DENDROCLIMATIC ANALYSIS OF TEAK (*Tectona grandis* L. f.)

FROM CENTRAL INDIA

TO EVALUATE THE POTENTIAL FOR CLIMATE RECONSTRUCTION

by

REJI MARIYA JOY K.

(2011-20-122)

THESIS

Submitted in partial fulfilment of the

requirements for the degree of

B.Sc.-M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

Kerala Agricultural University

ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH

VELLANIKKARA, THRISSUR - 680 656

KERALA, INDIA,

2016

DECLARATION

I, hereby declare that this thesis entitled **"DENDROCLIMATIC ANALYSIS OF TEAK (*Tectona grandis* L. f.) FROM CENTRAL INDIA TO EVALUATE THE POTENTIAL FOR CLIMATE RECONSTRUCTION"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Vellanikkara,

Date : 13-03-2017

Reji Mariya Joy K.

(2011-20-122)

CERTIFICATE

Certified that this thesis entitled "**DENDROCLIMATIC ANALYSIS OF TEAK (*Tectona grandis* L. f.) FROM CENTRAL INDIA TO EVALUATE THE POTENTIAL FOR CLIMATE RECONSTRUCTION** " is a record of research work done independently by Ms. Reji Mariya Joy K. (2011-20-122) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Vellanikkara,

Date: 18-03-2017

Dr. E. V. Anoop
(Major Advisor, Advisory committee)
Professor and Head,
Dept. of Wood Science,
College of Forestry,
Vellanikkara.

CERTIFICATE

We, the undersigned members of the advisory committee of **Reji Mariya Joy. K. (2011-20-122)**, a candidate for the degree of **B. Sc. -M. Sc. (Integrated) Climate Change Adaptation**, agree that the thesis entitled **"DENDROCLIMATIC ANALYSIS OF TEAK (*Tectona grandis* L. f.) FROM CENTRAL INDIA TO EVALUATE THE POTENTIAL FOR CLIMATE RECONSTRUCTION"** may be submitted by Ms. Reji Mariya Joy. K., in partial fulfillment of the requirement for the degree.

Dr. E. V. Anoop
(Chairman, Advisory Committee)
Associate Professor and Head,
Dept. of Wood Science
College of Forestry
KAU, Vellanikkara

Dr. S. Sengupta
(Member, Advisory Committee)
Scientist-D,
IITM, Pune

Dr. Hemant Borgaonkar
(Member, Advisory Committee)
Retired Scientist ,
IITM, Pune

Dr. E. K. Kurien,
(Member, Advisory Committee)
Special Officer,
ACCER, KAU, Vellanikkara

Dr. K. M. Sunil,
(Member, Advisory Committee)
Assistant professor (Agricultural University)
ACCER, KAU, Vellanikkara

EXTERNAL EXAMINER
A. Nicodemus
Scientist 'F'
IFGTB, Coimbatore

Vellanikkara,
Thrissur - 680 656
Date.............

4

Acknowledgement

It was a long contentment voyage, in quest of uncloaking the secrets lurking within tree rings. I would like to express my sincere gratitude to a list of prodigious people who made this work a reality with their rousing knowledge and cheerful encouragement.

I would like to first thank my thesis major advisor ***Prof. Dr. E. V. Anoop****, Head of the Dept. of Wood Science, for his valuable guidance and suggestion for thesis work. I would also like to thank him, for his advice and assistance in keeping my progress on schedule.*

I would like to express my deep gratitude to ***Dr. S. Sengupta*** *(Scientist-D, IITM, Pune) and* ***Dr. Hemant Borgaonkar*** *(Retired Scientist, IITM, Pune), my co-guides and advisory members, for their patient guidance, enthusiastic encouragement and useful critiques of this research work. The door to their office was always open whenever I crippled with doubts or had a question about my research or writing. They consistently allowed me to work independently but always steered me in the right direction when I was doing lab work as well as while writing thesis.*

I wish to extend my profound gratitude to my advisory committee members ***Dr. E. K. Kurien****, Special Officer, ACCER and* ***Dr. K.M Sunil****, Assistant Professor, ACCER for their indispensable moral support and crucial assistance during critical point of thesis correction and submission.*

I wish to acknowledge the help provided by ***Shri A. B. Sikder*** *(Scientist E, IITM) and* ***Dr. Naveen Gandhi*** *(Scientist D, IITM) for lab work.*

I would like to express my very great appreciation to ***IITM*** *(Indian Institute of Tropical Meteorology) and CCCR (Center for Climate Change Research) department for permitting me to carry out my thesis work successfully. I am thankful to the* *director of IITM and whole IITM scientific community for providing good lab, library and accommodation for completing my research work.*

I would like to express my sincere gratitude towards teaching and non-teaching staffs of ***ACCER*** *and* ***College of Forestry*** *for the abiding support and impetus effort provided during my graduation and post-graduation. I believe, I am blessed to do my graduation followed by post-graduation in these beautiful institutions.*

Finally, I must convey my very deep gratitude to my family and to my classmates for providing me with abiding support and incessant encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

Reji Mariya Joy K.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SYMBOLS & ABBREVIATONS

AAO	Antarctic Oscillation
AD	Anno Domini era
ALLA	Allapalli site chronology
ARSTAN	Auto Regressive Standardization software
C E	Current Era
CEP	cumulative eigenvalue product
CRU	Climate Research Unit
DIR	Deficient Indian Rainfall
EDUG	Edugurapalli site chronology
EID	East Indian Drought
El Ni~,	El Niño
ENSO	El Niño–Southern Oscillation
ERW	Early Wood Width
IITM	Indian Institute of Tropical Meteorology
IMD	Indian Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter Tropical Convergence Zone
KTRC	Kerala Tree Ring Chronology
LGY	Low Growth Years
LRW	Late Wood Width
MADA	Monsoon Asia Drought Atlas
MI	Moisture Index
MXD	Maximum Latewood Density
NAGZ	Nagzira site chronology
NAO	North Atlantic Oscillation
NE	North East monsoon
NXD	Minimum Early Wood Density

PC	Principal Component
PC1	First Principal Component
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
RWI	Ring Width Index
SOI	Southern Oscillation Index
SPI	Standardized Precipitation Index
SST	Sea Surface Temperature
SW	South West monsoon
THAT	Thatibanda site chronology
TNI	Trans-Niño Index
TRW	Total Ring Width
WRSI	Water Requirement Satisfaction Index

CHAPTER 1
INTRODUCTION

Agriculture is the major livelihood of tropical and subtropical countries which requires substantial rainfall. Studies show a decreasing trend of rainfall in last 2-3 decades as a consequence of climate change (Doll, 2002; Yusuf and Francisco, 2009). This considerably affects crop production and subsequent vulnerability of the society. In order to make successful mitigation plans for water management, understanding of frequency, intensity and duration of drought episodes are extremely important which is, till date, not sufficient.

As per Intergovernmental Panel on Climate Change (IPCC, 2007), studies of past climate changes are essential to understand the background of recent climate changes rainfall, relative humidity and temperature. Various projection models usually involve many temporal trend analyses of those parameters. The significance level of the trends largely depends on how better those trends were constrained in the past (since last 400-500 years). A Paleo-proxy perspective is the reliable way to understand the variation of the related atmospheric parameters beyond the period of instrumental observation. Paleoclimatology or knowledge of climate during past centuries can both improve our understanding of natural climate variability and help to address the causal connection between past and modern climate change.

Paleoclimatology is the study of climate prior to the instrumental record (Bradley, 1985). Instrumental records are available for a period nearly 100-150 years, which is inadequate for explaining the climate variability and climate change in past millennial time scale. The climate change information in such time scale is often preserved in various natural archives (ice core, pollen, lake sediment, tree-ring). These proxy records are of different temporal extent and resolutions.

Ocean sediment cores are potentially available for 70 percentage of the

Earth's surface, and may provide continuous proxy records of climate spanning many millions of years. However, these samples are difficult to date accurately; commonly there is a dating uncertainty of plus or minus 5 percentage of the sample true age. Mixing of sediments by marine organisms and generally low sedimentation rates also make it difficult to obtain samples which represent less than 500-1000 year intervals (Bradley, 1985).

Dendroclimatology is the study of past climate using tree ring as a proxy. The reason for trees is a valuable resource in terms of studying the past is the fact that they provide absolute time resolution data. Dendroclimatology is currently the only viable method to provide annually-resolved, calendricaly dated, well-replicated proxy climate record. Regional tree-ring research over the past few decades has demonstrated that quantitative reconstruction of past climate (last few centuries) is possible through dendroclimatology. In dendroclimatology a variety of techniques are used to treat the absolutely dated tree-ring measurement in such a way that climate related information is conserved within the data with minimum distortion as well as non-climate information's are removed as far as possible. Dendroclimatology involves different methods to test the response of the various instrumentally observed climate parameters on tree ring parameters for a significant period and use the response function to obtain climate information beyond the period of instrumental observation. The primary step for dendroclimatic reconstruction is to assign a particular year to a ring by using various techniques collectively known as dendrochronology. The prefix *dendro* is from the Greek word for tree, *dendron,* and the word *chronology* is the name of science that deals with time and the assignment of dates to particular events.

Climatic reconstruction from tree rings is having significant value in four major fields. First, they may be used to provide an extended climate data base to be used in the testing of models of climate. Second, they may provide a longer and more representative database for the calculation of climate and climate related statistics.

Third, they may provide detailed descriptions of climate in distant periods which may be used as analogues of possible future changes in climate. Fourth they may be used in the verification of other proxy records of climate, including historical (or documentary) data, for pre-industrial times. (Huges, 1982).

Every single annual ring is a result of a single yearly flush of growth, which begins in the spring and ceases in the summer or in early autumn, so that single layer is produced every year. The ring width is the measurement of perpendicular distance between latewood (dark band) of one annual ring to latewood of next annual ring. The basic principle of dendroclimatology is that the annual growth rings of trees provide the information of both extrinsic factors (climate, pest attack, forest fires, etc.) and intrinsic factors (growth trends, diseases). The difference of the ring width in a sequence of annual rings often shows a common pattern over a region. If extrinsic factors like climate controls the tree growth of that region, the common regional pattern may be found spatially extensive.

The main objective of this work is to understand the potential of tree ring for the dendroclimatic reconstruction of past climate. In view of this, I have studied tree-ring samples of teak from four sites of Central India with the following objectives.

1. To understand the dendrochronological techniques in detail using the data of four teak (*Tectona grandis* L. f.) tree-ring sampling sites from central India.
2. To understand the dendroclimatic potentials of Teak.
3. To develop models for tree growth - climate relationship using response function analysis in order to understand the applicability for reconstructing the climate over past few centuries.
4. Evaluation of transfer function for the reconstruction of past climate based on the potential revealed by response function analysis of the chronology.

CHAPTER 2

REVIEW OF LITRATURE

Dendroclimatic study was initiated by the insight of an astronomer, Andrew Ellicott Douglass. He was working at the Lowell Observatory in Flagstaff, Arizona, and was interested in the sunspot cycle and its relation to terrestrial climate. He envisioned tree ring as a proxy measure. He suggested that growth of trees is affected by the limiting factor (Douglass, 1914). Dendroclimatic study extended in Europe by the end of the 1940s (Huber, 1941).

Dendroclimatic study in the tropics and subtropics encountered multifaceted problems. They are one of the major oldest and the most productive ecosystem on the globe with heavy rainfall and high temperature. Variety of species is the characteristic of these regions. The impact of climate on each species is different (Williams *et al.*, 2008). Thus, the number of trees having potential for dendroclimatic studies is restricted. Teak tree ring studies from India, Myanmar, Thailand, and Java are valuable dendroclimatological studies for ready climate response.

In this thesis work, tropical Indian teak samples were studied. The natural distribution of teak extends from India to the Philippines (Gyi and Tint, 1985). Bhattacharya and Yadav (1989) studies showed that teak is the best available tropical species for dendroclimatic study in India. Therefore, a literature survey related to tropical and subtropical dendroclimatology (including both from teak and conifers) with special emphasis on Asian as well as Indian teak studies is presented below in the literature survey.

