Maejo Int. J. Sci. Technol. **2021**, *15*(01), 81-95

Maejo International
Journal of Science and Technology

ISSN 1905-7873
Available online at www.mijst.mju.ac.th

Full Paper

Occurrence of annual and intra-annual rings related to meteorological records in Khasi pines of northern Thailand and twentieth-century climate reconstruction

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Received: 14 May 2020 / Accepted: 19 April 2021 / Published: 21 April 2021

Abstract: In order to project the climate fluctuations back to the past and predict the changes in the future, climate variability inducing annual and intra-annual ring formation in Khasi pines (*Pinus kesiya*) growing in northern Thailand was investigated and the past climate was reconstructed. Annual and intra-annual rings from several Khasi pines were identified using the techniques of cross-matching and cross-dating. All of the 88 wood core samples were successfully cross-dating with a 118-year growing period from AD 1898 to AD 2015. The annual growth was significantly affected by the mean temperature in April (r = -0.423) and total rainfall in March-April (r = 0.371). The equatorial sea surface temperature during August-November of the previous year also significantly stimulated the growth of these pines (r = 0.370). Regression analysis indicated that the maximum temperature influenced the formation of intra-annual rings and could explain 48.1% of the variance in the intra-annual rings. It was also found that the total rainfall during the summer period of March-April declined from 68.1 mm in AD 1898 to 54.1 mm in AD 2015 with the average of total rainfall of 60.4 mm in the period. The rainfall projected in AD 2065 was around 48.1 mm, while the mean temperature in April gradually increased from 30.10 °C in AD 1898 to 30.45 °C in AD 2015 with the average temperature of 30.33 °C and should continuously increase to 30.60 °C in AD 2065.

Keywords: climate change, dendrochronology, false ring formation, Khasi pine, *Pinus kesiya*

INTRODUCTION

Climate change has impacted human life and natural systems worldwide. The frequency of natural disasters related to change in climate has been continuously increasing since AD 1950. According to the global warming trends, the Intergovernmental Panel on Climate Change (IPCC) [1] has indicated that the average global temperature rose by 0.85 °C during the period from AD 1880 to AD 2012 and that the rate of increase in sea level since the mid-19th century has been greater than the mean rate during the two previous millennia. If temperature continues to increase at the current rate, IPCC [2] also indicates that global warming is likely to reach 1.5 °C during AD 2030 – 2052. However, trends based on short-term records do not reflect the precise long-term climate trends in general. As an example, IPCC [1] reported that the variation of warmer periods during AD 1998 – 2012 implied from the measured temperatures was 0.05 °C (–0.05 to 0.15 °C per decade) with a strong El Niño effect. This variation was smaller than the calculated value since AD 1951 of 0.12 °C (0.08 to 0.14 °C per decade). It can therefore be concluded that the meteorological data recorded during this century is not enough to predict the accurate climate trends in the future. Therefore, an understanding of the past climate system is necessary and should be combined with the recorded data to construct a climate model to predict the future climate trends.

Tree ring analysis, namely dendrochronology, is generally used by many researchers in several countries including Thailand to reconstruct past climate patterns and also to forecast trends in the future. Studies in Laos PDR and Thailand revealed that, similar to teak trees, two mountain pine species, *Pinus kesiya* and *P. merkusii*, are appropriate for such analysis [3-11]. Pumijumnong and Wanyaphet [4] also found a significant and positive relationship between cambial activity of these mountain pines and precipitation, supporting the development of annual rings in the wet season. However, dendrochronologists are not only interested in the variations of annual ring width, but also in changes in other characteristics such as earlywood, latewood and wood density, in order to relate them to climate [6]. The anomalous occurrences of intra-annual rings, inducing errors in tree-ring research, are also difficult to identify and eliminate from annual ring width series. The formation of these false rings in temperate pine species is induced by anomalous fluctuations in climate and other environmental factors such as canopy class and tree age [12-16], but the factors affecting false ring formation in tropical pine species has not yet been clarified.

In this paper we try to understand the past climate from the annual ring width analysis of *Pinus kesiya*, generally growing in the tropical regions and highlands of Southeast Asia and how the variations in climate might have affected the growth and intra-annual ring formation of this Khasi pine, especially in Thailand. The relationship between annual growth of *P. kesiya* and climate is analysed, the causation of false ring formation is explained, and the reconstructed past climate estimated from annual ring width analysis is presented in the following sections.

MATERIALS AND METHODS

Study Site and Climate Data

The study site, namely Ban Wat Chan pine forest, is an undisturbed natural pine stand under the care of the Forest Industry Organisation, located in Galyani Vadhana district, Chiang Mai province. The site is located in the north of Thailand at latitude 19°05'05" N and longitude 98°19'53" E with an elevation of 900-1,000 m above mean sea level. Monthly climate data (AD 1951 - 2015) of rainfall, temperature and relative humidity for climate-growth analysis was derived from the nearest meteorological station of Mae Hong Son province [17], which is 45 km from the study site. Based on the average of total rainfall and mean temperature in each month, the local climate is divided into the dry season during November - April and the wet season during May - October by using the Walter-Lieth climate chart (Figure 1). During the wet season, the total rainfall in each month is higher than 100 mm while the total rainfall in the dry season is lower than 100 mm a month. The dry season can be divided into winter (November-February) and summer (March-April) when the mean monthly temperature is lower or higher than 25 °C respectively.

