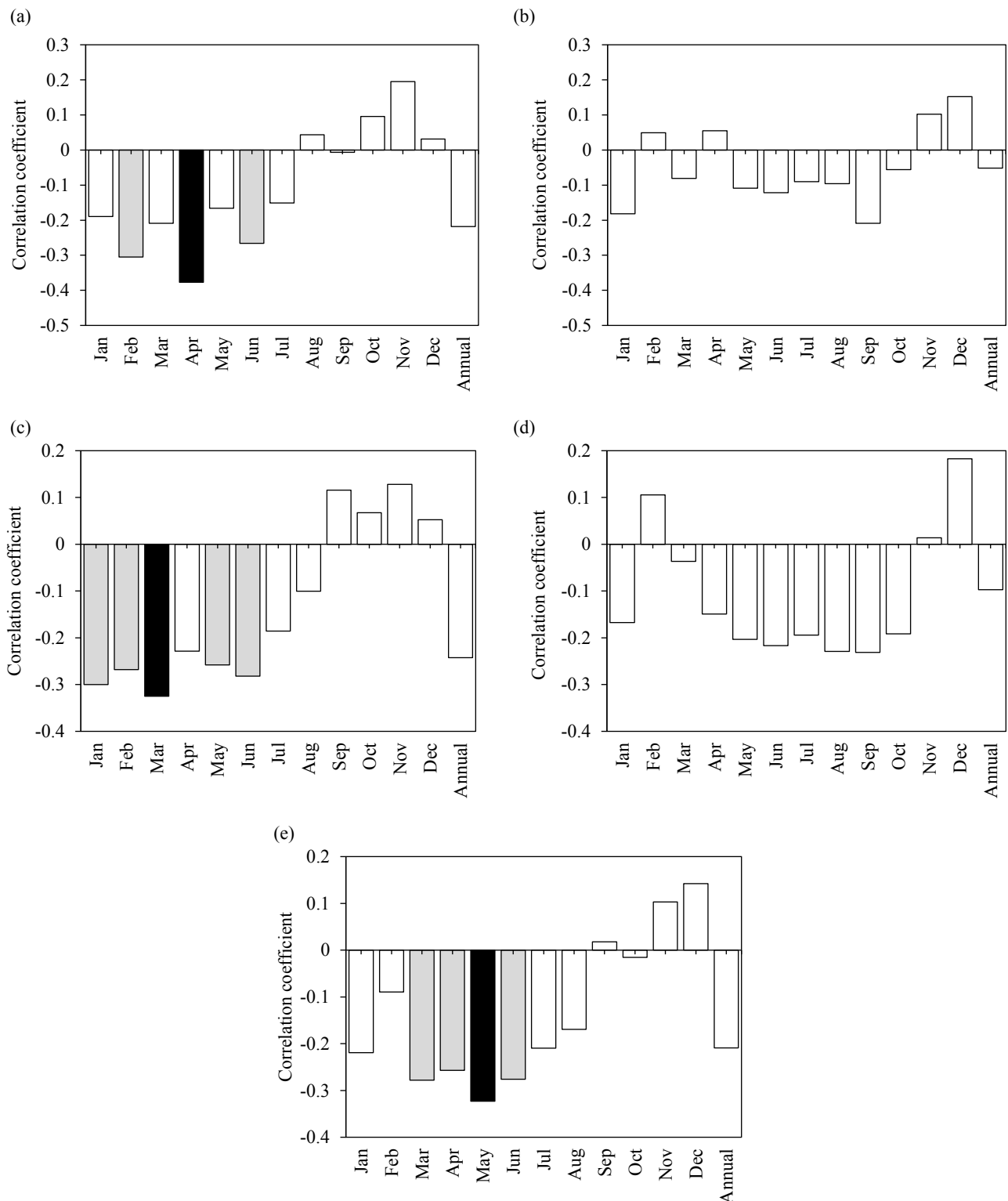
Figure 4. Correlation coefficient between annual ring width index and climate data of extreme maximum temperature (a), extreme minimum temperature (b), mean maximum temperature (c), mean minimum temperature (d), and mean temperature (e). Gray and black bars indicate the significant ($p<0.05$) and highly significant ($p<0.01$) correlation between variables.