2.1 ASIAN CONIFER STUDIES

Dendroclimatic work in Asia was initiated in the second decade of the 20th Century. A single 250_year old *conifer (Cryptomeria japonica)* from Miyazaki, Central Japan was studied and found a prominent periodicity of 33-years in ring width series (Yamazawa, 1929). Dendroclimatological studies in China were initiated by the fourth decade of the 20th century. Based on 70 samples from three conifer species *(Pinus bungeana, Juniperus chinensis* and *Thuja orientalis)* at Beijing (Peking), tree ring indices were prepared which were found to be sensitive to local moisture condition (Douglass, 1935).

Buckley *et al.* (1995) developed four pine chronologies for *Pinus kesiya* and *Pinus merkusii*. Three dendrochronology studies were performed on *P. kesiya* and one study focused on *P. merkusii* at northern and northwestern Thailand. The results of these studies revealed that the tree-ring index of *P. kesiya* at the Nam Nao site (Phechabun province) showed a positive correlation with rainfall and a negative correlation with November temperature. Whereas, the tree-ring index of *P. merkusii* at SLM (Thung SalaengLuang, Phitsanulok province) unveiled a strong negative correlation with year-round precipitation.

D'Arrigo *et al.* (1997) performed dendroclimatic studies on *P. merkusii* and *P. kesiya*. He reported the oldest Thai pine (*P. merkusii*) from Phu Kradung existed during 1647 to 1993. It is discovered that the lowest growth rate observed for *P. kesiya* occurred during 1979 due to severe drought occurred during that year.

Buckley *et al.* (2005) studied the relationship between tree-ring and Asian monsoon temperature with the help of pine samples collected from Thailand, India, and Bhutan along with gridded meteorological data collected from tropical Indian Ocean, tropical eastern Pacific Oceans and the high-latitude Asian landmass. Tree ring width and global temperature were compared to last 150 years by computing correlation between the tree ring width and seasonal temperatures (winter (Dec–Feb), pre-monsoon (Mar–May), and the monsoon season (Jun–Sep)). Thai and Indian pine (both *P. merkusii*) showed a good correlation with the tropical climate of the Indian and Pacific Oceans, whereas Bhutan pine, *P. wallichiana*, showed the strongest association with climates of the northern Pacific and Asian land masses. All of these correlations are strongest during pre-monsoon season.

Buckley *et al.* (2007b) investigated 262-year long (1743 to 2005 AD) tree ring climate relationship of *P. merkusii* from Laos (Lao Peoples Democratic Republic) by correlating the tree ring parameters (tree-ring width, early wood width, and late wood width) with climate data from 13 nearby weather stations in Thailand. All three tree ring parameters showed significant negative correlation with prior June rainfall and positive correlation with August-September maximum temperature for the previous year. Prominent ENSO signals were highlighted in the study.

Sano *et al.* (2009) studied 535 years long *Fokienia hodginsii*, a rare conifer from northern Vietnam. The study showed that the growth of *Fokienia* was determined by the available soil moisture content during pre-monsoon season. Drought of mid-eighteenth and late-nineteenth centuries was also divulged in this study.

Buckley *et al.* (2010) reconstructed a 759-year drought (Palmer Drought Severity Index) history (1250–2008 AD) of the early monsoon (March-May) by using ring width records of *F. hodginsii* growing at two sites in the highlands of Vietnam's Bidoup Nui Ba national park. This study revealed weaker monsoons in the mid to late fourteenth century and a shorter, most severe drought in the early fifteenth century.

Cook *et al.* (2010) reconstructed the seasonalized Palmer Drought Severity Index (PDSI) by using tree rings from more than 300 sites of Monsoon Asia

(Monsoon Asia regional emphasis of the monsoon over Africa, India, East Asia and South Asia into northern Australia) in Monsoon Asia Drought Atlas (MADA). This survey, based on 327 tree-ring chronologies unveiled a millennium long record of deficient monsoon and massive drought occurred in Asia. The survey reported a drought from 1638 to 1641 during the reign of the Ming dynasty and drought that took place during 1756–1768. It was verified using historical and other proxy records. In addition, Cook *et al.* (2010) presented the evidence for the East Indian Drought (EID) of 1792–1796 and the Great Drought of 1876–1878. It was apparent through his work that it is potential to restore the climate over the earth if a proper web of tree ring data is usable.

Pumijumnong and Eckstein (2011) have-not only reconstructed the pre-monsoon (1834-2001 AD) weather conditions in Northwest Thailand using the pine tree-ring network of *P. merkusii* and *P. kesiya* but also could accurately demonstrate the warm/dry and cool/wet periods from 1834.

Cook *et al.* (2013) developed a summer temperature reconstruction for East Asia using regional average of 585 individual grid point summer temperature reconstructions produced using an ensemble version of point-by-point regression for a period 800-1989 CE. The reconstruction suggests a reasonably warm early medieval epoch (850–1050 CE), followed by generally cooler 'Little Ice Age' situation (1350–1880 CE) and 20th century is getting continuously warmed up.

Kang *et al.* (2014) developed 207 year long drought reconstruction (AD 1804-2010) based on five chronologies from Songmingyan Nature Reserve, north-central China which is the northern fringe of the Asian summer monsoon region. Study revealed a 60 year interval between consecutive severe droughts over this region (1860s, 1928-1932 and 1991-2000). The principal component of site chronologies showed good agreement with the other site chronologies of nearby areas, which articulate the quality of chronology for understanding moisture availability. The study suggests that the Pacific Decadal Oscillation might have been the reason behind the multi-decadal drought variability over north-central China, with the PDO warm phases being associated with drought conditions and the cold phases corresponding to wet conditions.

Gou *et al.* (2015) reconstructed 1,002-year long record (1009–2010 CE) of drought variability over East Qilian Mountains of China. June – July five month scale standardized precipitation and evapotranspiration index along with tree ring width reconstruction showed the evidence of persistent drought during the fifteenth century and the dramatic pluvial period since the nineteenth century.

Chen *et al.* (2016) compared the drought reconstruction of juniper tree ring chronologies (*Juniperus turkestanica* and *Juniperus phoenicia)* from northern Tajikistan (Central Asia) and southern Jordan (West Asia) over last four centuries. Study divulged a similar wet/dry period, and a regional dry condition in both chronologies during AD 1600–1621, 1627–1635, 1683–1697, 1731-1735, 1758–1791, 1810–1812, 1843–1862, 1871–1875, 1926–1941, and 1963–1968 despite of their disparity in the time period of response towards climate. Inter-annual and decadal variations existing in drought reconstruction suggest the influence of the North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), and solar activity on the drought variations in Central and West Asia.

2.2 INDIAN CONIFER STUDIES

Pant (1979 and 1983); Pant and Borgaonkar (1984) examined the sensitivity of Himalayan conifers towards climate change and potential for reconstruction of temperature and rainfall. It is interesting to note that depending on sample locations, responses of rainfall and temperature to the ring width indices(RWI) change considerably among Himalayan conifers. The ring width indices of Chir pine (*Pinus* *roxburghii*) from the Kumaon (Uttarakhand) were found to be sensitive to both regional rainfall and temperature.

Bilham *et al.* (1983) revealed the dendroclimatic potential of Juniper (*Juniperous macropoda*) by analyzing millennium long tree ring width chronology from Karakoram mountains in the western Himalaya.

Bhattacharyya *et al.* (1988) developed 450 years long (1469-1983) ring width chronology based on two conifer species *Cedrus deodara* and *Pinus gerardiana* at lower altitudes (2000m) from Pir Panjal Range, south of Kashmir and their results revealed that narrow ring width of chronologies is coinciding with major drought years in the history.

Borgaonkar *et al.* (1994) presented 371 years (AD 1612-1982) long reconstruction of summer precipitation using tree-ring chronologies of *Abies pindrow* and *Picea smithiana* based on samples collected from forest sites around Pahalgam in the Kashmir Valley during 1982. They showed a significant negative relationship with RWI (Ring Width Index) and summer temperature as well as a significant positive relationship with summer precipitation.

Similarly, Borgaonkar *et al.* (1996) reported a significant negative relationship with summer (March-April-May) temperature and positive relationship with summer precipitation by using *Cedrus deodara*. They reconstructed pre-monsoon summer (March-April-May) temperature in Shimla using the relationship obtained from the calibration and verification of results. From these studies, it is found that the subalpine trees have the potential for reconstruction of temperature and precipitation depending on the spatial and altitudinal variation.

Singh and Yadav (2000) presented 410 year old (AD 1590–1999) ring-width chronology of Himalayan pine (*Pinus wallichiana*) based on large replication of samples derived from a pure, mixed age stand growing in compact soil with almost even topography near Chirbasa, Gangotri. The chronology showed an abrupt surge in tree growth during the late 20th century, with the highest growth indices recorded in the 1990s. Strong correlation noted between ring width index and winter temperature, which shows winter warmness, is one of the major factors responsible for the twentieth century growth surge. This growth surge is closely associated with the area vacated by melting and subsequent retreat of Gangotri Glacier. Low growth prior to the 1950s reflecting cooler conditions indicated that the glacier should have been stationary for a long time with some episodic advances.

Chaudhary and Bhattacharyya (2002) studied the suitability of *Pinus kesiya* in Shillong, Meghalaya for tree-ring analyses. Out of five site chronologies developed, two site chronologies showed a positive relationship with precipitation of previous year December and at two other sites showed this relationship during the growing year March.

Yadav and Singh (2002) presented a reconstruction of mean spring (March–May) temperature variations back to AD 1600 based on a network of 12 tree-ring width chronologies of Himalayan Cedar (*Cedrus deodara*) from the western Himalayan region. The most noticeable feature of the temperature reconstruction is the long-term cooling trend since the late 17th century that ended early in the 20th century. The warmest 30-year mean of the 20th century recorded during 1945–1974 in this study.

Singh *et al.* (2004) reported 1198-year long (AD 805–2002) ring width chronology of Himalayan cedar (*Cedrus deodara*) from a site at Bhaironghati, Garhwal Himalayas. Study uncloaks the phenomenon of pre-monsoon (March to May) temperature cooling in the western Himalaya during the latter stage of the 20th century, which may be attributed to the sudden decrease of minimum temperature (3 times) compared to the increased maximum temperature.

Singh and Yadav (2005) reconstructed 256 years long (1731-1986 AD) spring precipitation using 15 site ring width chronologies of Himalayan Cedar (*Cedrus deodara*) from the moisture-stressed sites of the western Himalayan region. The study showed that extremely dry and wet situation prevailed during the 20th century, while considering the whole reconstructed climate. 10 years and 20 year means of data is also pointing to this conclusion. Earlier reconstruction of spring precipitation for the western Himalayan region using single-predictor chronology [Yadav and Park, 2000] indicated similar wet and dry periods in the nineteenth and twentieth centuries. However, this reconstruction is not comparable with the reconstruction available for the Kashmir region (Hughes, 1992; Borgaonkar *et al.*, 1994), which could be due to the existence of different climatic regimes in the above two regions.

Bhattacharyya *et al.* (2006) described the potentiality of tree ring data of Birch (*Betula utilis*) for the analysis of Himalayan glacial fluctuations. Tree rings of Birch growing along moraines around Bhojbasa, close to the snout of Gangotri Glacier. This study found that the growth of Birch has a negative relationship with temperature of January, March and April, and direct positive relationship with precipitation of March, April and June, and temperature of February. In addition, increased tree growth in recent years has also been recorded coincided with the rapid retreat of Gangotri Glacier.

Yadav (2009) demonstrated millennium long temperature reconstruction over Keylong, Himalaya. This study shows the indications of multi-century warm and cool anomalies consistent with the Medieval Warm Period and Little Ice Age anomalies. Few tree-ring based regional temperature reconstructions (from other parts world) indicate cooling trend in summer temperature (Hughes, 2001; Cook *et al.*, 2013; Yadav, *et al.*, 2004) and warming trend in annual and winter temperature since last four centuries (Esper *et al.*, 2002; Cook *et al.*, 2013) similar to the trends obtained elsewhere in the northern hemisphere from tree ring, ice cores and other high resolution proxies (Mann *et al.*, 1999).