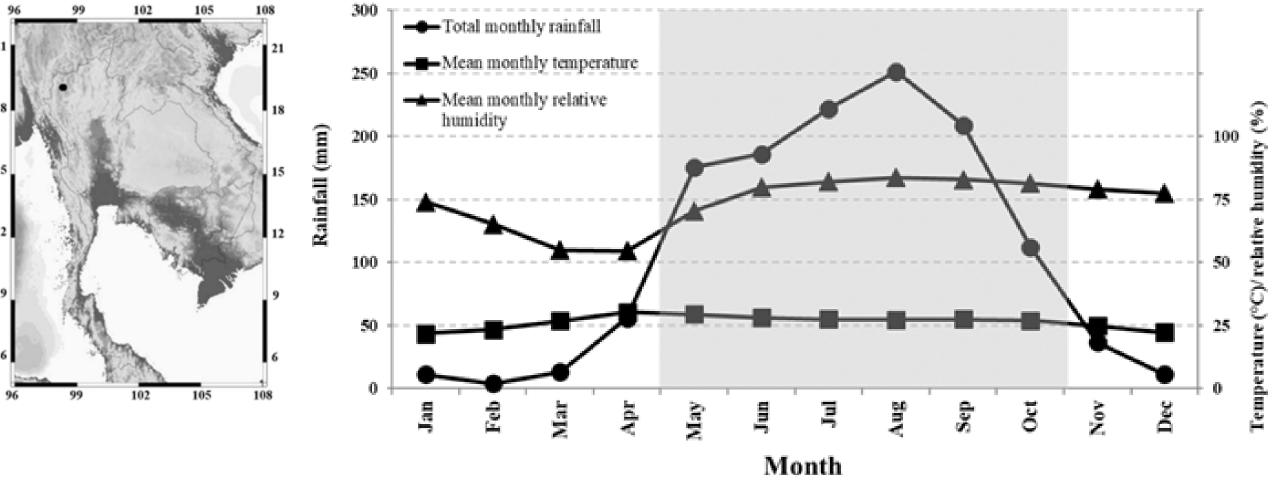

Figure 1. Pine sample collection site north of Thailand (Ban Wat Chan pine forest indicated by black dot in map) with Mae Hong Son climate data. Gray band indicates the wet season in the area

Sample Collection and Preparation

An increment borer with a drill bit of 40 cm in length and 0.5 cm in diameter was used to extract cores of 22 healthy pine trees (88 sample cores) in cardinal directions (north, east, west, south), either at the breast height or at a height of 1.3 m in order to avoid the effect of buttress. The wood cores were dried at room temperature, fixed on support wood, and carefully sanded following the standard method of dendrochronology [18] to obtain clean and smooth wood surfaces to expose the ring boundaries.

Annual Ring Measurement and Data Analysis

Under a stereo microscope, the polished increment cores were examined for variations in annual ring width patterns using cross-matching among wood cores in order to identify the year during which the annual ring was formed. Anomalous intra-annual rings were identified and marked during this step. Annual ring widths were then measured using the TA Unislide Tree-Ring Measurement System (Velmex Inc., USA) with an accuracy of 0.010 mm m^{-1} and the data processing was done in 2 steps. The first step involved the identification of the exact growth year and was verified using COFECHA software [19], and the second step involved the development of a ring width index by using the ARSTAN software [20]. The expressed population signal (EPS), a function of the average correlation between tree-ring series (Rbar) and the sample depth, was calculated to indicate the acceptable number of the sample size and common variance. The accepted EPS value should be greater than or equal to 0.85 [21-23].

Later, the ring width index was correlated with local climate which included total rainfall (accumulated rainfall in each month), number of rainy days, maximum rainfall (the highest daily rainfall in each month), extreme maximum temperature (the highest temperature in each month), extreme minimum temperature (the lowest temperature in each month), mean maximum temperature (the average of the daily maximum temperature in each month), mean minimum temperature (the average of the daily minimum temperature in each month), mean temperature (the average of the daily temperature in each month), and mean relative humidity (the average of the daily relative humidity in each month). Growth-climate correlations with regional climate were also analysed, as indicated by Equatorial Southern Oscillation Index (EQ_SOI) and Equatorial Sea Surface Temperature (EQ_SST), obtained from the National Oceanic and Atmospheric Administration – Physical Sciences Laboratory [24] in order to describe the climate-growth response using the statistics of correlation and regression analysis. SOI indicates a proxy of El Niño or La Niña events in the tropical Pacific Ocean with negative and positive values accompanied by El Niño or La Niña episodes respectively, while an increase in SST indicates severe drought in many regions [25].