The regional climate data of Equatorial Southern Oscillation Index (EQ_SOI) and Equatorial Sea Surface Temperature (EQ_SST) were significantly correlated with the annual ring index (Figure 5). It was found that the EQ_SOI in January, March and April were significantly related to the merkus pine index as indicated by $r=0.270$ ($p<0.05$), 0.360 ($p<0.01$) and 0.282 ($p<0.05$), respectively, while the EQ_SST was not significantly correlated with the pine growth.
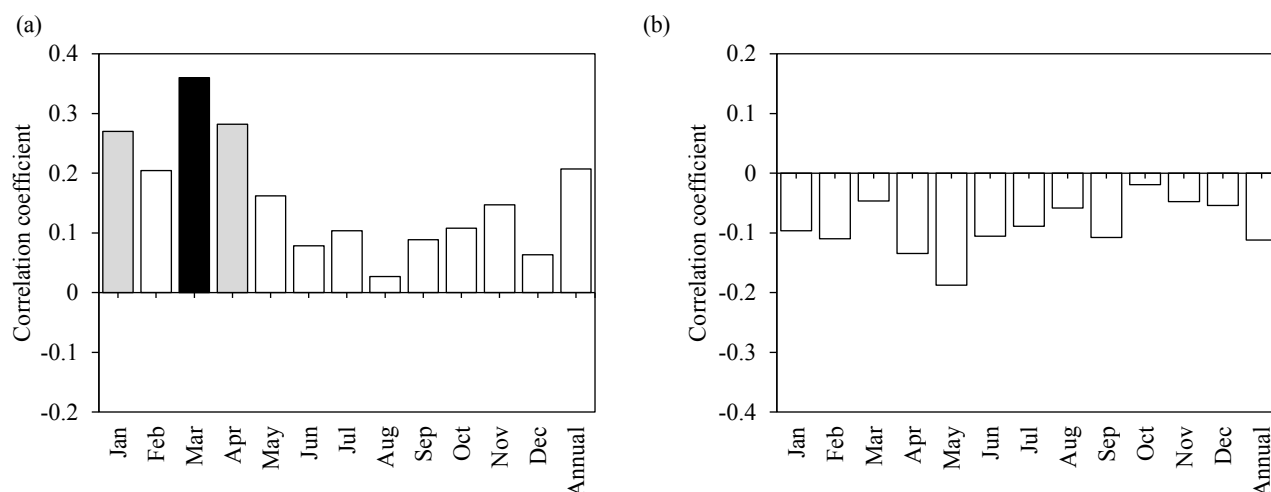
Figure 5. Correlation coefficient between annual ring width index and the regional climate data of Equatorial Southern Oscillation Index (a) and Equatorial Sea Surface Temperature (b). Gray and black bars indicate the significant (p<0.05) and highly significant (p<0.01) correlation between variables.

The regional climate, as measured by EQ_SOI during the hot season (Mar-Apr) was highly significantly related with the growth of merkus pines, while their growth in the easternmost part Thailand was significantly correlated with EQ_SOI and EQ_SST during the dry season of the current year and the monsoon season of the previous year (Duangsathaporn and Palakit, 2013). In Lao PDR, Buckley et al. (2007a) found a direct growth response of merkus pines to gridded SST over the central and eastern tropical Pacific and was strongest during Mar-May. It could be suggested that the pine growth in Thailand and other countries in Southeast Asia was mainly forced by local and regional climate variations which are then appropriate to study climate variability in the past and future.