Yadav (2011) reconstructed annual precipitation (August-July) back to AD 1330 (1330-2008) using a tree ring data network of Himalayan Cedar (*Cedrus deodara* (Roxb.)) from the Lahaul-Spiti region in the western Himalaya, India. The study reveals that the magnitude of multi- decadal drought was high during 14th and 15th centuries. Thereafter, precipitation increased till 20th century.

Dawadi *et al.* (2013) established a 458-year long tree ring width chronology (back to AD 1552) of Himalayan Birch trees at two sites in the Langtang National Park, central Nepal (49 tree-ring cores from 41 trees). The study revealed a strong positive correlation with precipitation in May and March–May ($p < 0.001$) and an inverse relationship with temperature in May and precipitation in August ($p < 0.05$). Thus the study shows the potential of Himalayan Birch for the reconstruction of pre-monsoon.

Ram and Borgaonkar (2013) demonstrated the growth of trees (*Abies pindrow* and *Picea smithiana*) from Western Himalaya is affected by moisture index rather than the rainfall received. Soil moisture and the moisture availability to trees determine the annual tree ring width. Tree ring chronology showed good correlation with the Palmer Drought Severity Index.

Ram and Borgaonkar (2014) utilized tree-rings parameters such as total ring width (TRW), early wood width (ERW), latewood width (LRW), maximum latewood density (MXD), and minimum early wood density (NXD) of fir (*Abies pindrow*) from Chandanwadi, Jammu and Kashmir for understanding tree ring climate relationship. It was found out that the Total ring width (TRW) and early wood width (ERW) compared to the latewood width (LRW) are strongly correlated with Palmer Drought Severity Index (PDSI) during summer season (March to October) over a period of 72 years (1876–1948 AD) and thereafter the relationship got weakened due to temperature changes occurred over the region. Maximum latewood density (MXD) uncloaked significant negative association with PDSI during summer season as well as positive response with monthly mean, maximum and minimum temperatures during August to September.

Ram and Borgaonkar (2016) reconstructed heat index of spring season (February–May) back to AD 1839 using tree-ring width index chronologies of two species (*Cedrus deodara* and *Pinus roxburghii*) of the western Himalaya. First principal component (PC1) of tree ring indices from three sites showed a significant negative correlation with a heat index (−0.60), positive correlation with Palmer Drought Severity Index (PDSI) (0.37), and positive correlation with moisture index (0.59) for the period 1901–1988. The study showed that the growth of a tree is mainly influenced by the moisture availability in the root zone.

Yadava *et al.* (2016) reconstructed boreal spring precipitation for the western Himalaya over a period covering last millennium (1030–2011 CE). The study was carried out using Himalayan cedar (*Cedrus deodara*) and neoza pine (*Pinus gerardiana*) from 16 ecologically homogeneous moisture stressed settings in Kinnaur, western Indian Himalaya. The study revealed a persistent spring drought from 12 to early 16th century. Late 15th and early 16th centuries (1490–1514 CE) were the driest episode, with precipitation being ~15 percentage lower than the long-term mean and early 19th century (1820–1844 CE) was the wettest period of the past millennium, with mean precipitation ~13 percentage above the long-term mean.

2.3 TROPICAL TEAK STUDIES

Dendrochronological studies in the tropical and subtropical forest belt, were for a long time believed impossible and impractical. Relatively few tree-ring chronologies have been developed in the tropics. The increasing demand for paleoclimatic information stimulated dendroclimatologists to extend their study areas from the southern and northern temperate zones towards the equator (Baas and Vetter, 1989). The earliest studies on periodic tree growth in the tropics extend back to 1850 in India (Liese, 1986). Later, Coster (1927) investigated the periodicity of diameter growth for more than 200 tree species in Southeast Asia. A dendrochronological approach was first applied by Berlage (1931) on teak in Java.

Teak (*Tectona grandis* L. f.) is one of the most successful tree species for tropical dendroclimatology (Buckley *et al.*, 2007; D'Arrigo and Smerdon, 2008). The natural teak (*Tectona grandis* L. f.) distribution in South Asia (India) and Southeast Asia (Thailand, Myanmar, and Laos) are the most relevant sources for dendrochronological studies in this area. The Philippines and Indonesian teak are thought to have originated from Indian seeds (Lamprecht 1986). The natural teak forest is found in deciduous forest as well as in monsoon climates. Teak wood is commercially important, durable, with attractive straight grains and resistant to fire.

Teak grows in different elevations and it varies from place to place. In Taiwan teak is found over a range of 100–900 m ASL (above mean sea level); in India, elevation range is from 400 to 800 m ASL and to even 1,000 m ASL in some areas; in Myanmar, teak trees range from 900 to 1,000 m ASL up to 1,400 m ASL (Dahms, 1989). During the dry time of year, teak sheds its leaves and new leaf bud flushes at the start of the rainy season, a process important for the formation of distinct annual rings. Growth rings are anatomical structures of the wood that represent one year of their life or other seasonal periods of tree growth (Fritts, 1976). The tree growth can be affected by many factors, e.g., environmental factors, physical spaces, edaphic conditions, topographic features and competitive factors (Zanon; Finger, 2010). It is already demonstrated through the studies from Indonesia, Thailand, Java, and India that the teak (*Tectona grandis* L. f.) is a potential source for reconstructing rainfall, drought frequencies and intensities, ENSO/El Ni~, moisture index, etc. (Pant and Borgaonkar, 1983; Murphy and Whetton, 1989; Jacoby and D'Arrigo, 1990; Bhattacharayya *et al.*, 1992; D'Arrigo *et al.*, 1994; Pumijumnong *et al.*, 1995; S Ram *et al.*, 2008; Borgaonkar *et al.*, 2010; Ram *et al.*, 2010).

Berlage (1931) was the pioneering scientist who published 400 year long teak chronologies from Java in 1931. This study established a relationship between chronology and precipitation from June to October. His study also revealed that the number of rainy days is the most important factor affecting the teak growth rather than the total amount of rainfall and it is affecting directly to the current year growth as well as indirectly influencing the growth of the following year. The study could not find any correlation between tree growth with temperature, rainfall amount, or the number of dry months. Over time his work was studied by De Boer (1951), Jacoby and D'Arrigo (1990) and D'Arrigo *et al.* (1994).

De Boer (1951) compared the chronology developed by Berlage (1931) with the climate of Jakarta from 1864 to 1929. He found that the number of cloudy and rainy days is the major factor affecting the tree growth. Sunspots and the El - Niño phenomenon also exhibited a reasonable relationship with tree growth.

Murphy and Whetton (1989) reconstructed Southern-Oscillation Index (SOI) by comparing the chronology of Java teak and SOI. This study updated the Berlage's (1931) chronology up to 1989 using samples from a teak plantation.

Jacoby and D'Arrigo (1990) analyzed the correlation between the Java teak and climate data, and established that the growth depends on the timing of the beginning of rainfall.

D'Arrigo *et al.* (1994) extended the Berlage chronology (1514–1929) by 62 years (up to 1991). This updated chronology is positively correlated with rainfall and inversely correlated with sea level pressure during the dry monsoon season (around May to October) just prior to the period of growth in Java.

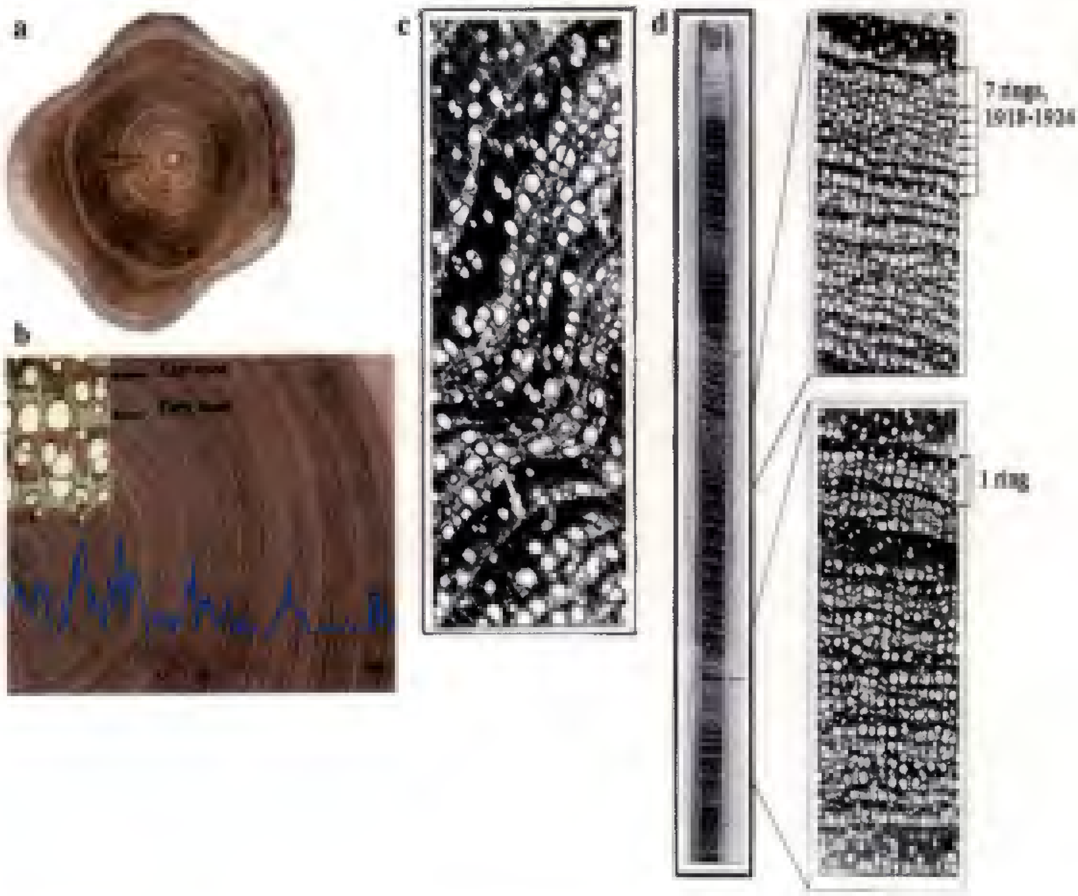


Fig. 1 Photographs of teak features. (a) Teak disk, (b) Teak tree-ring width, (c) Teak surface with wavy rings, and (d) Complicated ring.

Source: Pumijumnong (1995)

Pumijumnong *et al.* (1995a) established a teak tree-ring study in northern Thailand, and found that the primary factor controlling the growth of teak is pre-monsoon rainfall (April to June). The reconstructed pre-monsoon rainfall shows an evidence of moderately wet environment in northern Thailand for the previous two decades.

Buckley *et al.* (2007) developed 448-year long teak chronology from northwestern Thailand, which is used to assess past changes in the strength of the summer monsoon. Inter annual growth of teak greatly depends on the rainfall and soil moisture condition of early and late monsoon season. The chronology reveals two prominent periods of decadal-scale drought in the early and mid-1700s that correspond to persistently warm sea surface temperature anomalies in the tropical Pacific as derived from Galapagos Island coral records.

D'Arrigo *et al.* (2011) showed that teak growth is positively correlated with rainfall and Palmer Drought Severity Index variability over Myanmar, during and prior to the May–September monsoon season. This tree ring index is also significantly correlated with the core Indian rainfall and ENSO. The tree ring chronology of teak from Myanmar and the surface air temperatures of the north and west of India gives a significant positive correlation, which may reflect the long-term postulated association between Eurasian temperatures and the monsoon; (Kumar *et al.*, 1999) and negatively with Niño-3 SST, consistent with the tendency for El Niño warm events to be linked to drought over southeast Asia. This chronology reveals a regional to global climate signals because the drought signals extracted from the Myanmar is coinciding with the mega droughts identified anywhere in the southeast Asia, including Thailand and Vietnam (Buckley *et al.*, 2007, 2010), previously attributed to variability in the tropical Indo-Pacific climate system and the ITCZ.

Pumijumnong (2012) studied the influence of rainfall and temperature on teak growth at different elevation ranges 100-600 m above the sea level (a.s.l.) from Mae

Hong Son province, Northwest Thailand. All five site chronologies showed a common response to climate. March- July rainfall showed a positive relationship with tree growth, whereas temperature showed a negative response with tree growth.