Based on the patterns of climate-growth response derived from the above statistical analysis, the past climate was reconstructed and statistical verification of the reconstruction was also performed. The level of correspondence between measured and reconstructed climate data was used to confirm the efficiency of the climatic response equations. The calibrated and verified procedures employed several statistics such as Pearson product-moment correlation (Rp), the sign-product test (ST), the reduction of error test (RE), T-value, means and standard deviation (SD). The Rp was applied to measure the relative variation between measured and reconstructed climate data while the ST illustrates the consistent differences between pairs of these data. The RE offers a highly sensitive measure of reliability: the maximum of 1.0 indicates a perfect estimation. T-value indicates the significant difference between means of 2 data sets while the SD is a measure of data scattering from the mean. These statistics were calculated using the VFY software under the Dendrochronology Program Library. Future trend in climate variation to a lead time of 50 years (AD 2065) was then constructed by projecting the model linear trend line obtained from the past values to the present.

Factors Affecting False Ring Formation

The frequency of false ring occurrences, indicated by the cell structure during the cross-matching step, was calculated as the number of wood cores forming false rings divided by the number of wood cores forming annual rings in a given year and was converted into a percentage and termed as false ring frequency (Fn) after multiplication with 100. However, a change in sample depth, n, in time created a bias, which was addressed by an adjustment proposed by calculating an adjusted false ring frequency [26] as $f = Fn^{0.5}$, where f is the stabilised false ring frequency and Fn is the percentage of false ring frequency. Finally, these data were related to the local and regional climatic data to determine the factors affecting the formation of false rings using the statistics of linear correlation and multiple regression analysis.

RESULTS AND DISCUSSION

Tree-ring Data

All of the 88 wood core samples were obtained from 22 mature Khasi pines whose diameters at breast height ranged between 38.4-58.5 cm. These core samples were successfully cross-dated with a 118-year growing period of AD 1898 – 2015. The rapid growth of the Khasi pines at about 3.392 mm/yr is a good indication of their well-being and good natural regeneration. The values of intercorrelation series, autocorrelation and mean sensitivity are 0.396, 0.591 and 0.316 respectively. The annual growth and growth rate increased rapidly in the first 40 years (AD 1898 – 1937) and then gradually declined till the present period (Figures 2a and 2b). The rapid growth of these mature Khasi pines (3.392 mm/yr) is higher than the mean growth rate of the species in Thailand (2.15 mm/yr) [3]. The mean growth rate of these pines is also higher than *P. merkusii* (1.28 mm/yr) [3], which are generally distributed in the north, north-eastern and central parts of Thailand. Although these Khasi pine trees are approaching maturation, their growth is faster than young trees planted outside the natural setting. Missanjo and Matsumura [27] reported an annual growth rate of only 1.44 mm/year for the young Khasi pines planted in the tropical savannah of southern Africa.

The annual ring width index was constructed to maximise the climatic response and minimise or remove the unwanted noises. This was done by first detrending using a negative exponential curve or a straight line with a negative slope, followed by a second detrending using a 66-year spline curve which was fitted to each ring-width series. A tree-ring index was constructed based on the proportion of actual ring width and a double detrending value for each year. All standardised series were combined to obtain a master chronology by calculating the arithmetic mean (Figure 2c). The EPS in each segment ranges between 0.85-0.99, which is higher than the acceptable value of 0.85 (Figure 2d).

A high autocorrelation of 0.591 obtained between the annual ring width data of current and previous years reduces to 0.003 using the autoregressive modelling [28], while the mean sensitivity slightly increases from 0.316 to 0.335. The mean sensitivity derived from the annual ring width index is slightly different from that reported in the study of Pumijumnong and Eckstein [3], who stated that the mean sensitivity of *P. kesiya* in the northern region of Thailand was about 3.22. However, a study of *P. kesiya* in the north-eastern part of India indicated a low mean sensitivity value ranging between 0.165-0.249 [29]. After the age effect was reduced, it was observed that the decline in the growing index of the Khasi pine during the last 48 years could be due to environmental factors such as climate and pine growth competition within the forest stand [28]. It was reported that the growth of Merkus pine in Thailand and Lao P.D.R. was also below the mean between the years AD 1950 – 2000 [6, 7] and the annual growth of Thai Merkus pine has also rapidly increased since AD 2000 until the present time [30-31].