3.3 The Past climate reconstruction

The top three highest correlation coefficients between annual ring width index and climate included the number of rainy days during each year, the extreme maximum temperature in April, and the EQ_SOI in March and were selected to reconstruct the past climate up until AD 1825. The number of rainy days (Rainday$_{annual}$) during 1986-2015 was used to construct mathematical equations to describe the fluctuations of the index as indicated by Equation (1) and (2).

$$\text{Index} = 0.0015 + 0.0103 \ (\text{Rainday}_{annual}) \qquad (1)$$

$$\text{Rainday}_{annual} = 74.559 + 24.388 \ (\text{Index}) \qquad (2)$$

The annual number of rainy days reconstructed using Equation (2) during the years A.D. 1986-2015 and A.D. 1953-1985 were compared with the recorded meteorological data to verify the reliability of the climate model, using the statistics of Pearson correlation, sign product test, reduction of error (RE), and T-test, also known as the standard procedure of model calibration and verification (Table 1). The actual and reconstructed Rainday$_{annual}$ with its trend line are shown in Figure 6. It can be seen that the average number of rainy days during each year in Suphan Buri province was around 98.7 days. The trend of Rainday$_{annual}$ gradually increased from 97.7 days in the 1840s to be 100.9 days in the 1910s and gradually declined to 95.8 days during the 1980s. Rainday$_{annual}$ rapidly increased to 102.2 days during the 2000s and declined to 99.4 days in the current decade.

The extreme maximum temperature in April (Ext_MaxT$_{April}$) was negatively related with the variations in annual ring-width index. The related pattern of these 2 factors durig A.D. 1995-2015 was used to construct mathematical equations as shown in Equation (3) and (4).

$$\text{Index} = 7.4213 - 0.1607 \ (\text{Ext\_MaxT}_{April}) \qquad (3)$$

$$\text{Ext\_MaxT}_{April} = 41.362 - 1.7414 \ (\text{Index}) \qquad (4)$$

Table 1. Statistics of climate reconstructed with the number of rainy days (Rainday$_{annual}$), extreme maximum temperature (Ext_MaxT$_{April}$), and Equatorial Southern Oscillation Index (EQ_SOI$_{March}$)

Statistic	Rainday$_{annual}$		Ext_MaxT$_{April}$		EQ_SOI$_{March}$	
	Calibration	Verification	Calibration	Verification	Calibration	Verification
Pearson Correlation	0.49*>= 0.31	0.63*>= 0.29	0.55*>= 0.35	0.29*>= 0.26	0.41*>= 0.32	0.26*>= 0.26
Sign product test	9*<= 10	13<= 11	7*<= 7	18<= 14	7*<= 8	16<= 14
Reduction of error (RE)	0.24*>= 0.09	0.19*>= 0.09	0.30*>= 0.12	0.10*>= 0.06	0.17*>= 0.10	0.14*>= 0.07
T-test	2.11*>= 1.70	2.36*>= 1.70	1.72*>= 1.72	2.06*>= 1.68	0.60>= 1.71	2.69*>= 1.68
Degree of freedom	28	31	21	38	25	38