Hlaing *et al.* (2014) studied the liaison between tree-ring width of teak (*Tectona grandis* L. f.) and weather conditions at diverse age classes of two distinct weather condition areas located in Bago Yoma Range, Myanmar. The study revealed that the young trees are affected more by the changes in annual total rainfall than the mature trees by height. Young plantations showed a positive relationship with temperature, whereas mature plantations showed a negative relationship with temperature.

D'Arrigo and Ummenhofer (2015) showed the impact of Pacific Decadal Oscillation (PDO) on Myanmar's monsoon using instrumental reanalysis data and tree ring width chronology from Myanmar's central Dry Zone. Tree ring width chronology showed a positive relationship with the PDO index during December – May. Study revealed that the negative PDO phase corresponds to dry period (Low growth years) and positive PDO corresponds to wet period due to the moisture availability.

Dié *et al.* (2015) studied the response of managed and unmanaged teak plantation towards climate using 34 disc samples from two sites of Ivory Coast, a non-managed plantation (Gagnoa) and a managed plantation (Séguié). Studies show a faster growth rate, manifested in managing plantation as compared to unmanaged plantation which may be attributed to regular thinning. Gagnoa teak plantation showed a positive response with April rainfall and negative response with September-October rainfall of the growing year. But the Séguié, trees showed a positive relationship with the July rainfall, i.e., during latewood formation. Both plantations showed a similar relationship with summer temperature.

Venegas-González *et al.* (2016) studied large scale climate variability using tree ring width chronologies *Tectona grandis* (teak) and *Pinus caribaea* (Caribbean pine) from Southeastern Brazil. RWI has been compared with local (Water Requirement Satisfaction Index—WRSI, Standardized Precipitation Index—SPI, and Palmer Drought Severity Index—PDSI) and large-scale climate indices that analyze the equatorial Pacific sea surface temperature (Trans-Niño Index-TNI and Niño-3.4-N3.4) and atmospheric circulation variability in the Southern Hemisphere (Antarctic Oscillation-AAO). TNI and AAO influence has been identified from tree rings, with a radial growth reduction in months preceding the growing season with positive values of the TNI in teak trees and radial growth, increase (decrease) during December (March) to February (May) of the previous (current) growing season with positive phase of the AAO in teak (Caribbean pine) trees.

2.4 INDIAN TEAK STUDIES

Most of the conifers and some broad leaved trees produce visible growth rings which are generally found in temperate regions rather than the tropical areas. It is found that 25 percent of Indian tropical trees produce growth rings (Chowdry, 1964). Bhattacharya and Yadav (1989) studies show that even though a great turn of trees provides clear annual ring pattern in India (Table 2 and 3), most of the dendroclimatic studies were focused on teak (*Tectona grandis*).

The annual growth nature of the teak was first demonstrated by Brandis (1879). Dendroclimatic studies over Indian tropical region were initiated by Pant and Borgaonkar (1983). They developed annually dated tree ring width chronologies of teak (*Tectona grandis* L. f.) from Western Ghats of Maharashtra and showed the rings due to fluting or buttressing of the stem near the base causes problems in cross dating. Increasing sample depth of study is the possible solution for this problem (Bhattacharya and Yadav, 1989).

Table 1 Trees producing annual rings

Forest type	Name of trees
Wet Evergreen forest	*Cedrela toona*, *Cinnamomum cedidodaphne*
Semi Evergreen forest	*Terminalia citrina*, *Gmelina arborea*, *Magnolia* spp., *Michelia* spp., *Syzygium* spp. *Pterocarpus dalbergioides*, *Alianthus excels*, *Tectona grandis*
Moist Deciduous Forest	*Tecona grandis*, *Meliosma dilleniaefolia*
Littoral and Swamp Forest	*Carapa moluccensis*
Dry Deciduous Forest	*Melia azedarach*, *Santalum album*, *Pistacia integerrima*, *Anogeissus latifolia*, *Tectona grandis*, *Tamarix articulate*, *Limonia acidissima*
Thorn Forest	*Ziziphus jujube*, *Acacia catechu*
Dry Evergreen Forest	*Azadirachta indica*, *Pterospermum suberifolium*, *Gmelina arborea*

Source: Bhattacharya and Yadav (1989)

Table 2 Anatomical features delineating annual rings in tropical trees

Wood characters	Trees
1. Ring Porous	*Tectona grandis, Lagerstroemia speciosa, Melia azedarach*
2. Semi Ring Porous	*Juglans regia, Cedrela toona, Pterocarpus marsupium, Pterocarpus dalbergioides*
3. Differences in Frequency of Vessels in Early and Late Wood	*Anogeissus sp., Zizyphus* sp., *Mansonia* sp.
4. Initial Parenchyma Cells	*Terminalia tomentosa, Dalbergia latifolia, Albizca* sp., *Swietenia chloroxylon, Dyoxylum* sp.
5. Terminal Parenchyma Cells	*Michelia champaca, Magnolia campbelii.*

Source: Bhattacharya and Yadav (1989)

Bhattacharya and Yadav (1996) studied 115 years long (1872-1987) teak tree ring chronology from Korzi, Andhra Pradesh to understand the potential of reconstruction of teak samples. The study showed that the teak growth is mainly affected by the rainfall during previous year October, current year January, current year march and current year June to September.

In Indian context, based on teak tree ring chronology from three locations in central India (Bori, Sajpur and Edugurapalli), Ram *et al.* (2008 and 2010) showed tree growth corresponds well to a derived parameter moisture index (MI) (precipitation-potential evapo-transpiration) rather than rainfall and surface air temperature. He found that the moisture availability in the root zone is the important deciding factor which forces the tree growth.

Based on twenty two teak *(T.* grandais L. f.) disc samples (1835-1997) from a station at Hoshangabad, Shah *et al.* (2007) found that the growth of the tree is limited by the low monsoon precipitation. He reconstructed mean monsoon precipitation of June - September back up to AD 1835. The reconstructed climate reveals the alternating high and deficit monsoon episodes in which most of the drought years are correlating with the well-known drought years in the history of India, which are analyzed based on instrumental data covering a time span of AD 1771_1977 (Mooley and Pant, 1981).

Ram *et al.* (2008 and 2010) concluded that the summer month (April-September) moisture index showed significant positive response with tree ring chronologies just as Buckley *et al.* (2007) showed, the variability of annual growth in teak is dependent on rainfall and soil moisture availability at both the beginning and end of the monsoon season.

Borgaonkar *et al.* (2010) developed a 523 year long (1481-2003 AD) teak chorology from south India, which is the longest chronology of teak till date. This tree ring chronology shows a solid correlation with all India summer monsoon rainfall and related parameters like southern oscillation index (SOI). Most of the low growth years are correlated with Indian deficient monsoon rainfall as well as ENSO events from the 18th century. Prior to 18^{th} century, some of the low growth years correlate with known ENSO events. Spatial correlation gives a negative relationship between the Kerala tree ring chronology (KTRC) and sea surface temperature over the Nino region, which shows the high degree sensitivity of tree ring chronologies to the monsoon climate. Chronology shows a significant positive correlation between KTRC with PDSI of lag_1 and the current monsoon season (jjas). More than fifty percentage significant Low Growth Years {LGY, [Ring width Index < (Mean-std.dev.)]} are associated with the Deficient Indian Rainfall (DIR) records based on the instrumental data (Parthasarathy *et. al.* 1995; Kothawale, *et. al.* 2008). Tree growth corresponds well to derive parameter, moisture index (precipitation-potential evapo-transpiration) rather than rainfall and surface air temperature. He found that the moisture availability in the root zone is the important determining factor for the tree growth.

Deepak *et al.* (2010) showed that the growth of teak is affected by the rainfall received over a year, by studying the samples from Shimoga and Haliyal forest division. The common low rainfall years at two sites matched with the most of drought years of India.

Ram *et al.* (2011 and 2012) studied teak tree response to climate from Conolly's plot and Maharashtra, established a significant positive relationship between winter seasons's (October–March) Palmer Drought Severity Index (PDSI), Moisture Index and annual tree-growth. He found that the tree growth in current year is affected mainly by the moisture supplement available during the winter season

(October–March). The result shows that the relationship between tree growth and climate is getting stronger recently, due to the warming aroused as a result of global warming which in turn depleting moister availability for tree growth.

Anish *et al.* (2015) studied short period chronology from the plantation teak of Thrissur, Kerala. The study showed that the tree ring parameters such as ring width and vessel area showed a significant positive relationship with prior year monsoon rainfall (South West and North East monsoon) and annual rainfall. In addition to this vessel area also showed a positive relationship with the previous year October-November temperature, current October-November temperature and annual temperature.

CHAPTER 3
MATERIALS AND METHODS

The fundamental important aspect of dendroclimatic studies is the search and selection of suitable regions, sites, species, and trees. Practically every dendro-related branch (dendrochronology, dendroclimatology, dendroecology, etc.) follow some common principles and methodology for the collection and preparation of samples.

General methodology followed for dendroclimatology :

- Site selection.
- Tree-ring sample collection.
- Sample preparation in the laboratory.
- Cross matching and dating of individual sample and ring width measurement.
- Identifying ring width measurement errors, if any, using computer program COFECHA.
- De-trending tree ring width measurement series and standardization (Preparation of Master tree-ring chronology).
- Acquire Meteorological Data (temperature, rainfall). Quality control: test for homogeneity or large error.
- Model tree growth-climate relationship using Response function analyses.
- Reconstruction of past climate: Transfer function.