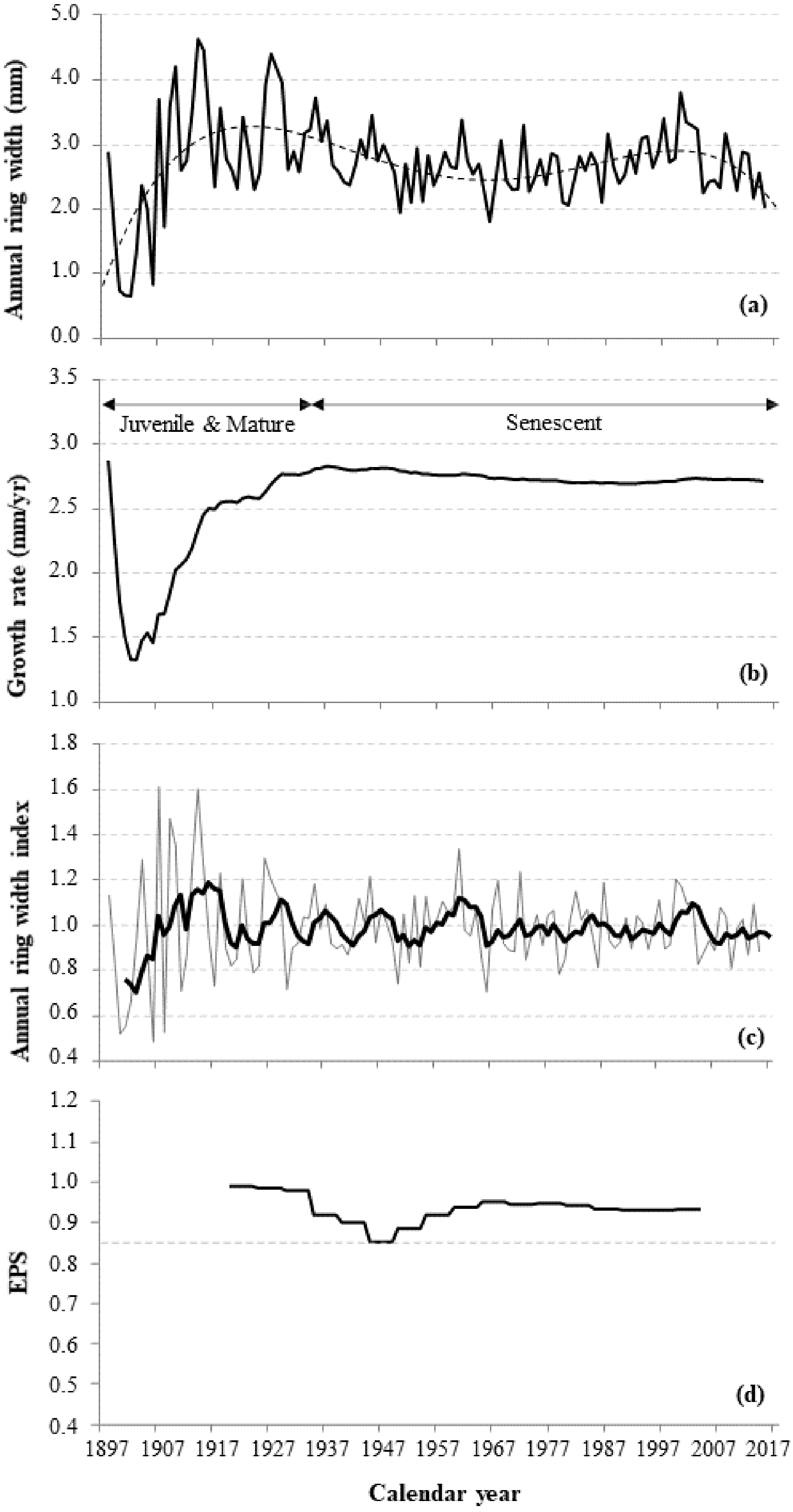

Figure 2. Average annual ring width (thick black line) with growth trend (dashed line) (a), growth rate (b), annual ring width index (thin grey line) with overlay of 5-year moving average (thick black line) (c), and expressed population signal (EPS) with acceptable value of 0.85 (straight dashed line) (d) of *P. kesiya* growing at Ban Wat Chan pine forest

Climate-Growth Response

The annual ring width index of the Khasi pines is significantly related to the local and regional climate data (Table 1). The growth is significantly related to the total monthly rainfall in January and April and to the total rainfall during the summer season from March to April. The variations in growth are also related to the number of rainy days in January and April of each growing year or the 'present' year, and to the number of rainy days in June of the 'previous' year. Seasonal rainy days during the summer period from March to April significantly correspond to the annual ring width index. Maximum rainfall of the present year in January, April and August and that of the previous year in August significantly correspond to the growth of the Khasi pine. The seasonal maximum rainfall in the summer season also significantly correlates with the pine growth. The annual ring width index and the relative humidity in April, summer season and annual data also significantly correlate as shown in Table 1.

The growth of the Khasi pine significantly correlates with the extreme maximum temperature both in May and July of the present year and also in January and October of the previous year. The pine growth is also significantly related to the annual extreme maximum temperatures during the summer season (Mar-Apr), rainy season (May-Oct), early rainy season (May-Jun) and mid rainy season (Jul-Sep). It is also related to the extreme maximum temperature in October (late rainy season) of the previous year and significantly correlates with the extreme minimum temperatures in August of the present year and September of the previous year. The temperature during the mid-rainy season of the previous year also significantly correlates with the annual-ring width index of these Khasi pines (Table 1).

Table 1. Relationships between annual-ring width index of *P. kesiya* and climate data

