Climate control on ring width and intra-annual density fluctuations in Pinus kesiya growing in a sub-tropical forest of Manipur, Northeast India

Article *in* Trees · October 2016

DOI: 10.1007/s00468-016-1402-9

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ORIGINAL ARTICLE

Climate control on ring width and intra-annual density fluctuations in *Pinus kesiya* growing in a sub-tropical forest of Manipur, Northeast India

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Received: 27 November 2015 / Accepted: 15 April 2016

Abstract

Key message **Growth ring study of *Pinus kesiya* (khasi pine) growing in sub-tropical forest in Manipur, northeast India was performed to understand climate signatures in ring widths and intra-annual density fluctuations.**

Abstract The growth rings in khasi pine (*Pinus kesiya* Royle ex Gordon) growing in sub-tropical Reserve Forest in Imphal, Manipur, northeast India were analysed to understand environmental signals present in ring-width series and intra-annual density fluctuations (IADFs). For this the growth ring sequences in increment core samples collected from 28 trees were precisely dated and a ring-width chronology spanning AD 1958–2014 developed. The correlation analyses between ring-width chronology and weather data of Imphal revealed that a cool April–May–June favour tree growth. The wood anatomical features of growth rings revealed the occurrence of IADFs in early- and latewoods. The IADFs in earlywood were found to be associated with reduced precipitation in months from April to July. However, the wetter conditions in late growing season, especially August/September triggered the formation of IADFs in latewood. Our findings endorse that the IADF chronologies of khasi pine could emerge as an important proxy of summer monsoon rainfall in long-term perspective in data scarce region of northeast India.

Keywords *Pinus kesiya* · Khasi pine · Ring-width · Intra-annual density fluctuations · Hydrological stress · Manipur · Northeast India

Introduction

The socio-economy of northeast India, a high-rainfall and biodiversity hotspot region, due to its predominant rainfed agriculture system is vulnerable to climate change. In view of this an understanding of regional climate change pattern is required for appropriate planning of agriculture and other socio-economic activities. However, temporally limited and spatially patchy weather records available from northeast India hinder climate science communities' efforts to understand the climate change pattern in long-term perspective. Thus far, high-resolution tree-ring proxy records from northeast India are very limited (Chaudhary et al. 1999; Chaudhary and Bhattacharyya 2000; Bhattacharyya and Chaudhary 2003; Shah et al. 2014; Shekhar and Bhattacharyya 2015; Yadava et al. 2015). Annually resolved tree-ring chronologies of *Abies densa* (Chaudhary et al. 1999; Bhattacharyya and Chaudhary 2003; Shekhar and Bhattacharyya 2015) and *Larix griffithiana* (Chaudhary et al. 1999; Chaudhary and Bhattacharyya 2000; Shah et al. 2014; Yadava et al. 2015), hitherto have been developed only from Sikkim, northeast India for climatic studies. The ring-width chronology of *Pinus merkusii* from northeast India has revealed significant

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Communicated by A. Bräuning and L. Eryuan.

Article Collection: Tree Rings.

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correlations with SSTs over the Indian and Pacific Ocean during March–April–May (Buckley et al. 2005). However, the ring-width chronologies of khasi pine developed from Shillong, northeast India did not show any climatic signal (Chaudhary and Bhattacharyya 2002; Shah and Bhattacharyya 2012), which they suggested to be largely due to high-degree of anthropogenic disturbances affecting tree growth.

The tree ring studies in India, barring a few on wood density (Hughes and Davies 1987; Hughes 1992, 2001; Borgaonkar et al. 2001) and stable isotopes (Ramesh et al. 1985, 1986; Managave et al. 2011), are largely restricted to the application of ring-width chronologies (Yadav et al. 2015; Yadava et al. 2016 and references therein) in climatic reconstructions. However, the potential to understand variations in climate during the growing season of trees using the intra-annual density fluctuations (IADFs) in annual rings has not yet been explored. In literature the IADFs are referred as false rings (Schulman 1938), multiple rings (Kozlowski 1971) or intra-annual growth bands (Fritts 1976) and these are produced in growth rings in response to short-term climatic changes during the growing season. Usually the wood cells formed in early growing season are large, thin walled (earlywood) and in late growing season small, thick walled (latewood). However, deviations from such features occur largely due to changes in growing conditions; with the formation of latewood like cells in earlywood part and conversely larger and thinner walled in latewood part due to alteration in climatic conditions becoming unfavourable (favourable) during early (late) growing seasons, respectively. The IADFs in trees growing in different geographic regions have been investigated by various authors to understand climatic information on intra-annual resolution (Priya and Bhat 1998; Bräuning 1999; Campelo et al. 2007, 2013, 2015; Cherubini et al. 2003; Copenheaver et al. 2006, 2010; De Luis et al. 2007, 2011; De Micco et al. 2007, 2014; Edmondson 2010; Gonda-King et al. 2012; Masiokas and Villalba 2004; Nabais et al. 2014; Novak et al. 2013; Olano et al. 2015; Olivar et al. 2012; Palakit et al. 2012; Ren et al. 2015; Rozas et al. 2011; Speer et al. 2004; Vieira et al. 2009; Wimmer et al. 2000). However, such studies are largely restricted to the high latitude temperate and Mediterranean regions and focus has not been given yet to monsoon regions where growing season is considerably longer. In present study we aimed to investigate the dendroclimatic potential of khasi pine growing in Imphal, Manipur, northeast India using ring width and IADF parameters. This study makes the first attempt to explore the potential of IADFs in understanding intra-seasonal climate phenomena and their role in wood formation.