Remark*: Indicates a significant correlation at p<0.05
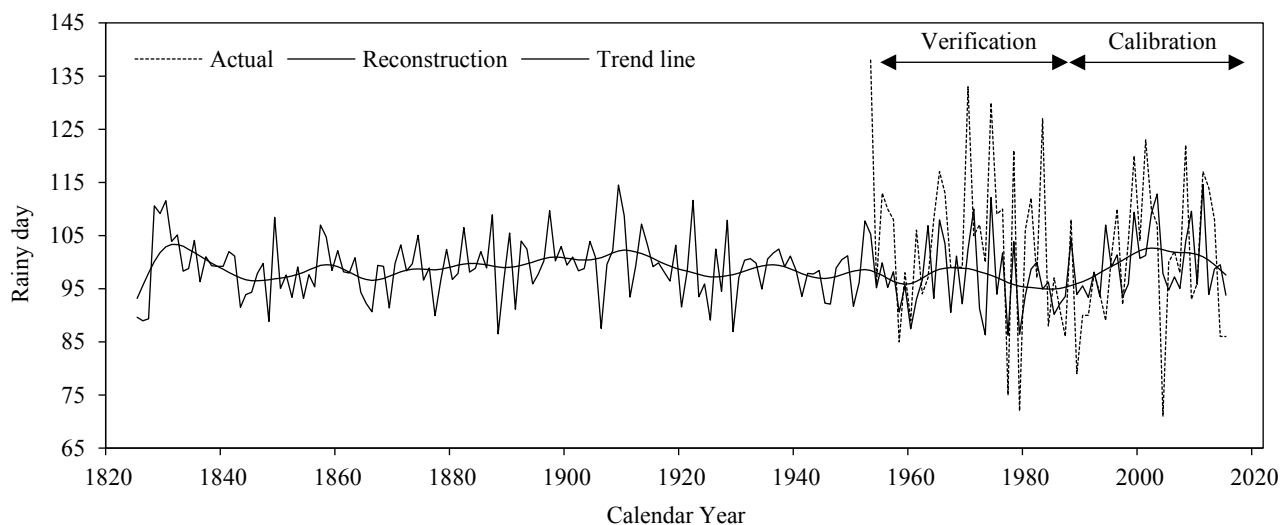
Figure 6. Actual and reconstructed values of the number of rainy days in Suphan Buri province.

The reconstructed values of extreme maximum temperature in April during the two phases of A.D. 1953-1994 and A.D. 1995-2015 were compared with the recorded data derived from the meteorological station to verify the reliability of the model (Table 1). The reconstructed and actual Ext_MaxT$_{April}$ are shown in Figure 7. The fluctuation in the trend line indicated that the extreme maximum temperature decreased from 39.7 °C in the 1840s to 39.5 °C in the 1900s. Later, the temperature gradually increased for 80 years with the highest maximum temperature during the 1980s at 39.8 °C and rapidly declined to 39.4 °C during the 1990s. In this decade, the temperature in April increased to 39.6 °C, while the average of the extreme maximum temperature in April was 39.6 °C.

The regional climate as measured by the Equatorial Southern Oscillation Index increased in March (EQ_SOI$_{March}$) and also stimulated the growth in merkus pine at this site. The relationship between EQ_SOI$_{March}$ and the index during A.D. 1989-2015 was used to construct mathematical equations as shown in Equation (5) and (6).

$$\text{Index} = 1.0251 + 0.1088 \ (\text{EQ\_SOI}_{March}) \quad (5)$$

$$\text{EQ\_SOI}_{March} = 1.5702 \ (\text{Index}) - 1.4836 \quad (6)$$

The reconstruction of EQ_SOI$_{March}$ during A.D. 1949-1988 and A.D. 1989-2015 was compared with the measured EQ_SOI$_{March}$ to verify the reliability of the model as shown in Table 1 and Figure 8. It was found that EQ_SOI$_{March}$ gradually declined from 0.14 in the 1820s to 0.03 in the 1850s and increased to 0.18 during the 1900s. Seventy years later, it decreased to -0.02 during the 1980s before rapidly increasing to 0.022 during the current decade.

The reconstructed climate indicated a declining trend in the number of rainy days in each year and increasing trends in the extreme maximum temperature and EQ_SOI in the twenty-first century which led to a reduced annual rainfall, while the temperature in April increased with a mild rainfall.