Period	Correlation Coefficient (r)										
	Rainfall (mm)			Relative humidity (%)	Temperature (Celsius)					EQ SOI	EQ SST
	Total	Max.	Rainy days		Extreme max.	Extreme min.	Mean max.	Mean min.	Mean		
Jan	**.280***	**.249***	**.400****	.150	-.231	-.031	-.200	.107	-.038	.199	-.315
Feb	.122	.138	.160	.208	-.223	-.026	-.225	.075	-.024	.087	**-.346***
Mar	.157	.182	.001	.187	-.233	.013	**-.257***	-.036	-.157	.014	-.220
Apr	**.362****	**.259***	**.296***	**.369****	-.234	-.128	**-.374****	**-.299***	**-.423****	.006	-.141
May	-.065	-.016	-.160	.119	**-.373****	-.208	-.110	-.176	-.129	-.087	-.011
Jun	.116	-.003	.121	.191	-.064	-.116	-.195	-.236	-.237	-.155	.114
Jul	-.002	-.012	-.192	.158	**-.290***	-.155	-.216	**-.272***	**-.278***	-.188	.159
Aug	-.094	**-.278***	-.077	.156	-.198	**-.312***	-.190	**-.280***	**-.276***	-.174	.263
Sep	.153	.014	.193	.227	-.147	.034	-.213	-.239	**-.291***	-.160	.283
Oct	.014	-.117	.128	.022	-.014	.163	.099	.113	.135	-.209	.319
Nov	.131	.098	.139	.002	.085	-.112	.023	-.025	-.002	-.166	.278
Dec	-.138	-.121	-.100	-.022	-.011	.054	-.012	-.089	-.062	-.203	.260
Annual	.187	-.044	.140	**.259***	**-.341****	-.088	**-.294***	-.151	**-.253***	-.103	.070
pJan	-.066	-.077	.002	-.205	**.292***	-.106	.180	-.025	.166	.157	-.181
pFeb	.149	.125	.159	-.130	.072	-.084	-.043	.027	.049	.195	-.117

Table 1. (Continued)

Period	Correlation Coefficient (r)										
	Rainfall (mm)			Relative humidity (%)	Temperature (Celsius)					EQ SOI	EQ SST
	Total	Max.	Rainy days		Extreme max.	Extreme min.	Mean max.	Mean min.	Mean		
pMar	.117	.139	.197	.015	-.089	-.057	-.176	-.060	-.109	.164	-.081
pApr	.022	.048	-.161	-.080	-.067	-.017	-.003	-.094	-.046	.153	-.159
pMay	.191	.227	-.055	.107	-.084	-.030	-.170	-.194	-.166	.142	-.212
pJun	-.149	-.070	**-.274***	-.092	.040	-.141	.003	**-.260***	-.070	.178	-.212
pJul	.066	.086	-.054	.076	-.117	-.152	-.093	-.195	-.122	**.259***	-.298
pAug	.099	**.268***	-.034	.042	-.076	-.031	-.117	-.102	-.097	.183	**-.358***
pSep	.095	.042	-.119	.052	.000	**-.348****	-.206	**-.276***	**-.258***	.202	**-.363***
pOct	-.155	-.106	-.134	.097	**-.295***	-.059	-.226	-.150	-.165	.223	**-.348***
pNov	.014	.056	.022	-.038	.024	-.087	.010	-.029	.031	.173	**-.357***
pDec	.105	.116	.056	-.015	-.013	-.118	-.064	-.044	-.012	.118	-.323
pAnnual	.100	.025	-.150	-.037	-.011	-.205	-.121	-.162	-.091	.234	-.338
May-Oct	.045	-.087	.014	.194	**-.303***	-.081	-.196	-.241	-.232	-.176	.208
Mar-Apr	**.371****	**.276***	**.258***	**.361****	**-.262***	-.069	**-.379****	-.204	**-.355****	.011	-.186
May-Jun	.029	-.041	-.025	.165	**-.265***	-.210	-.169	-.229	-.191	-.125	.053
Jul-Sep	.030	-.136	-.026	.211	**-.275***	-.162	-.232	**-.299***	**-.330****	-.180	.243
Oct	.014	-.117	.128	.022	-.014	.163	.099	.113	.135	-.209	.319
Nov-Feb	.017	.071	-.011	-.021	-.026	-.003	.012	-.013	.024	-.182	.279
pMay-pOct	.075	.050	-.206	.069	-.079	-.208	-.156	**-.284***	-.194	.215	-.333
pMar-pApr	.075	.067	-.034	-.046	-.085	-.043	-.087	-.091	-.088	.174	-.120
pMay-pJun	.035	.091	-.214	.040	-.011	-.094	-.105	**-.255***	-.151	.166	-.216
pJul-pSep	.139	.096	-.105	.067	-.091	**-.266***	-.154	-.228	-.185	.223	**-.354***
pOct	-.155	-.106	-.134	.097	**-.295***	-.059	-.226	-.150	-.165	.223	**-.348***
pNov-pFeb	.185	.159	.206	.104	-.187	-.107	-.159	.039	-.015	.154	-.341

Note: * and ** indicate significant correlation at $p < 0.05$ and $p < 0.01$ respectively. The 'p' before individual month or month interval in Period column indicates time interval of the 'previous' year.

The mean monthly, seasonal and annual maximum temperatures also have a significant effect on the annual growth. The mean maximum temperatures in March and April of the present year as well as the annual and summer season mean maximum temperatures are significantly related to the annual growth index. The mean minimum temperatures in April, July and August of the present year and those in June and September of the previous year significantly affect the growth. Significant correlations between pine growth and mean minimum temperatures in the late rainy season of the present year and early rainy season and throughout the year of the previous year are also observed (Table 1). The mean temperature in April of the present year has a high correlation with pine growth and the mean temperatures in July, August and September of the present year and September of the previous year are also significantly related to the growth. Also, as seen in Table1, the annual mean temperature of the present year significantly correlates with the annual ring width index and the summer and mid rainy season variations in mean temperature during the present year also illustrate a high correlation with the annual growth.