Materials and methods

Cambium activity and growth rings in khasi pine

The studies on khasi pine growing in tropical montane forests in northern Thailand (17°58′N and 98°22′E; Pumijumnong and Wanyaphet 2006) and sub-tropical forests in northeast India (25°34′N and 91°53′E; Singh and Venugopal 2011) have revealed distinct seasonality in cambium activity, and this has been largely associated with the availability of soil moisture. The khasi pine in northeast India shows usually three flushes of growth producing three whorls of branches in a year and the xylem production occurs over a long growing season from mid March until the last week of November and remains dormant from December to February (Singh and Venugopal 2011). In northern Thailand, the cambium in khasi pine is active in wet season (May to October) and dormant in dry season (November to April) (Pumijumnong and Wanyaphet 2006). Such an annual rhythm of wood formation in khasi pine results in the formation of anatomically distinct growth rings, which are dateable to calendar year of their formation (Chowdhury 1964).

Study area and tree ring data

The khasi pine is a large evergreen tree growing in subtropical forests in Khasi and Naga Hills, Assam, Manipur, Upper Myanmar, Philippines and northern Thailand usually at elevations ranging from 1200 to 1400 m (Sahni 1990; Pumijumnong and Wanyaphet 2006). To understand the effect of climate on khasi pine, we selected Khonghampat reserve forest located at a distance of ~17 km from Imphal Air Port, Manipur (24°53′01.1″N and 93°54′41.9″E) in northeast India (Fig. 1) where anthropogenic pressure is negligible. The khasi pine trees in the study area were occasionally found growing in association with broad leaf taxa, viz., *Lithocarpus fenestrate*, *Quercus serrata*, *Schima wallichii* and *Eugenia precox*. As the forest stand from where the trees were sampled is a reserve forest, the management practises like fertiliser application and irrigation are not applied. The khasi pine trees were found growing on gentle slope with mature sandy soil rich in organic matter. The colour of the soil was reddish to reddish brown owing to the presence of ferric compounds and pH being weakly acidic (pH 5.6). The senior author (DS) collected increment core samples from healthy khasi pine trees in April, 2015 using a 4 mm diameter Haglof increment borer. The trees free of any visible sign of injury were cored in opposite directions of the stem at breast height (~1.4 m). For present study 53 increment core samples collected from 28 trees were used.

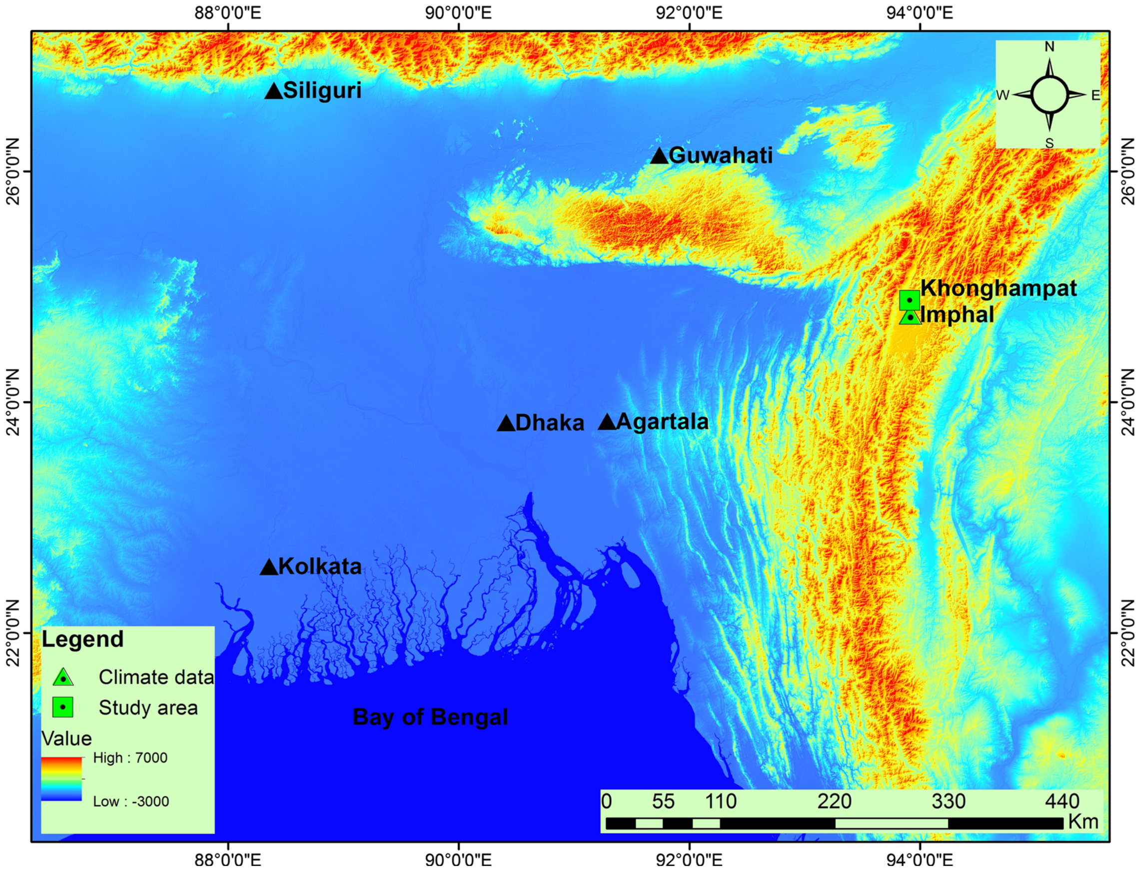


Fig. 1 Map showing the location of tree-ring sampling site and meteorological station used in this study