Using tree-ring analysis of *P. sylvestris* in northern Scandinavia, Esper et al. (2012) also found a rapidly increased temperature of 0.5 °C during the twentieth-century which was higher than that found this study of 2 °C. Using tree-ring analysis of merkus pines in central Vietnam, Viet et al. (2018) found a warming trend with the temperature increasing by 0.18 °C per decade. The observation of mild wet conditions during the month of April was consistent with the tree-ring study of northern Thai teak indicating an increased rainfall in April, which was higher than the average (Lumyai and Duangsathaporn, 2017).
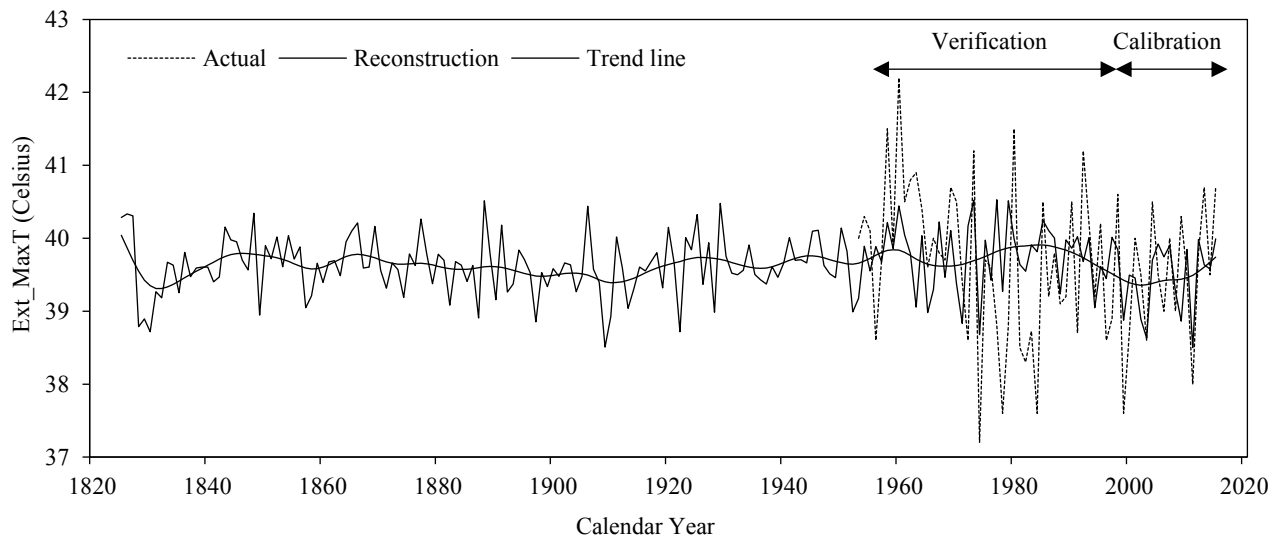

Figure 7. Actual and reconstructed values of the extreme maximum temperature in April.
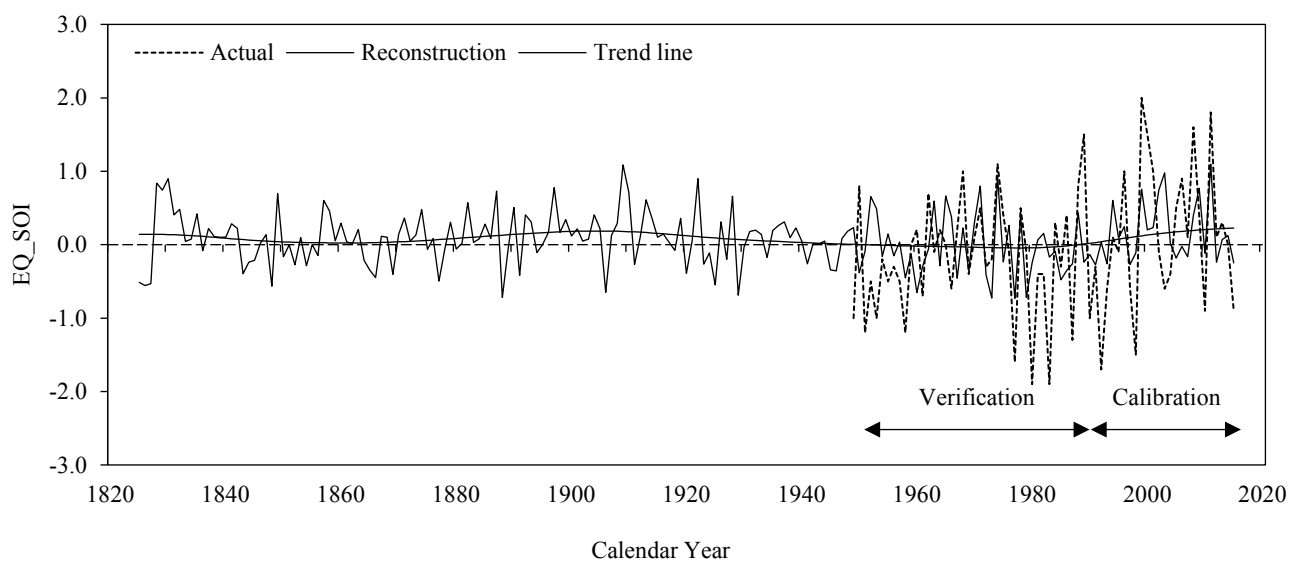