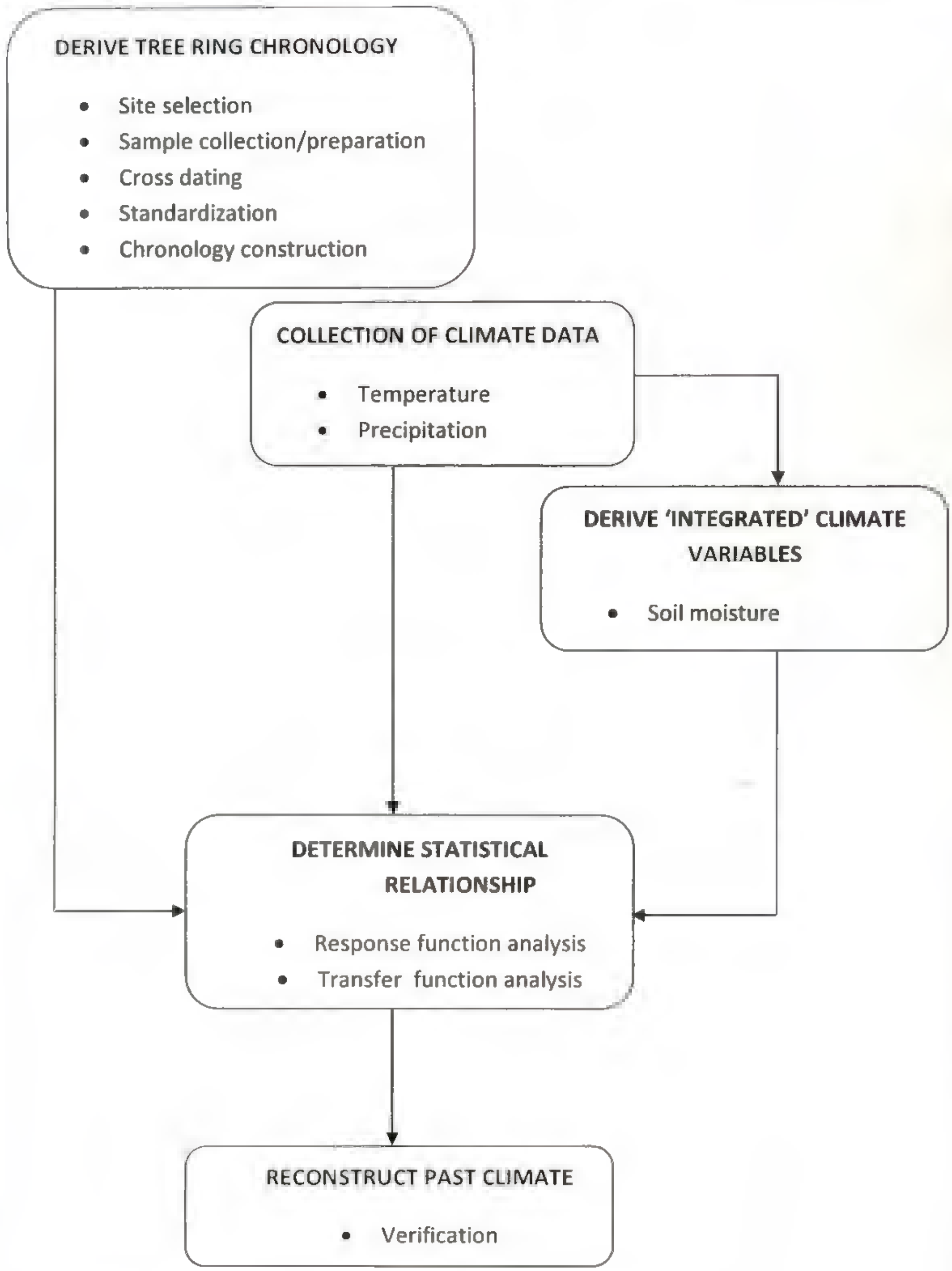


Fig. 2 Schematic diagram of general dendroclimatic procedures

The process of dendroclimatic modeling involves a hierarchy of systematic steps. The very first step is to develop the sampling strategy and to carry out the field sampling. Sampling sites should be decided according to project plan, availability of old healthy trees and a record of continuous meteorological data for a long period. The second step is careful preparation of samples in the laboratory, so that the ring structure is clearly visible. In the next step, all samples are cross matched among each other by examining each sample under microscope for its ring width variation sequence. Similar variations or narrowness of rings among the samples is crossing matched and dating of rings on each sample is recorded. Ring width measurements are carried out for all samples. The width of the ring is the perpendicular distance between the tangents on the last cells of previous year's growth to the tangent on the demarcation of the last cells of current year's growth. This includes the early wood and latewood cells. This is the basic data preparation. Special care should be taken in identifying double-ring structure, false ring occurrence and other abnormalities to prepare a good quality data. Next step is to prepare a master tree-ring chronology for a site. This includes fitting of an appropriate growth curve to individual tree-ring width series to maximize the climatic signal and minimize the non-climatic signals, such as biological growth trend (aging effect); some endogenous and exogenous disturbances contained in the raw ring width series. In addition to ring width, ring density and stable isotope ratio in tree-rings ($^{13}C/^{12}C$, $^{18}O/^{16}O$, D/H) can also be extracted as the time series representing the growth pattern. Each series is standardized by using the appropriate method (indexing). The ring width index series (standardized values) of all samples are averaged over a site to form the site chronology. The common variance explained by such chronologies is a very important statistical parameter as it represents the common signal exhibited by all the trees over a site and is supposed to be due to climate variations over a region. Chronologies which exhibit high values of common variance and mean sensitivity (a measure of relative narrowness of rings) may be considered as dendroclimatically potential chronologies and can be used in climate reconstruction modeling (Fritts and

Shatz, 1975; Fritts, 1976). In the final step, relationships between climatic elements such as rainfall, temperature etc. and tree growth parameters are established. For this purpose, response function and transfer function analyses are used. Response functions and transfer functions are generally based on the multiple regression analyses used in statistical models. The results of these analyses are tested for their significance, stability, etc. On the basis of these tests, the most appropriate relationship is used for the reconstruction of concerned climatic parameters in a backward direction, thus obtaining a long time series for further study.

3.1 SITE SELECTION AND SAMPLE COLLECTION

Various climatic factors control tree growth (rainfall, temperature, soil moisture and many more). Their response to tree growth can further be modulated by few other parameters (elevation of sample location, wind/ lee side of the mountain, local water table condition etc.). Moreover, the climate response to growth can also alter depending on the home ground, although the other aforementioned parameters remain same.

Considering this, some standard criteria generally followed during sample collection-

- The tree should bring forth a single annual ring per year.
- The tree should belong to a natural forest, in parliamentary procedure to ward off the issue of anthropogenic manipulation to tree environment.
- Climatic factors (temperature, rainfall and so on) controlling growth should be few in number so that their interference to resultant growth can be minimized and the response of individuals can be understood properly.
- Tree growth over a large area should be uniformly affected by the climatic factors. The factors should show annual variation in intensity which can be manifested through a corresponding variation in ring widths. (Stokes, 1996)

While taking cores from living trees, selection is normally subjective rather than random. Trees on disturbed sites as well as trees subjected to competition, diseases, stresses and injuries are normally rejected in order to avoid the inclusion of non-climatic signals. (Fritts, 1976)

For the present study, tree-ring core samples of teak (*Tectona grandis* L. f) from Allapalli and Nagzira of Maharashtra, Edugurapalli and Thatibanda of Andhra Pradesh have been selected for collecting samples for tree ring study (Table 3 and Fig. 3). These samples were collected by IITM, Pune. I have used these samples to understand the various steps of dendrochronological technique and to develop tree growth- climate relationship to evaluate the dendroclimatic potential of these sites.

3.2 EXTRACTION AND PREPARATION OF SAMPLE

Tree ring cores are collected using an increment borer (Fig. 4). The borer is a precision tool designed to extract core of a living tree without causing much harm to it. The little hole left in the tree after sampling is sealed by sap in order to prevent any pest or disease attack in the hereafter. The large screw threads along with the razor sharp leading edge serve to draw the border into the tree as the shaft is turned by the handle. Normally borer of about 12 to 24 inches long and a diameter of about 4 to 5.15 mm are used. Increment cores were collected at breast height using increment borers. The tip of the assembled borer pierces into the tree trunk until it reaches the pith by rotating the handle in a clockwise direction, right angle to the trunk. Then the extractor tray is inserted into the borer from the handle end and the handle is turned counterclockwise so that the core separates from the tree.

Extracted cores are kept in either plastic straws or wrapped in paper envelopes. Increment cores were air dried and glued onto wooden mounts with the transverse axis up (Fig. 5). Site name, species name and identification number of samples notes on the wooden mount using permanent ink.

Table 3 Details of teak core sample location

Si. No.	Site Name	Location	Elevation(m)	No. of cores (trees)
1	Thatibanda (Andhra Pradesh)	17.80^0 N 82.49^0 E	978	26(10)
2	Edugurapalli (Andhra Pradesh)	17.74^0 N 81.18^0 E	122	18(10)
3	Allapalli (Maharashtra)	19.43^0 N 80.06^0 E	175	26(14)
4	Nagzira (Maharashtra)	21.25^0 N 79.99^0 E	345	26(13)

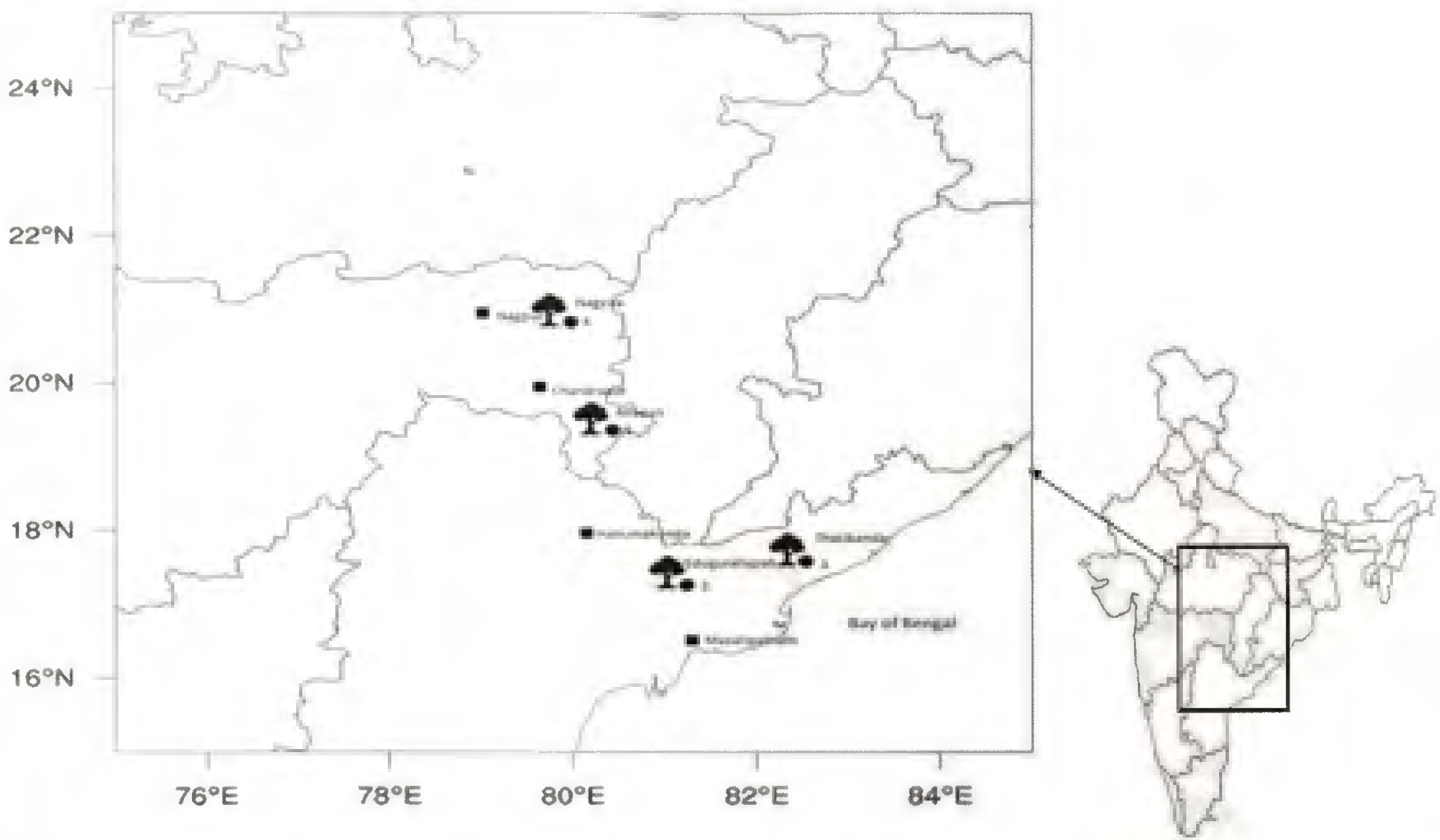


Fig. 3 Map showing tree ring sites (tree icon), IMD sites (square icon ■), CRU data grid point sites near to tree ring site (circle icon ●)

45

The identification numbers are given such that, the first three letters identify the site, next two letters identify the species name and remaining three digits show the sample number. For example, EDUTG01A is the designation number of *Tectona grandis* L. f. sample collected from a site named Edugurapalli (EDU). 01 is the sample number and A indicates the first core of the tree, such like EDUTG01B is the second core from the same tree.

Surface (cross section) of the sample is rubbed with a sharp razor blade and then brushed up with different grades of sandpaper until cellular details became clear under the binocular stereomicroscope. Coarser sand paper is applied first; it is then followed by finer grit size sandpaper (400–800) with the help of a mechanical hand sander. The grit size of the sandpaper depends on the quality of rubbing surfaces and the stiffness of wood.

3. 3 CROSS DATING

After preparation of tree-ring samples for further processing (measurement of ring width and so forth), rings of each sample are to be exactly dated. Knowledge of year of shaping of the outermost ring is really significant for dating purposes. This is the year of sampling, if the sample is a core taken from the living tree or year of thinning out the tree, if the sample is a disc from a dead tree. Once this is known, counting inward by one ring per year will provide the dates for the inner rings. However, the dating process becomes complicated if there are multiple rings in a single year or if there are missing rings. It is not possible to know how many missing or multiple (false) rings will be found in the material of a given species in a given habitat until a good number of tree-ring samples from an area have been checked and cross-compared. Generally, trees belonging to the same species are regarded for cross dating. Cross dating involves comparison of ring width sequences from each core so that characteristic patterns of ring width variation are correctly matched (Stoke and Smiley, 1968). Cross dating is imperative for assuring each ring width is dated appropriately so its corresponding climatic value is placed in proper time sequence (calendar year).