The cross surface of increment core samples affixed on wooden frames was polished with different grades of abrasives until the cellular details became clearly discernible under the stereo zoom binocular microscope. The growth ring sequences in core samples from different trees were crossdated using standard dendrochronological techniques (Fritts 1976). This involved skeleton plotting (Stokes and Smiley 1968) and synchronic presence of signature rings (Schweingruber 1996). The ring widths in precisely dated increment core samples were measured with the resolution of 0.01 mm using linear encoder LINTAB coupled with computer (Rinn 2003). The ring-width measurements were again used in crosschecking the dating quality using software COFECHA (Holmes 1983) that uses cross-correlation of individual measurement series with mean series that is created from all the series used in the analysis. Very good coherence in growth pattern of trees as revealed in COFECHA analyses (Holmes 1983) (mean $r = 0.56$) and year-to-year similarity in ring-width plots endorses common climate forcing affecting growth of trees over the site. The ring-width measurements of samples showing weak correlation with the master series were rechecked and possible errors, if any, corrected. The programme ARSTAN (Cook 1985) was used to develop tree-ring-width chronology using measurements from 53 increment core samples from 28 trees. As the ring-width measurement series are short ($\sim$60 years) we used a detrending procedure to maximise year-to-year variations in the chronology. For this, we detrended the ring-width measurement series using 10 year cubic spline with a 50 % frequency response function cut-off (Cook and Peters 1981). The ring-width measurement series were power transformed to stabilise variance in the heteroscedastic tree-ring-width measurement series prior to detrending (Cook and Peters 1997). The growth trends were removed from the power transformed ring-width measurement series by subtraction, which minimises the end fitting-type bias as compared to the ratios. To reduce the influence of outliers, the detrended ring-width measurement series of respective trees were averaged to a mean chronology (standard) by computing the biweight robust mean (Cook 1985). Another set of chronologies was prepared where low-order autocorrelation from detrended series was removed using autoregressive moving average (ARMA) modelling and the resulting residual series averaged to a mean site

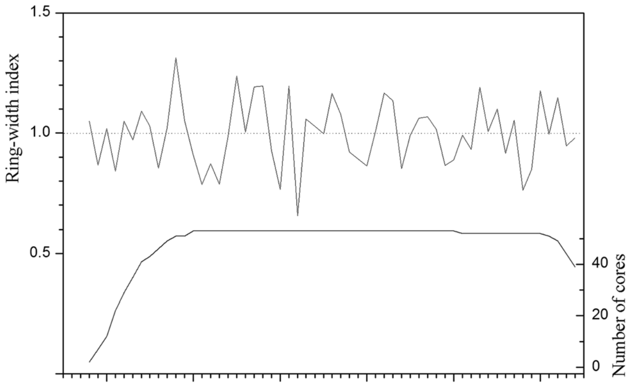


Fig. 2 Ring-width chronology (residual) of *Pinus kesiya* prepared from Manipur (AD 1958–2014) with the number of cores used in the development of chronology

chronology (AD 1958–2014; Fig. 2) by computing the biweight robust mean (Cook 1985). The expressed population signal (eps), a measure of population signal in the mean residual chronology (Wigley et al. 1984), was ≥0.93 back to AD 1968 with the replication of 40 tree samples before which it declined with the decrease in number of samples.

Intra-annual density fluctuations (IADFs)

The correctly dated growth ring sequences in cores were examined for IADFs under stereo zoom binocular microscope with the magnification up to 50×. The IADFs appear as a narrow band of thick-walled tracheids (latewood like) in earlywood part (Fig. 3), which is surrounded on both sides by thinner-walled, larger diameter tracheids (earlywood). Conversely, the IADFs in latewood part are thin walled tracheids (earlywood like) surrounded on both sides by thicker-walled, smaller diameter latewood tracheids. As the formation of IADFs is driven by changes in climate during the growing season, their precisely dated occurrences should serve as a strong proxy of the environmental variables on resolution of intra-seasonal level. In present study IADFs were recorded in trees when both the cores had IADF in an annual ring in case of two cores from a tree; however, in case of only one core from a tree the IADFs in respective rings were taken into account, taking the single core representing one tree. The percentage (F) occurrence of IADFs in growth rings of samples for respective years was calculated for early and latewood part of the growth ring sequences with precisely dated increment core samples as ratios:

$$F = 100 * n/N$$

where n is the number of trees that formed IADF in a given year in early/latewood and N is the total number of trees in that particular year.