Figure 8. Actual and reconstructed values of Equatorial Southern Oscillation Index in March

3.4 Climate inducing intra-annual ring formation

Intra-annual rings, which were marked during the cross-matching and cross-dating steps, were abundantly found in A.D. 2001 in 15 cores sampled out of the total 16 cores. It was also frequently found in A.D. 1883, 1907, 1919 and 2009 in 14 sample cores (Figure 9(a)). To eliminate the effect of sample size variation in each year, the intra-annual ring frequencies were transformed to stabilize intra-annual density fluctuations (IADFs), as illustrated in Figure 9(b). By using a stepwise regression analysis, a relationship between the stabilized IADFs and climatic data at local and regional scales indicated that the occurrences of intra-annual ring formation could be explained by the fluctuations in the extreme rainfall (r^2=16.8%, $p<0.05$), monthly total rainfall (r^2=29.1%, $p<0.05$), relative humidity (r^2=32.7%, $p<0.05$), extreme maximum temperature (r^2=40.5%,

$p<0.05$), extreme minimum temperature ($r^2=15.3\%$, $p<0.05$), mean maximum temperature ($r^2=34.5\%$, $p<0.05$), mean minimum temperature ($r^2=15.7\%$, $p<0.05$), mean temperature ($r^2=29.7\%$, $p<0.05$), EQ_SOI ($r^2=16.3\%$, $p<0.05$), and EQ_SST ($r^2=11.9\%$, $p<0.05$). The mathematic model described

a causation of intra-annual ring formation by using the highest significant relationship among the intra-annual ring occurrences and the extreme maximum temperature in February, June, September and November as shown in Equation (7).

$$\text{Stabilized IADF (\%)} = 18.147 - 5.684(\text{Ext\_MaxT}_{Feb}) - 8.916(\text{Ext\_MaxT}_{Jun}) \qquad (7)$$
$$+7.995(\text{Ext\_MaxT}_{Sep})+7.904(\text{Ext\_MaxT}_{Nov})$$

In central Thailand, intra-annual ring occurrences in merkus pines were related to several climatic factors, especially the extreme maximum temperature (40.5% variance explained), which declined at the beginning of the wet season and increased during the transitional period of the late rainy and cold seasons. Due to anomalous fluctuations in temperature, water stress was a possible cause of the intra-annual ring formation, which reduced the photosynthesis and cambial cell division (Cherubini et al., 2003; Copenheaver et al., 2006; De Micco et al., 2016).