3.3.1 Principle of Cross Dating

Atmospheric circulation, rainfall pattern, mountain ranges and such climatic elements divide the earth's surface into numerous macroclimatic sites. At these macro sites, it can be presumed that the annual meteorological conditions vary uniformly on a relative scale, and thus the region can be considered to have a homogeneous climate. Since the change in climate elements on an annual or the seasonal scale is roughly proportional over a given climatic area, the ring patterns throughout this area should be similar. This has been found to be generally true with the result that the trees within this area can be cross dated, that is, their ring patterns can be matched. The local or microclimatic difference is reflected in the individual ring patterns which can be reconciled in detailed examination and averaging for many samples from a site. It is necessary to point out that while all datable trees growing on sensitive sites within the climatic area produce similar patterns, the total growth differs greatly which may be due to soil conditions, slope, aspect and such other factors, which may significantly influence the tree growth. Cross dating involves the accompanying operations.

3.3.2 Skeleton Plotting

Skeleton plot is a technique of plotting narrow rings in a graph paper based on visual identification (Fig. 6). Skeleton plotting is the traditional method of cross dating. A skeleton plot is separately made for each sample of a site.

A strip of graph paper labeled with the sample number along with a zero value marked on the extreme left side of graph paper is used in order to facilitate measuring from left to right. Every tenth vertical line to the right is numbered. Every single vertical line in the graph corresponds to an annual ring. The sample is examined through a hand lens or with a low power optical microscope. Absence of bark in a

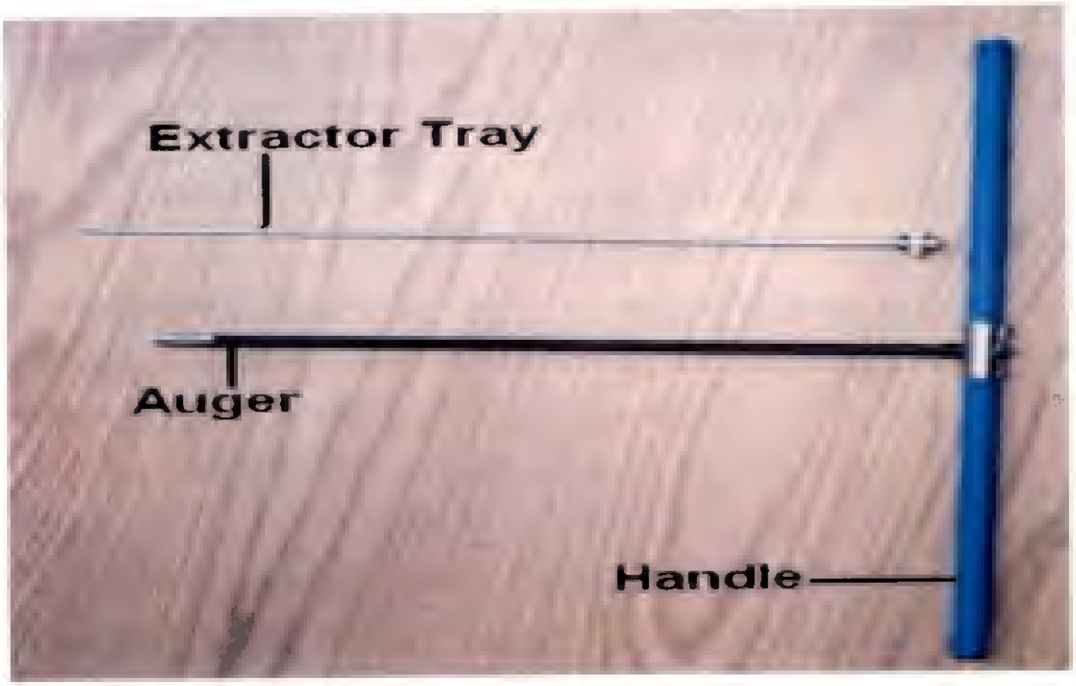


Fig. 4 Increment borer

Fig. 5 Increment core glued onto wooden mount

sample is specified along with the sample number. Narrow rings (smaller width) are marked as longer line on the graph. The length of the lines should be proportionate to the narrowness of the ring (longest line for the narrowest ring). Narrowness of a ring is determined by comparing it with the immediate neighboring rings.

Skeleton plots prepared for all samples from the same site are compared together. It is possible to identify the commonalities in their ring patterns by moving (to some agreeable extent) skeletal plots of the individuals. Hence, similar patterns are lined-up one under the other as illustrated in Fig. 7. This matching helps to align all rings for any given year (although not yet assigned a date) in the same vertical line. The aim of aligning the individual plots is to detect a time period common to all of the samples. So the samples are dated relative to each other, but not in the scale of calendar years. For most of the materials, particularly those from the sites in which environmental factors are severely limiting to growth, narrow rings are more important for cross dating than the wide rings. The skeleton plot method is used to compare samples, detect false and missing rings and finally to assign appropriate dates on each growth ring. This is a very time consuming process, but by far the most reliable dating technique. Details of the method are described by Stokes and Smiley (1968).

Dendroclimatology laboratory at IITM has a tree ring measurement set up along with TROPMETRINGS, Version 2.1, 1992 which is a tree-ring width measurement software developed by Dr. K. Rupa Kumar, IITM, Pune (Fig. 8). This measuring set up enable us to measure tree ring width efficiently and accurately. The Set up includes a stereomicroscope with a zoom lens system, a moving platform driven by precision screw and a digital encoder coupled with PC via RS-232C interface attached to moving platform which converts movements of moving platform in to a corresponding digital value. The ring width is measured at 0.01mm (10^{-3} cm) accuracy.

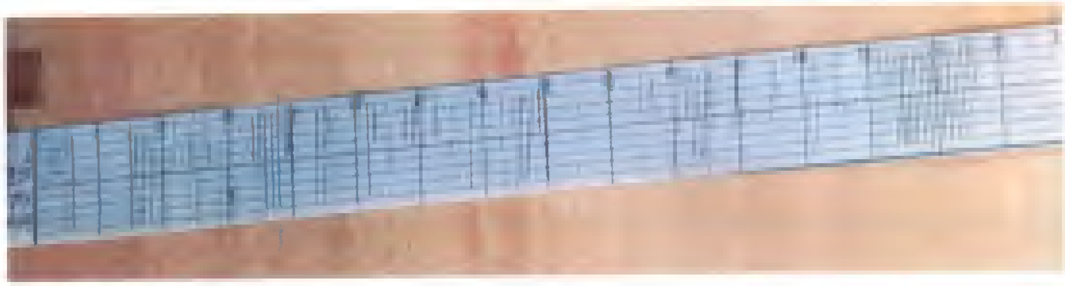


Fig. 6 Skeleton plot of a single sample

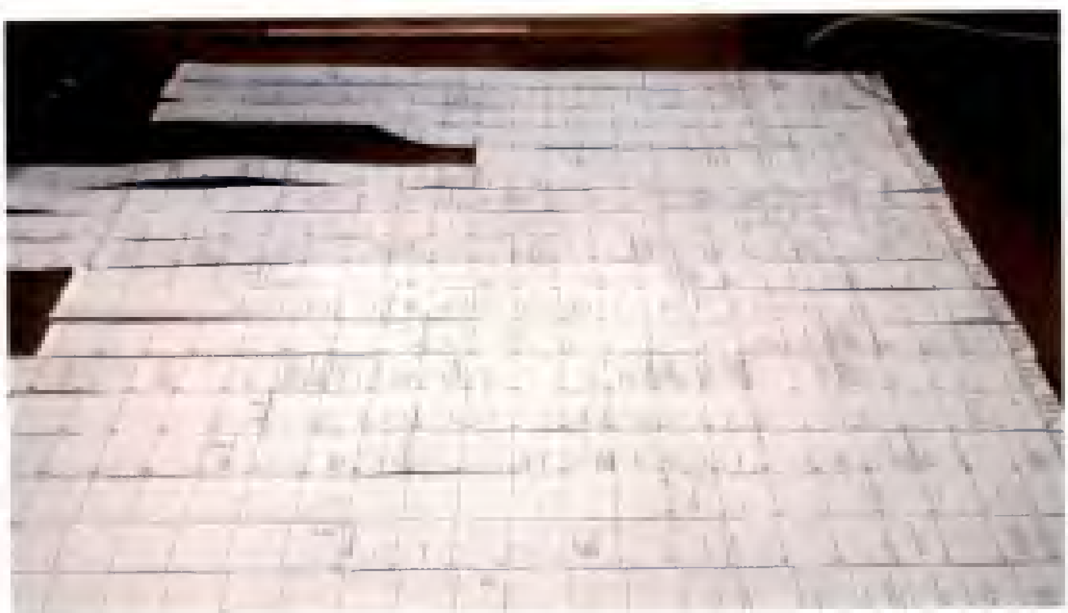


Fig. 7 Cross dating of samples using skeleton plot

3.3.3 Measurement of Ring Width

Ring width is the perpendicular distance between latewood (dark band) of one annual ring to latewood of the next annual ring. Depending on the orientation of tree rings the axis of measurement needs to be rotated slightly in order to measure the distance perpendicularly. Cross wires in the ocular are considered as a reference point for the measurement. All samples have been measured with backward direction, that is measurement starts with the latest dated year and the measurements have been saved in decadal format. The significant information such as species name, location, and altitude of the site are routinely sought by the software in the main menu while operating for actual measurement.

Later on the measurement of ring widths of all dated samples of the sites considered in this study, the series have been marked for possible measurement or dating errors using the computer program called COFECHA (Holmes, 1983). This program not only provides cross dating among the ring width series, but also suggests possible ways to improve the dating further. The output of COFECHA provides statistics (Interval of each series in a site, Number of mismatch points between series, Correlation with master chronology, standard deviation, Autocorrelation and Mean sensitivity) of cross dating within a tree ring site as well as sites from a region. COFECHA program transforms each sample series by fitting a cubic spline of 50 percentage cutoff of 32 years, autoregressive modeling and log transformation. Thus a low frequency variation (all non-random variations in ring width that last longer than eight years) is removed by the program. The accumulated series of all transformed series is then divided by the counter series (mean of transforming series) for developing a master chronology (mean chronology that represent a site) which allows us to cross date transformed series by comparison with master chronology (Holmes, 1986).

Fig.8 The stereo microscope and tree ring measurement setup, used for measuring tree-ring width at IITM, Pune.

COFECHA uses segmented as well as overlapped time series correlation techniques to better the quality of cross-dating in measurement series, i.e. the transformed chronologies are considered as 50 years long segments with 25 year overlap between each segment for serial correlation. COFECHA output does not provide a platform to cross date, but it provides guidance for how to carry out cross dating. The output supplies a description of the series that are poorly correlated with the corresponding master chronology (it is not possible to cross date between a segment in a transformed series with the corresponding section of master chronology with permitted adjustment of ring width position) or which correlate better at a place other than the position presently dated (It is possible to attain a reasonable level of cross dating by adjusting the ring width position within a permitted limit).

The basic statistics of the data are available as a table in output of COFECHA. It is significant to note that the result of COFECHA can help us to verify other preliminary cross dating techniques (skeletal plot) but entirely based on these results, exclusion of any particular samples cannot be determined.

3.4 STANDARDIZATION

Growth of a tree in a natural environment is influenced by intrinsic (species and growth form) as well as extrinsic factors. Every annual tree ring is affected by resultant of the aggregate effect of five signals (Fritts, 1976; Cook *et al.*, 1990) which is represented by the conceptual linear aggregate model for tree ring.

$$R_t = B_t + C_t + \delta DI_t + \delta D_t + E_t \tag{3.1}$$

R_t - Ring width in a year t.

B_t - Biological growth trend of tree

C_t . Climatically related signals common to all trees in a site

δDI_t - Endogenous disturbance limited to individual trees due to competition between trees from the same site.

δD_t - Exogenous disturbance such as fire, disease, pollution etc which affect all trees in the same stand.

Et - Random growth signal unique to each tree

This linear model is a simplified model to understand the concepts associated with each component. Mostly tree ring width properties are nonlinear multiplicative in nature (i.e. the relationship between the mean and standard deviation of tree ring width). Such nonlinear relationships are linearized by transforming the ring width in to logarithms. The 'δ' associated with and D_t is a binary indicator of the presence (δ=1) and absence (δ=0) of respective disturbance at some time t in ring width. B_t, C_t and Et are continuously affecting the tree growth, but DI_t and Dt may not affect growth unless there is a intervention of disturbance occurred over time t.