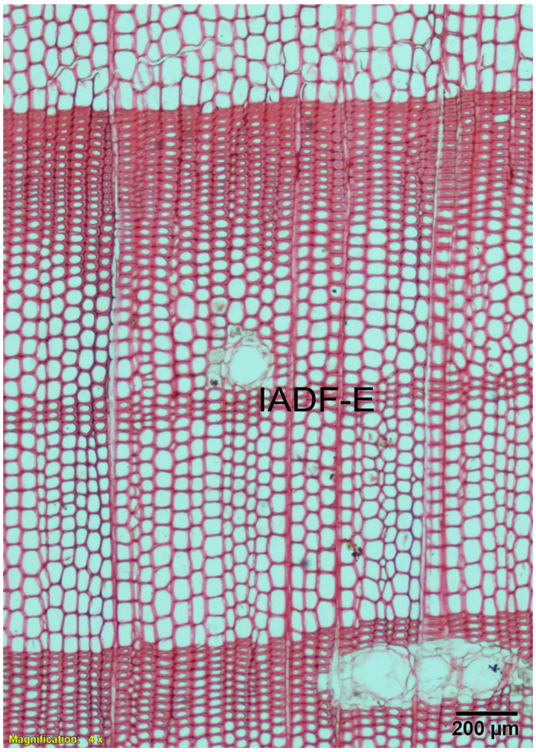


Fig. 3 Cross section of *Pinus kesiya* wood showing intra-annual density fluctuation in earlywood (IADF-E)

Climate data

The weather records for the northeast Indian region are spatially very patchy and not continuous. However, for present study, the weather data of monthly precipitation and mean temperature of Imphal Airport Meteorological station (24.76°N and 93.90°E, 774 m asl), very close to tree-ring sampling site and spanning 1955–2012 were available with us. The box and whisker plot of the climate data show that May to September is very humid with over 2/3rd of the annual precipitation ($\sim$1400 mm) occurring during this period (Fig. 4a). June is the wettest month with total precipitation reaching over 256 mm. The temperature records show September being the hottest (24.7 °C) and January the coolest (12.8 °C) (Fig. 4b). To understand the homogeneity in data and impact of aircraft flying on local climate, if any, we compared temperature records of Imphal with that of Guwahati (26.10°N, 91.58°E, 167 m asl; aerial distance 269 km). For this the monthly mean temperature data of two stations for the common period (1955–2012) were used in the analyses. The annual mean temperature data of the two stations closely followed each other with significant correlation ($r = 0.51$, 1955-2012, two tailed $p < 0.0001$) and showed significant increasing trends (Fig. 5). However, the increasing trend in annual temperature of Imphal was observed to be higher (3 °C/100 years) compared to that of Guwahati (1.16 °C/

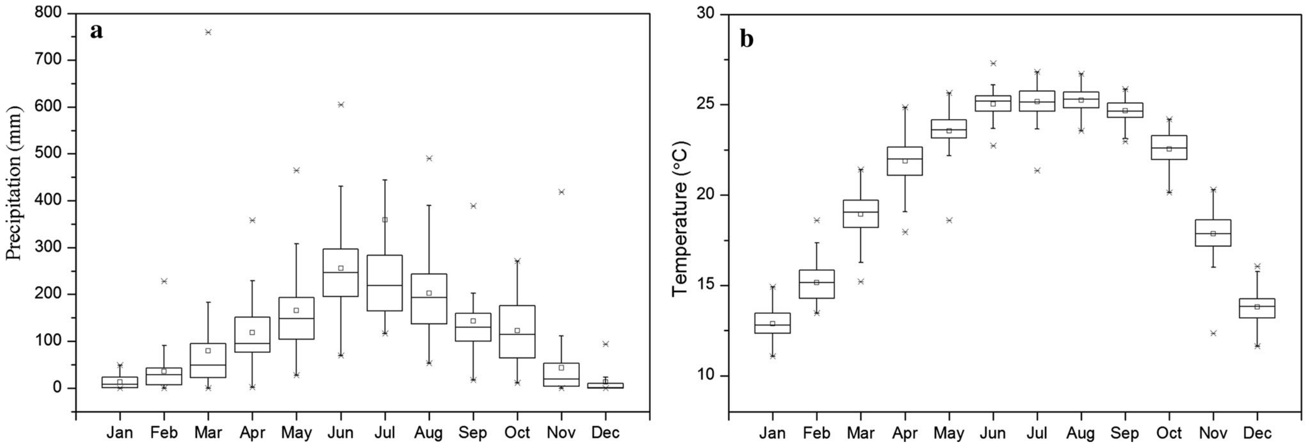
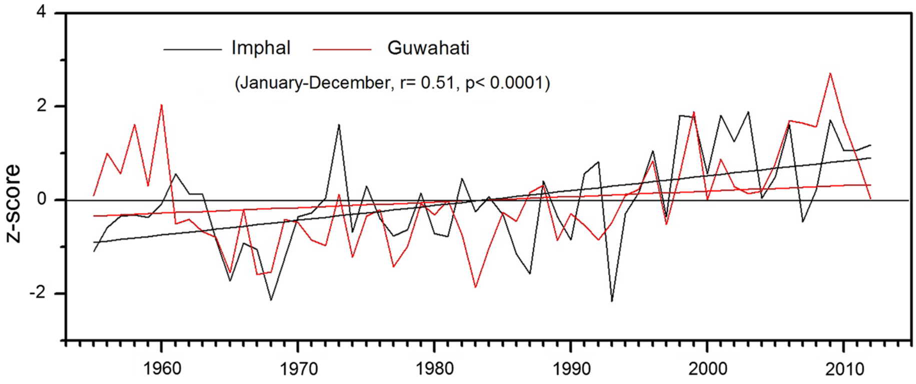