The local climate, as measured in terms of rainfall and temperature in the dry period of March-April, is the main growth factor of the Khasi pines growing in the northern part of Thailand, similar to the growth of Khasi pines in Meghalaya, India, which was reported to have a significant relation with the variations in temperature and rainfall during the dry period of March [28].

Pumijumnong and Eckstein [3] reported a significant relationship of temperature and rainfall to the Khasi and Merkus pine growth in the north of Thailand, illustrating the importance of the pre-monsoon (Mar-May) climate on tree growth. Not only does the pre-monsoon climate induce the annual growth increment, but the post-monsoon temperature in October is also a decisive factor for the growth of Merkus pine in central Thailand [30].

The regional climate data as measured by EQ_SOI and EQ_SST are found to have effects on the annual ring index (Table 1). The EQ_SOI in July of the previous year and the EQ_SST in February of the present year as well as August, September, October and November of the previous year significantly affect the growth. The average EQ_SST during the mid and late rainy seasons of the previous year could significantly explain the variations observed in the Khasi pine growth (Table 1). The growth of Merkus pine in the easternmost part of Thailand also significantly and positively correlates with January-April SOI and July-December SST [31]. Buckley et al. [6] found significant correlations of annual ring width, earlywood and latewood indices of Merkus pine with gridded SST over the central and eastern tropical Pacific. It was suggested that the mountain pine species in both Thailand and other countries in Southeast Asia could be used to study the climate response both at local and regional scales and also the teleconnections.

Climate Reconstruction and Prediction

The highest values of correlation indicate a significant correspondence between the pine growth index and the mean temperature in April (-0.423) and total rainfall in the hot season (0.371). Thus, these patterns of climate-growth response were used to reconstruct the mean temperature in April ($\mathrm{Tmean}_{\mathrm{April}}$) and the total rainfall in the hot season ($\mathrm{Rain}_{\mathrm{hot}}$) projected back up to the year 1898. By using the regression analysis, current $\mathrm{Tmean}_{\mathrm{April}}$ during 1981-2015 can be used to generate a mathematic equation to explain the variation in annual ring width index as shown in Eq. (1), and the annual ring index (Index) value of each year can be used to estimate $\mathrm{Tmean}_{\mathrm{April}}$ as mathematically shown in Eq. (2):

$$\mathrm{Index} = 2.5039 - 0.05(\mathrm{Tmean}_{\mathrm{April}}) \tag{1}$$

$$\mathrm{Tmean}_{\mathrm{April}} = 33.908 - 3.6174(\mathrm{Index}) \tag{2}$$

The mean temperature in April, reconstructed during 1981-2015 and 1955-1980, was compared with the recorded data to verify the reliability of the climate model using the Pearson correlation, sign product test, reduction of error and T-test (Table 2). The reconstructed and recorded $\mathrm{Tmean}_{\mathrm{April}}$ are shown in Figures 3a and 3b. Similar to the reconstructed temperature, by using the regression analysis, $\mathrm{Rain}_{\mathrm{hot}}$ during 1951-1964 also significantly affects the annual ring width index as mathematically shown in Eq. (3), and $\mathrm{Rain}_{\mathrm{hot}}$ values can be reconstructed using the annual ring width index (Index) as mathematically described in Eq. (4):

$$\mathrm{Index} = 0.9064 - 0.002(\mathrm{Rain}_{\mathrm{hot}}) \tag{3}$$

$$\mathrm{Rain}_{\mathrm{hot}} = 145.99(\mathrm{Index}) - 85.814 \tag{4}$$

The total rainfall in the hot season (Mar-Apr), reconstructed during AD 1951-1964 and AD 1965-2015, was compared with the recorded data to verify the reliability of the model (Table 3). The reconstructed and recorded $\mathrm{Rain}_{\mathrm{hot}}$ are shown in Figures 3c and 3d. The linear trend line of the reconstructed total rainfall in the hot season gradually declined from 68.1 mm in AD 1898 to 54.1 mm in AD 2015 and is predicted to be around 48.1 mm during 2065, while the mean temperature in

April slightly increased from 30.10 °C in AD 1898 to 30.45 °C in AD 2015 and is projected to reach 30.60 °C in AD 2065.

Table 2. Statistics used to quantify reliability of reconstructed mean temperature in April

Statistic	Calibration	Verification
Pearson correlation	0.42* >= 0.28	0.45* >= 0.33
Sign product test	13 <= 12	11 <= 8
Reduction of error	0.18* >= 0.08	0.17* >= 0.11
T-test	1.74* >= 1.70	2.55* >= 1.71
Degree of freedom	33	24

* significant correlation at $p < 0.05$

Table 3. Statistics used to quantify reliability of reconstructed total rainfall in March-April

Statistic	Calibration	Verification
Pearson correlation	0.54* >= 0.46	0.37* >= 0.23
Sign product test	5 <= 3	19* <= 19
Reduction of error	0.29* >= 0.21	0.08* >= 0.05
T-test	2.03* >= 1.78	1.81* >= 1.68
Degree of freedom	12	49