Not only was the formation of intra-annual rings in merkus pines influenced by anomalous climate, but this was also the case with khasi pines at the beginning and during the late growing season. Singh et al. (2016) reported a causation of intra-annual ring formation in khasi pines growing in the northeastern part of India, which was caused by a reduction in precipitation during the growing season (Apr-Jul) and increased precipitation in the late

growing season (Aug-Sep). Effect of water stress on the intra-annual ring formation was also confirmed by Vieira et al. (2010), who found the occurrence of intra-annual ring associated with the amount of rainfall during the transition period of summer and rainy seasons.

Intra-annual rings of Austrian pines (*P. nigra*) were frequently found in the years in which water stress during the wet season was recorded (Wimmer et al., 2000). This observation was similar to the occurrence of intra-annual rings in *P. halepensis*, with an increased water stress from increased rainfall during the dry period and increased temperature at the beginning of the rainy season, respectively (de Luis et al., 2011). A relatively higher frequency of intra-annual rings was found in younger trees, with narrow annual ring widths (Bogino and Bravo, 2009). It was shown that changes in the current and past climates at local and regional scales could be detected by using annual and intra-annual ring widths of pine trees as a valuable proxy in Thailand and other countries.
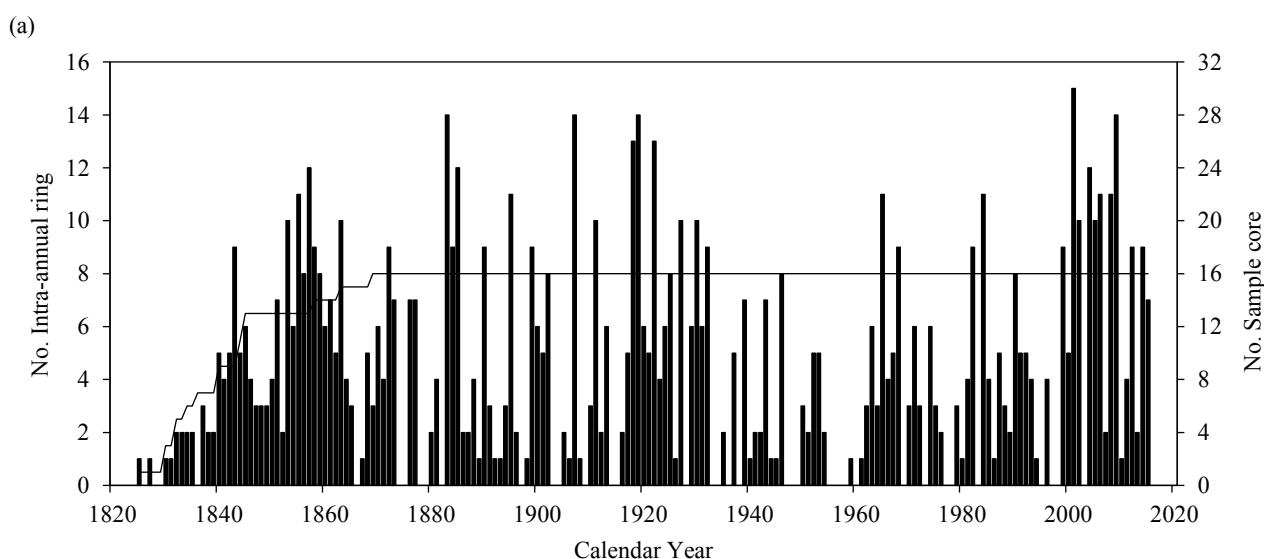
(a)

Figure 9. Intra-annual ring frequencies: a) number of intra-annual ring in each year; b) stabilized intra-annual ring in each year. The horizontal line indicated number of sample core in each year.