Fig. 4 *Box* and whisker plots showing monthly variations in precipitation (**a**) and mean temperature (**b**) of Imphal, Manipur, northeast India

Fig. 5 Annual temperature (z-scores) series of Manipur and Guwahati (AD 1955–2012) with respective *trend lines*



100 years). The increasing trend in temperature of Guwahati is subdued due to high temperature values in the beginning of series, i.e., 1955–1960. Earlier studies on temperature trend in Manipur have also shown significant increasing trend in annual mean temperature (rise of 3 °C during 1951–2010) (Rathore et al. 2013). We observed that the mean temperature of April–May–June of Imphal and Guwahati closely followed each other with correlations still higher ($r = 0.62$, 1955–2012, two tailed $p < 0.0001$) than the annual mean temperature. The close relationship in temperature records of two stations indicates that the region around the study area is showing a general increase in temperature.

Climate signal in ring-width chronology

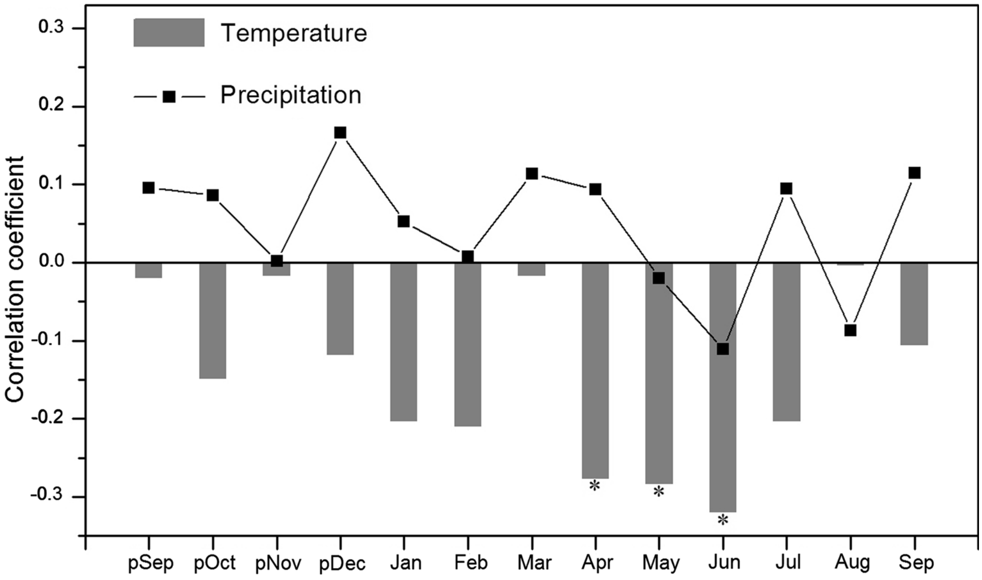
The residual version of ring-width chronology (Fig. 2, AD 1958–2014) was used in Pearson correlation analyses with monthly climate variables (monthly total precipitation and monthly mean temperature data of Imphal) from September of the previous year to September of the current year. For this, we performed bootstrapped correlation analyses using software DENDROCLIM2002 (Biondi and Waikul 2004) for the chronology period 1968–2012 for which sufficient sample replications were available in the ring-width chronology (Fig. 6). As autocorrelation was removed from the chronology by detrending and autoregressive modelling, the correlations were calculated without the prior year's indices.

Results and discussion

Growth-climate relationship revealed in ring-width chronology

Tree growth and climate relationship study using residual version of ring-width chronology revealed that the radial growth of khasi pine has significant negative correlation with the monthly mean temperature of Imphal, especially April–May–June (Fig. 6). The seasonalized mean temperature of April–May–June showed significant negative correlation with the ring-width chronology ($r = -0.38$, 1968–2012, two tailed $p = 0.01$) (Fig. 7). However, in case of precipitation no significant relationship between tree-ring indices and monthly precipitation of Imphal was

Fig. 6 Correlation analyses between ring-width chronology and monthly climate variables (monthly mean temperature and precipitation) of Manipur. The correlations were calculated for the common period AD 1968–2012. *Represents correlation values significant at 95 % confidence level



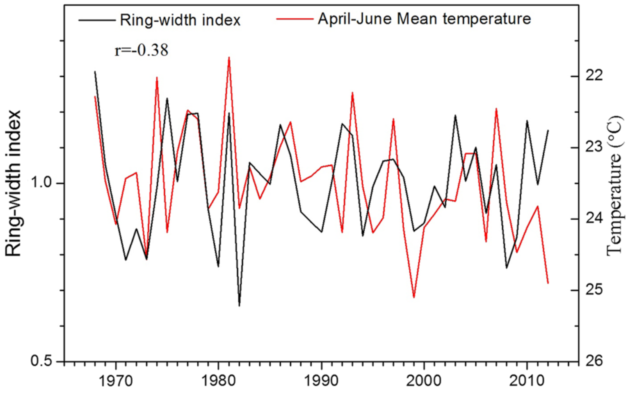


Fig. 7 Ring-width chronology and seasonalized April–May–June mean temperature *plotted* together to show the relationship. The temperature data are plotted in reverse *scale* for ease in comparison. The two series showed Pearson correlation −0.38 (two tailed p value 0.01, 1968–2012)