The growth rate of a tree (B_t) is not uniform throughout its life span. Maximum growth of the tree occurs in first 10 to 30 years due to its juvenile effect, and then the growth rate reduces. For this, the variance of the ring width series decreases with increasing age. This trend is more prominent in open environments where competition and disturbance are minimal.

C_t represents an aggregate of all factors that has climatically related environmental variable affected growth, except for those associated with stand disturbances. It includes precipitation, temperature, moisture availability, etc. This factor is assumed to affect all trees in a standby similar fashion. Thus C_t is a signal common to all trees in a stand.

The response of tree to local or endogenous disturbance is represented by DIt. This response of tree is referred to as pulse, produced as a consequence of gap-phase stand development, in which removal of individual tree affect neighboring tree only, but does not affect stand as a whole (White, 1979). Forest management practices like thinning, selective cutting and removal of undergrowth fall into this category of disturbance.

The response of tree to stand wide disturbances is represented by Dt. Fire, insects, disease, logging, and perhaps pollution are the major potential causes of stand wide exogenous disturbance. Exogenous disturbance can be differentiated from endogenous disturbance by checking the synchrony of pattern in all trees sampled from a site.

Et represents the unexplained variance in the ring widths after taking into account the contributions of B_t, C_t, DI_t, and D_t. It arises as a result of micro site differences within the stand, gradients in soil characteristics and hydrology, and measurement error. It is serially uncorrelated within and spatially uncorrelated between trees in a stand.

$$G_t = f\,(B_t, \delta\, DI_t\ , \delta\, D_1) \qquad (3.2)$$

The stochastic perturbation of pure age trends such as DI_t and D_t are represented along with δ (δ DI_t , δ D_t). δ is a binary operator which represents that the disturbance may or may not present in the stand(Cook *et al.*, 1990).

As in dendrocliamtology, climatic signals are reconstructed from ring widths, responses of only these climatic factors to ring growth are to be understood. This requires the elimination of other factors/noise (mentioned above) and subsequent amplification of climate signals (C_t) from the ring growth. Standardization transforms the non-stationary ring width into stationary, relative tree ring width indices that have a defined mean of 1.0 and a relatively constant variance (Cook *et al.*, 1990).

In order to remove noise from measured ring width data, software, program ARSTAN is used. Program ARSTAN aid us to develop standardized tree ring width chronologies from ring width measurement series, by detrending and indexing the series and then by estimating the robust mean function value in order to remove the stand disturbances.

In ARSTAN, depending on the distribution of ring widths, various curves are fitted in order to remove growth trend, G_t (detrending). Several methods of curve fitting are possible from straight lines to complex cubic spline. Among them, negative exponential curve and cubic spline are commonly employed. The negative exponential curve is used for trees having significant juvenile growth effects. The polynomial (Fritts, 1976; Graybill, 1979) and cubic spline curves (Cook and Peters, 1981) are commonly used for others. Cubic spline fitting is useful for teak trees growing in interior forest, where competition among trees is more. Selection of spline length depends on the frequency of signals needed to be taken out. As samples for the present study are majorly collected from forests, cubic spline of 35 percentage of length is utilized for the samples from Allapalli (Fig. 9), Edugurapalli (Fig. 10) and Thatibanda (Fig. 11). Since samples from Nagzira (Fig. 12) show significant juvenile effect exponential curve is used for detrending.

The ring width index (I_t) of a year is then computed by the following equation:

$$I_t = W_t / Y_t \tag{3.3}$$

I_t - Ring width indices for a year t

W_t - Measured ring width

Y_t - Expected yearly growth obtained from curve fitting

Autoregressive modeling is applied for prewhitening (discarding of persistence) to each series and the bi-weight robust mean is used to reduce effects of stand disturbances as well as the influence of outliers in the computation of mean chronologies. Treatment of the autoregressive modeling for indices might improve the common signal by removing the autocorrelation persist in the series. Extensive statistical analysis of series for a common time interval provides the common characteristics of data.

The program ARSTAN develops three versions of the chronology at the end of the standardization which includes STD (Standard), RES (Residual) and ARS (Arstan) versions. The 'STD' version of the chronology provides detrended tree ring indexes combined into a mean value function of all series. 'RES' version is computed in the same way as that of 'STD' version, but it produces a robust estimation of bi-weight mean value in order to develop a chronology with maximum common signal and with minimum persistence by prewhitening using autoregressive modeling. 'ARS' version is produced by reincorporating pooled auto regression (persistence) in to the 'RES' version chronology.

a)

b)

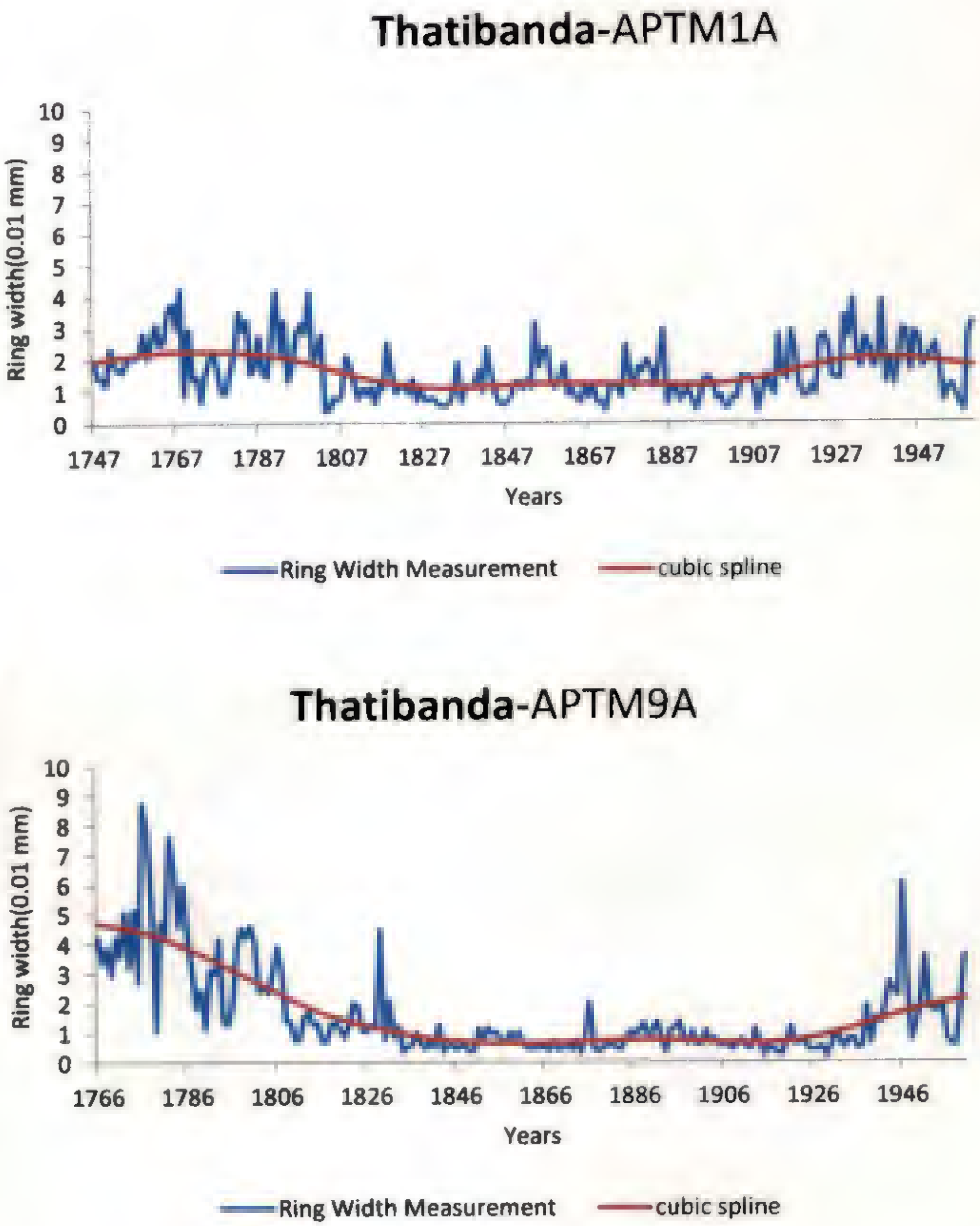
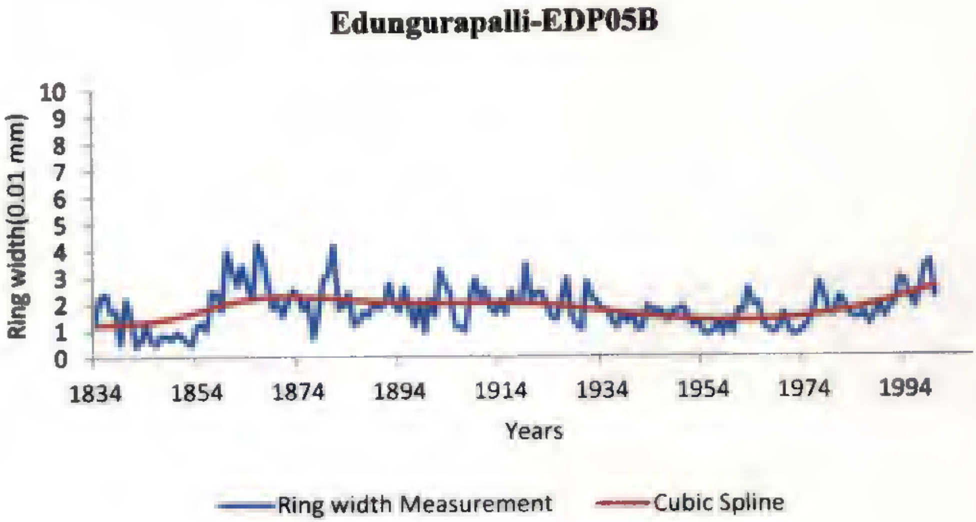


Fig. 9 Ring width measurement plotted against years in two samples of Thatibanda (a, b) and smoothed line by cubic spline.

a)



b)

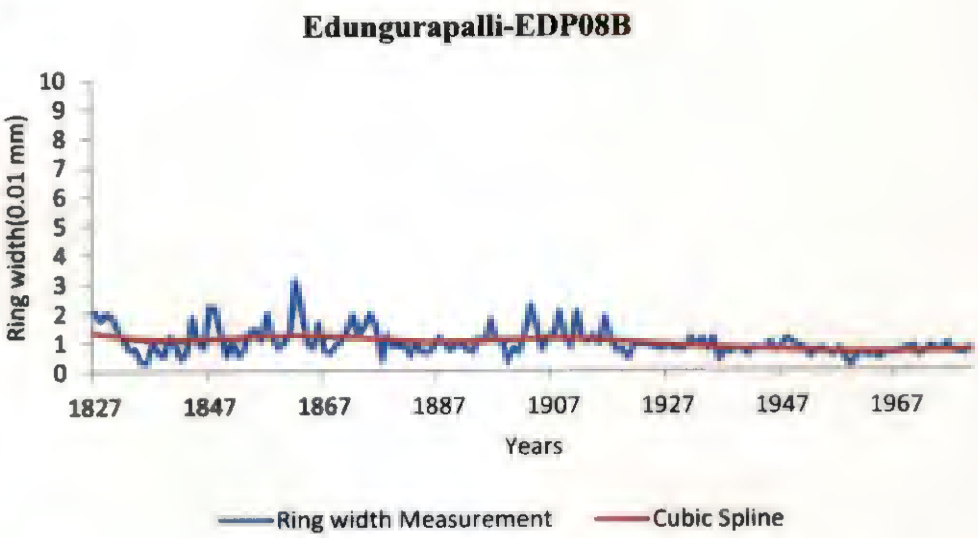
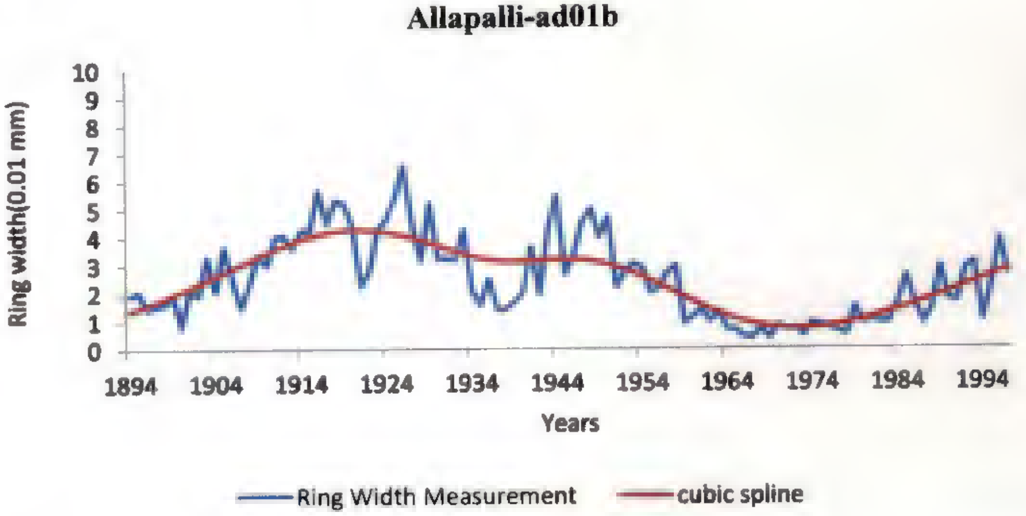