* significant correlation at $p < 0.05$

Fluctuations in the reconstructed rainfall in March-April (Rain_{hot}) and the mean temperature in April ($\text{Tmean}_{\text{April}}$) support a global warming scenario occurring worldwide and are similar to the annual climate trends derived from meteorological stations [32]. This change will affect the distribution of tropical pine stands in Southeast Asia if the annual temperature rises up to 36 °C. The increasing temperature will severely limit the growth of pine and will kill adult trees [33]. By using the reconstructed climate data from living and subfossil pines (*P. sylvestris*), Esper et al. [34] found a long-term cooling trend of -0.31 °C per 1,000 years from 138 BC - AD 1900, followed by a rapid increase during the twentieth-century. The fluctuations in temperature during the last century, reconstructed from *P. sylvestris* in northern Scandinavia [34] and *P. kesiya* in northern Thailand in this research, demonstrate similar rising trends of about 0.5 °C.

Causation of False Ring Formation

Remarkably, false rings derived from the unusual cross-matching were found in several years along the sample core from the bark to the pith (Figure 4). The highest frequency of false rings occurred in 26 sample cores growing in the year AD 1960. False ring frequency (Fn) was then transformed to stabilised intra-annual density fluctuations (stabilised IADFs). A regression analysis was done between the stabilised IADFs and climate data. It was found that the causation of false ring formation could be explained by fluctuations in rainy days (r^2 = 21.1%, $p < 0.05$), relative humidity (r^2 = 31.8%, $p < 0.05$), extreme maximum temperature (r^2 = 38.4%, $p < 0.05$), extreme minimum temperature (r^2 = 19.6%, $p < 0.05$), mean maximum temperature (r^2 = 48.1%, $p < 0.05$), mean minimum temperature (r^2 = 13.0%, $p < 0.05$), mean temperature (r^2 = 25.0%, $p < 0.05$) and

EQ_SST (r^2 = 44.6%, $p < 0.05$). The highest significant relationship between false ring occurrences and mean maximum temperature is described mathematically in Eq. (5):

$$f = 437.772 + 10.206(Tmax_{Jan}) - 9.054(Tmax_{Feb}) - 7.624(Tmax_{Aug}) - 5.349(Tmax_{Sep}) \qquad (5)$$

where f is stabilised IADFs.