noted. The negative relationship between ring-width chronology and April–May–June mean temperature could be associated with the enhanced evapotranspirational losses causing soil moisture stress on tree growth. In concurrence with our findings, the khasi pine ring-width chronologies from north and northwest Thailand also have shown strong temperature signal of March–April–May (Pumijumnong and Eckstein 2011). Our findings are quite encouraging and reject the earlier notion on unsuitability of khasi pine in dendroclimatic studies in northeast India (Chaudhary and Bhattacharyya 2002; Shah and Bhattacharyya 2012). With our results we are quite optimistic that the network of ring-width chronologies of khasi pine developed from undisturbed sites could be successfully utilised to develop late spring and early summer mean temperature records for the data scarce region of northeast India. In line of this we are attempting to prepare longer and network of tree-ring chronologies of khasi pine from various sites in northern Manipur bordering Myanmar.

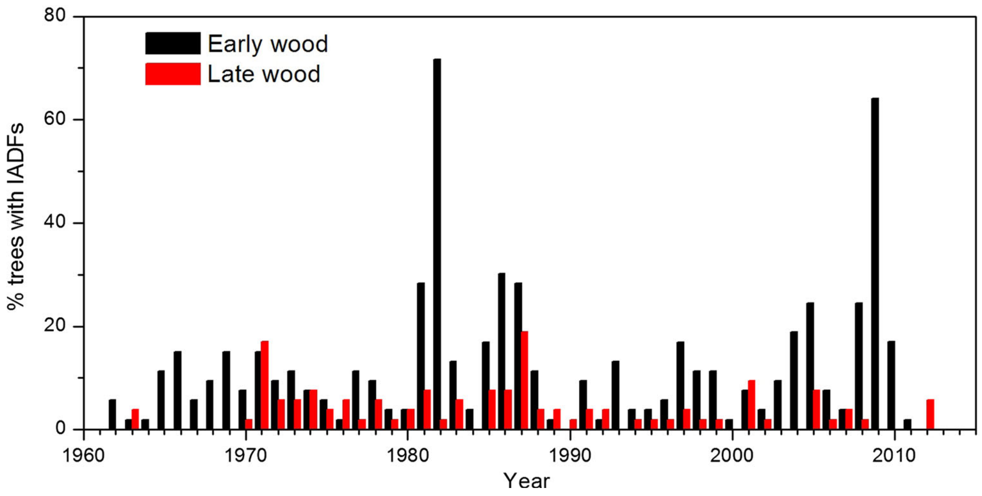
Climatic implications of IADFs

The differences in morphological features of xylem cells such as wall thickness and lumen size of tracheids are dependent on tree water status during the growing season (Larson 1994). We observed that the IADFs in khasi pine were found to be very common in early- as well late-wood (Fig. 8) indicating common variability in moisture conditions during the growing season. In several studies it has been shown that the propensity of IADFs in growth rings are associated with tree age, canopy class and also the size of rings (Bräuning 1999; Copenheaver et al. 2006; Bogino and Bravo 2009). However, in our samples most of the trees were nearly of similar age and growth rings wide, for this reason we could not address the effect of age and ring size on the occurrence of IADFs. To understand the triggering factors for IADFs, the weather data of years with predominant occurrence of IADFs were analysed. For this the z-scores of monthly precipitation and temperature data of vegetation period from April to September with respect to the mean and standard deviation of 1968–2012 (Fig. 9) were used.

Climatic interpretation of IADFs in earlywood

The IADFs in earlywood (IADFe) are narrow lumen, thick walled tracheids formed due to deficient soil moisture

Fig. 8 Earlywood and latewood IADF chronologies of *Pinus kesiya* trees growing in reserve forest in Imphal, Manipur, northeast India