(b)

Figure 9. Intra-annual ring frequencies: a) number of intra-annual ring in each year; b) stabilized intra-annual ring in each year. The horizontal line indicated number of sample core in each year.
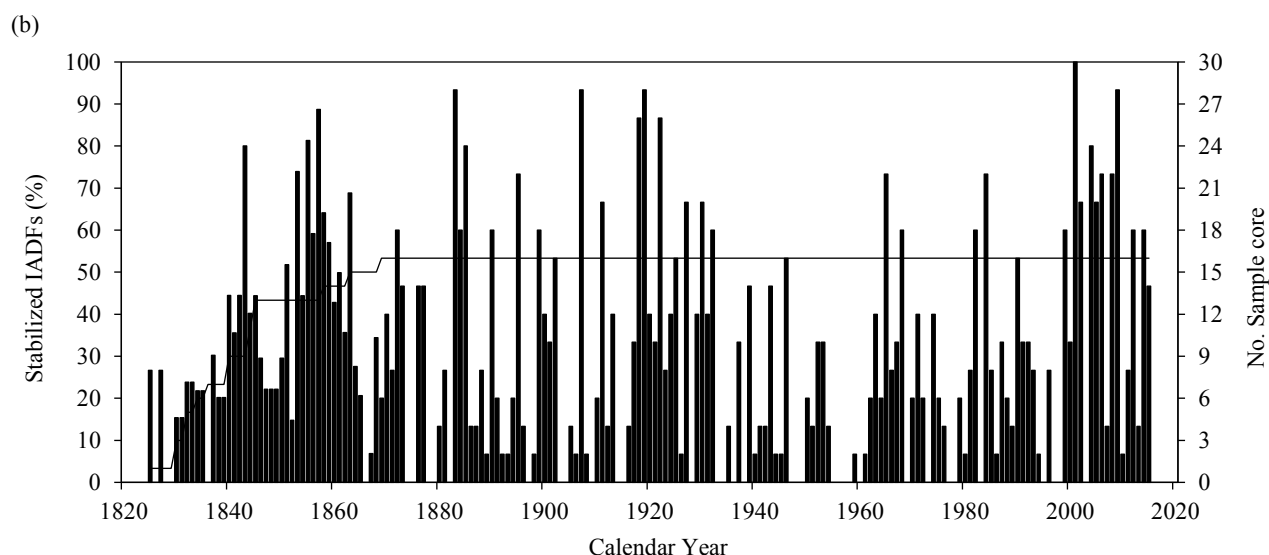
4. CONCLUSIONS

In this study, we found that the formation of annual and intra-annual rings in the merkus pine (*Pinus merkusii*) of central Thailand could be explained by the fluctuations in local and regional climates. The local and regional climate variables most strongly related to the variations in annual ring index included the number of rainy days in each year, the extreme maximum temperature in April, and the Equatorial Southern Oscillation Index in March (EQ_SOI$_{March}$), and were chosen for the past climate reconstruction. Since AD 1825, the number of rainy days during each year gradually increased until the beginning of the twentieth century and declined towards the end of the century. It shortly increased during the first decade of the twenty-first century followed by a declining trend in this decade. This was in contrast with the extreme maximum temperature in April which declined at the beginning of the nineteenth century and increased during the twentieth century with a short period of decline in temperature observed towards the end of the century followed by an increase during the current period. Reconstruction of EQ_SOI$_{March}$ indicated mild fluctuations during the 19th century, reduction in the twentieth century and increase in the last century. Not only could the model explain the climate variations longer than 150 years in central Thailand but the study explored, for the first time, the variability in climate using the formation of intra-annual rings in Thai merkus pine. The occurrence of these anomalous annual rings could refer to and explain the climate abnormalities compared to normal years when the extreme maximum temperate decreased at the beginning of the wet season and increased at the transitional period of the late rainy and cold seasons. Additionally, to support the forest and plantation management, the activity of watering, especially at the beginning of the wet season when anomalous increased temperature occurred, shall be contained in the forest management plan in order to increase annual pine growth and wood formation. To confirm this observation of homogenous factors inducing annual and intra-annual ring formation, merkus pines growing in other regions of Thailand shall be analysed and compared with this study in the near future.

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