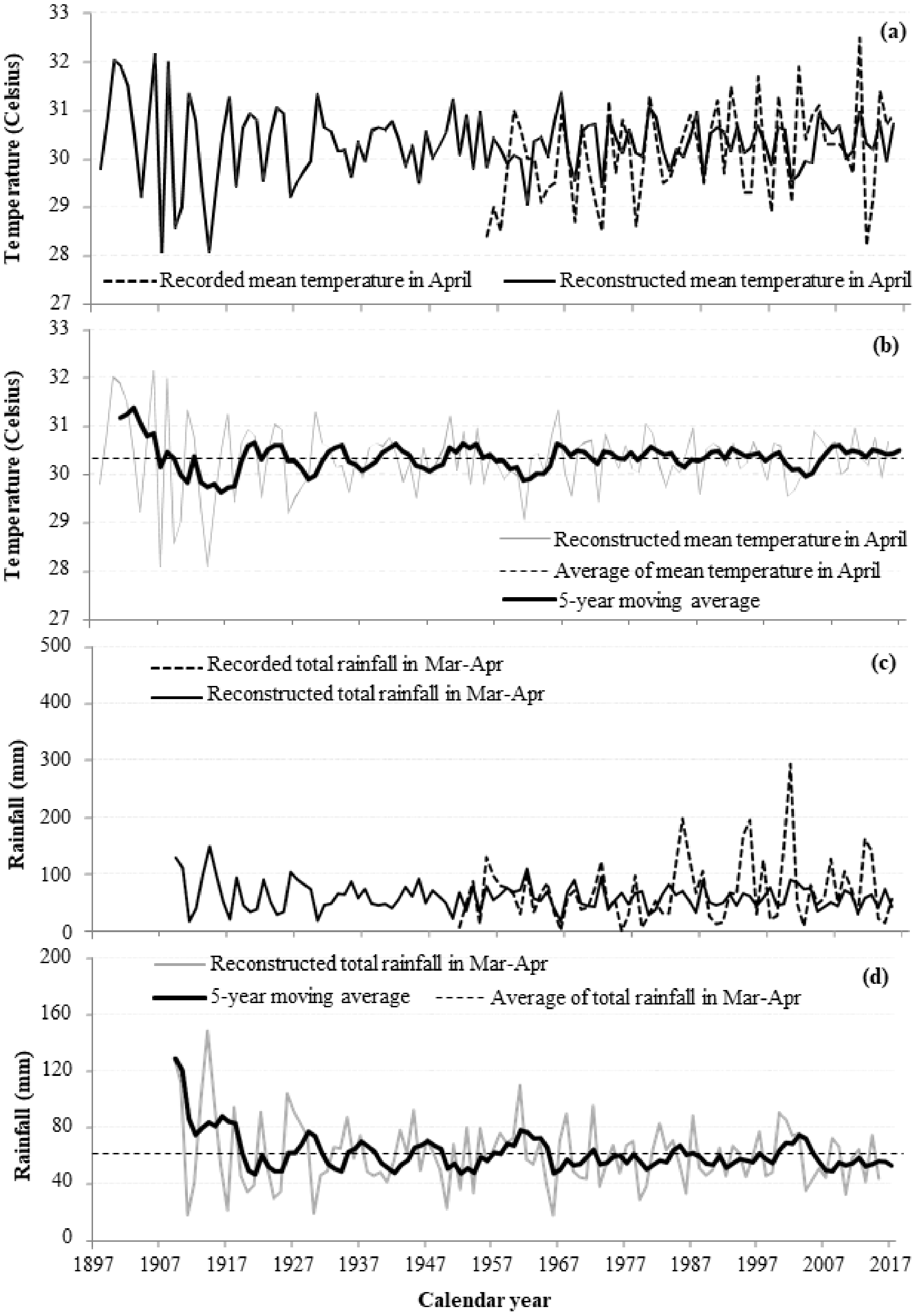

Figure 3. Reconstructed and recorded climate data of mean temperature in April (a-b) and total rainfall in March-April (c-d)

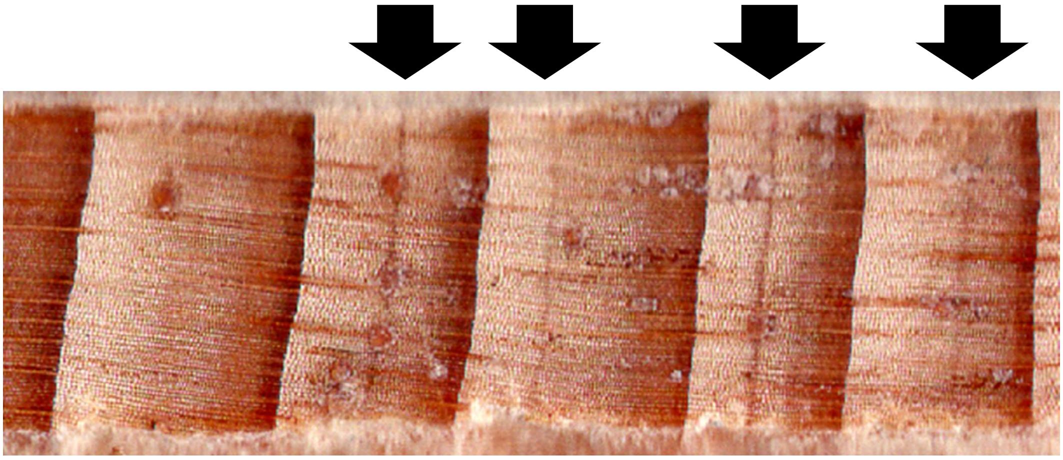

Figure 4. Occurrences of annual rings and false rings in *P. kesiya*. Black arrows indicate false rings.

The occurrence of false rings in Khasi pines growing at Ban Wat Chan, northern Thailand, can be explained by several climatic factors, but the mean maximum temperature has the highest significant relationship and can explain 48.1% of variance observed in the formation of false rings. It is possible that the anomalous temperature fluctuations induced a water stress condition and reduced the photosynthesis and cambial activity, leading to the formation of false rings [12, 35, 36]. IADFs in both the earlywood and latewood zones were also found in Khasi pines growing in north-east India. False rings in the earlywood zone were found to be associated with reduced precipitation during the growing season in April-July, while wetter conditions in the late growing season, especially August/September, triggered the formation of IADFs in the latewood zone [37].

Vieira et al. [38] related occurrence of intra-annual rings in *Pinus pinaster* to water stress, and false ring frequency was negatively correlated with precipitation in the mid rainy season and positively correlated with precipitation during the transition period from summer to wet season. Bogino and Bravo [39] reported a high frequency of false rings in younger trees and narrow annual rings. Increase in rainfall during the dry period of August and higher temperature at the beginning of rainy season in January-April induced the formation of false rings in the latewood and earlywood zones of *P. halepensis* respectively [15]. Additionally, the false ring formation in *P. halepensis* was particularly related to high minimum temperatures and wet conditions during the late summer and autumn [40]. Not only does the annual ring-width index help in the study of climate-growth response and the reconstruction of past climate, but the indices and the associated anomalies such as anatomical characteristics of false rings and their frequency also provide a valuable proxy of the past climate.

CONCLUSIONS

The variations in annual and intra-annual ring widths of Khasi pine growing naturally in northern Thailand during a 118-year growing period between AD 1898-2015 reflect a changing climate at both the local and regional scales. The local climate as measured by the mean temperature in April and total rainfall during the months of March-April contributes significantly to the increment in annual ring width, as does the regional climate indicated by the EQ_SST in August-November of the previous year. Past climate reconstruction and projection indicates an increase in temperature and reduction in rainfall during the 20th century. The major cause of false ring formation can be explained in terms of the variation in mean maximum temperature during the growing season.

ACKNOWLEDGEMENTS

This research was funded by the Thailand Research Fund (Grant No. MRG5980167). We thank the Laboratory of Tropical Dendrochronology at the Faculty of Forestry, Kasetsart University for the instruments used in sample collection, preparation and measurement. We also thank the Forest Industry Organisation for granting permission to collect the pine samples.

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