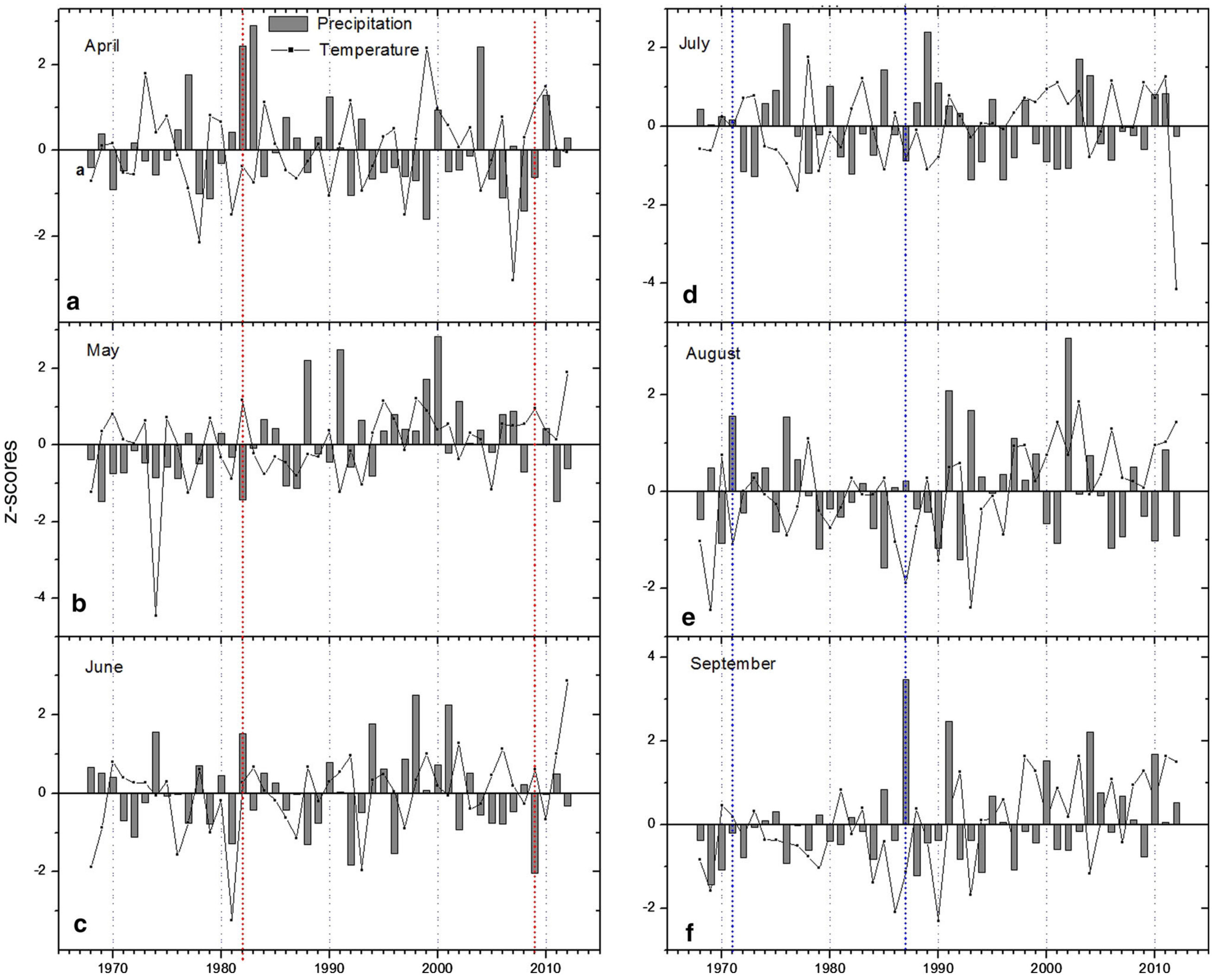


Fig. 9 Precipitation and temperature data of Imphal for the vegetation period from April to September. The data are z- scores relative to the mean and standard deviation of 1968–2012 data. The *red vertical dotted lines* are the years of intense formation of IADFs in earlywood and *blue dotted lines* in latewood (colour figure online)

availability during the early vegetation period. In our study we noted that the IADFs in earlywood were more frequent relative to that in latewood of khasi pine growing in subtropical forests of Imphal, Manipur. The IADF chronology revealed predominant occurrence of IADFe in growth rings of 1982 (72 % trees) and 2009 (64 % trees). The weather records of Imphal (Fig. 9) indicated that the precipitation in April and June 1982 were above the 1968–2012 mean but it failed in May. The early onset of rain showers in April replenishing the soil moisture could have triggered the fast growth of trees but failure of rains latter in May caused soil moisture deficit that slowed the growth of trees resulting in the formation of thicker walled and narrower lumen tracheids resembling latewood. The precipitation in May was very low amounting 31 mm only, which was 84 % deficient relative to 1968–2012 mean. The monthly mean temperature of May was also relatively higher (24.8 °C) than the average of 23.5 °C for 1968–2012. Similarly, the drought situation in 2009 was also very grim and summer monsoon precipitation nearly failed (Fig. 9). The earlywood tracheids could have formed in the beginning of the growing season for which previous years photosynthetic reserves play an important role. However, the failure of rains in whole of the summer monsoon season led to soil moisture deficit that caused the formation of thicker walled and narrower lumen tracheids. The precipitation in April (79 mm) and June (69 mm) were very low as compared to 1968–2012 mean of 135 mm for April and 238 mm for June, respectively. It is notable that the precipitation in May, 2009 (156 mm) was also lower than the 1968–2012 mean (184 mm). It is notable that whole of the northeast Indian region experienced drought in 2009 and the drought conditions were worst in Manipur, Nagaland and Meghalaya (Das et al. 2009). The rainfall till July 20, 2009 was deficient by 67 % in Manipur, 63 % in Nagaland, 56 % in Meghalaya, and 34 % in Assam (Das et al. 2009). The studies on environmental implications of IADF in trees growing in summer monsoon influenced region, thus far, are very limited (Bräuning 1999). Similar to our findings the formation of IADFe in *Pinus densata* in summer monsoon influenced southern Tibet (Bräuning 1999) has also been attributed to drought conditions in early vegetation period, especially May, June and their frequency in a given year largely depends on the intensity of rainfall.

Climatic interpretation of IADFs in latewood

The IADFs in latewood (IADFl) are formed due to increase in radial expansion and decrease in wall thickening of tracheids largely due to increase in soil moisture later in the growing season (Uggla et al. 2001). Though, in khasi pine the IADFl was not found to be a predominant feature as compared to the IADFe, many of the growth rings showed IADF in early as well as latewoods (Fig. 8) indicating variability in climate during early and late growing seasons. To explore the triggering climatic factor for IADFl the climate records of years with predominant occurrences of IADFl were analysed. The khasi pine trees showing larger number of IADFl were noted in 1971 (17 % trees) and 1987 (19 % trees), however, nearly the equal number of trees also had IADFe in these years as well. The precipitation and temperature data plotted as z- scores relative to the mean and standard deviation of 1968–2012 showed reduced precipitation in April, May and June as well as July of 1971 (Fig. 9a–d). The monthly precipitation, i.e., 91 mm in April, 92 mm in May, 181 mm in June and 243 mm in July of 1971, were lower relative to the 1968-2012 mean of 120, 156, 254, and 370 mm, respectively. The precipitation in 1971 August was higher (341 mm) relative to the long-term average (203 mm) of 1968–2012 (Fig. 9e). Similarly, the IADFs in 1987 were recorded in earlywood (28 %) as well as latewood (19 %). The climate data revealed that the precipitation in May (57 mm) and July (157 mm) were much reduced as compared to the long-term average of 156 mm and 371 mm in respective months of 1987. The drought like situations in May and July due to reduced precipitation resulted in the formation of IADFe in large number of trees. However, during the later part of the vegetation period, especially September, the precipitation picked-up and was much higher (389 mm), nearly 2.7 fold higher than the long-term average of 143 mm (relative to 1968–2012) (Fig. 9f). The mean temperature during 1987 September was also lower (23.8 °C) as compared to the long-term average (24.7 °C). Higher supply of moisture and reduced evapotranspiration due to relatively lower temperature could have favoured the growth of trees and formation of larger diameter tracheids in latewood part of the growth ring in 1987. The precipitation patterns associated with the IADF occurrence in latewood indicate that higher precipitation in August/September is largely associated with IADFl in khasi pine growing in Manipur, northeast India.

Socioeconomic implications of IADF chronology

To evaluate the socio-economic implications of IADF chronology in khasi pine growing in Imphal, Manipur, northeast India we studied the fluctuations in agriculture production data though available only for short period of 2001–2013. The cropping pattern in Manipur is mainly paddy based, and performance of agriculture largely depends on timely occurrence of rainfall. Usually the paddy is sown in late April to May and harvested in August to September. The paddy production data of Manipur, though temporally very limited (2001–2013) showed that the paddy crop production was very low in 2009

(Anonymous 2013). The year 2009 is featured by the presence of IDAFe in large number of khasi pine trees in the study area. During this year the precipitation in April and June was extremely reduced as compared to the 1968–2012 average. The drought of 2009 was widespread in the entire northeast India and the entire region suffered ~25 % reduction in paddy production during 2009–2010 and ~24 lakh tonnes of additional food grain was imported to compensate the loss (Das et al. 2009). The weather was so dry that it left a significant number of farmlands in northeast India without any tilling activities even up to the first week of August (Das et al. 2009). This finding, though based on very short data length, raises the possibility of the utilisation of IADFe chronologies to understand variability in paddy production. But at this stage due to limited availability of crop production and tree-ring data we hold caveats on this finding. To underpin such a relationship in IADFe chronology and paddy production data series from a larger network of sites in northeast India should be very useful.

Conclusions

Tree-ring materials of khasi pine collected from a reserve forest in Imphal, Manipur, northeast India were studied to develop ring-width and IADF chronologies. The ring-width chronology (AD 1958–2014) was developed using 53 increment core samples collected from 28 trees. The ring-width chronology, which reflects the environmental signature for the year/season, revealed that warm late spring and early summer (April–May–June) negatively affected the growth of trees over the study site in Imphal, Manipur. However, IADFs, which reflect short-term anomalies in precipitation during the growing season, displayed interesting, but differing climatic signatures from that of the ring-width series. The IADFs were noted to be very common in early as well as latewood part of the growth rings indicating high intra-seasonal variability in climate. The study of monthly climate data of Imphal revealed that the intense formations of IADFs in earlywood of khasi pine are associated with dry early growing season (April–July). However, IADFs in latewood are formed due to increased precipitation in late growing season usually during August–September. The present analyses of ring-widths in combination with the IADFs in khasi pine from northeast India, carried out for the first time, has indicated immense potential in environmental studies. However, for more precise temporal delineation of early- and late-wood formation in khasi pine this study needs to be supplemented with the periodic cambium phenological studies using micro-cores and dendrometer measurements.

Author contributions statement DS collected the samples RRY, DS, NV, VS, AKY, KGM, TBS, and CS analysed the data RRY, DS, VS, AKY, and KGM wrote the paper

Acknowledgments VS, AKY and KGM thank Dr. Sunil Bajpai, Director, Birbal Sahni Institute of Palaeobotany, Lucknow for providing necessary facilities. Authors express their sincere gratitude to Prof. Achim Bräuning, University of Erlangen-Nuremberg for his critical comments and valuable suggestions on the manuscript. Authors also express their sincere thanks to two anonymous reviewers for their critical comments that helped in improvement of the text. The senior author (DS) expresses his sincere thanks to the Department of Science and Technology, Government of India, New Delhi for financial support under Fast Track Young Scientist programme (SB/YS/LS-29/2014).

Compliance with ethical standards

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

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