Fig. 10 Ring width measurement plotted against years in two samples of Edugurapalli (a, b) and smoothed line by cubic spline.

a)



b)

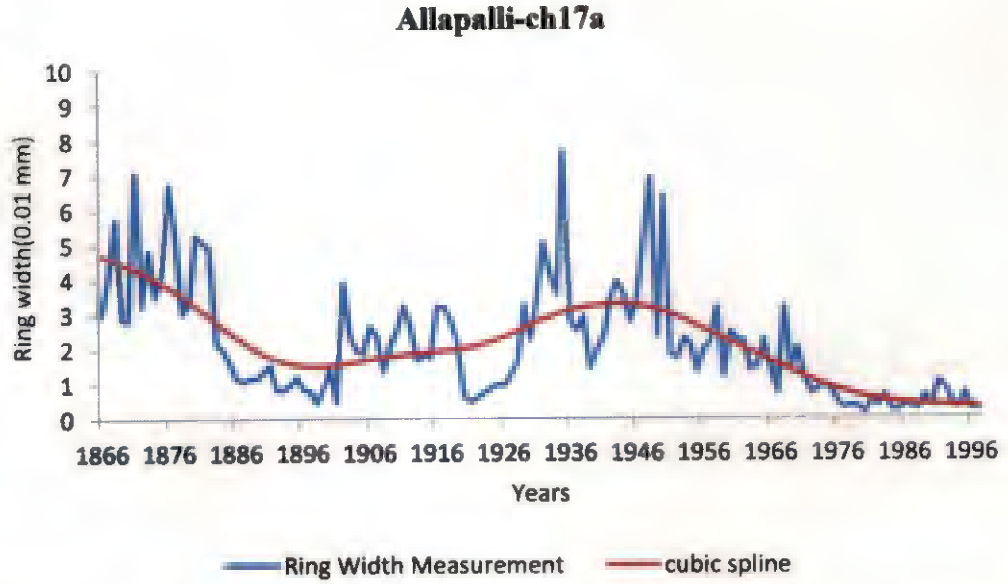


Fig. 11 Ring width measurement plotted against years in two samples of Allapalli (a, b) and smoothed line with cubic spline.

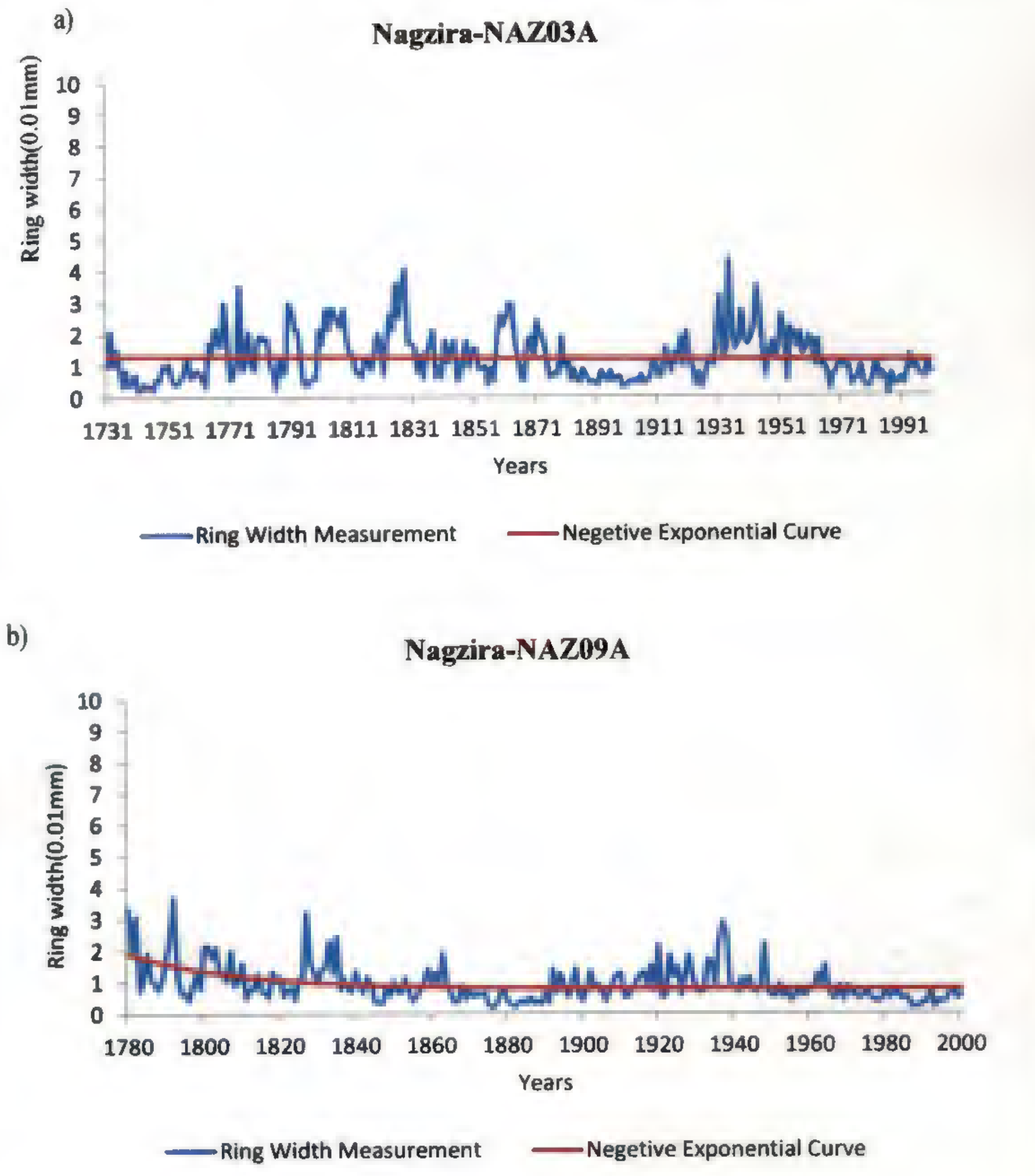


Fig. 12 Ring width measurement plotted against years in two samples of Nagzira (a, b) and smoothed line by exponential curve.

3.4.1 Estimating the chronology confidence

Various statistics of the four chronologies have been calculated for the entire period as well as for the common period of the respective chronologies, to evaluate the different characteristics of the chronologies and their dendroclimatic potential. A common period of a particular site chronology is generally selected as the optimum common interval, which is the maximum time span covered by maximum number of index series.

The mean sensitivity is defined as (Fritts, 1976):

$$MSx = \frac{1}{(n-1)} \sum_{t=1}^{n-1} \left| \frac{2(X_{t+1} - X_{t})}{(X_{t+1} + X_{t})} \right| \quad (3.4)$$

Where, X_t is the ring width parameter at year t. The theoretical range of mean sensitivity is zero to two. If there is no difference in the adjacent ring widths, the *MS* is zero and it is two when zero value occurs next to non-zero value.

In common period statistics, mean correlation coefficients defined in the table are the mean of correlation coefficients of all possible pairwise combinations of ring width series in common interval. This is also termed as mean correlation between the trees (Fritts, 1976). This statistic is used in the estimation of common signal in the chronology series. The common signal represented by the chronology is due to common forcing factor over a site. This may be a common climatic effect experienced by all trees over the site.

Signal to noise ratio (SNR) is defined as;

$$SNR = \frac{t \times V(Y)}{1 - V(Y)} \tag{3.5}$$

Where, t is the number of series and V(Y) is the common variance. It gives an idea regarding the degree to which the climate signals are expressed after averaging of chronologies. Noise (uncommon variance) will be cancelled in proportion to the number of samples.

When the common signal expressed as a fraction of total chronology variance, it is termed as Expressed Population Signal (EPS), whose value decides the agreement of sample chronology with the population chronology. Generally, the number of trees (replication) in the early part of the chronology span is less, which reduces the agreement with population chronology. Wigley *et al.* (1984) suggested the value of EPS equal or more than 0.85 as a reasonable choice and the chronologies with EPS (0.85 can be accepted as more reliable chronology for dendroclimatic reconstructions.

3.5 CLIMATOLOGY OF THE STUDY AREA

Understanding of climate of a region is a prerequisite for deciphering the relationship between climate and tree growth. It was discussed earlier in the chapter that the climate (especially temperature and rainfall) is one of the major controlling factors of growth. Climate of tree ring sites considered for our study ranges from maritime (Thatibanda) to continental (Nagzira) (See Fig. 3). Growth of tree is affected by local as well as global climate. In view of this, climatology and trend of monthly mean temperature and mean monthly cumulative rainfall are discussed.

3.5.1 Data Sets Used and Their Validation

Monthly maximum temperature, minimum temperature and cumulative rainfall data from nearby observatories of Indian Meteorological Department (IMD) are used in this study. Monthly mean temperatures of the stations are calculated by averaging the maximum and minimum temperatures of the corresponding stations. Monthly mean temperature and cumulative rainfall of Masulipatnam, Hanamkonda, Nagpur, and Chandrapur were used for determining the relationship between tree growth and climate (See Fig 3 and Table 5).

It is evident from the Fig. 3 that the selected observatory stations are located close to the respective tree ring sites compared to any other observatory locations. It is possible that, depending on local conditions (i.e. Topography, humidity, dew point, etc.) differences in climatology between the tree ring sites and observatories may occur, which can subsequently incorporate a sizable error in tree growth climate relationship. In order to estimate this discrepancy, CRU TS (time-series) 3.20 data (0.5x0.5 degree resolution) of monthly gridded temperature and rainfall over a period of 1901-2011, from the Climate Research Unit (CRU), University of East Anglia are used for comparison. Two kinds of comparisons are presented, i.e. the climate dataset extracted from gridded CRU data over the observatories is compared with the corresponding observed data and the extracted dataset over each tree ring site is separately compared with corresponding observed data from nearby observatories.

3.5.2 Climatology of Stations

As mentioned earlier, the observatories considered for this study are widely apart from each other and thus fall on different climatic zone, from maritime (Masulipatnam) to continental (Nagpur). The climatology of stations can be deciphered through plotting climate diagrams for each station. 100 years (AD 1901 to 2000).

Table 4 Details of tree ring site and meteorological data

SI. No	Tree ring site	Lat.	Lon.	Meteorological station	Lat.	Lon.	Time span of meteorological data	
							Rain fall	Temperature
1	Thatibanda	17.80^0 N	82.49^0 E	Masulipatnam	16.19 ^{0}N	81.14 ^{0}E	1871-2000	1901-2003
				CRU	17.8^0 N	82.25 ^{0}E	1901-2011	1901-2011
2	Edugurapalli	17.74^0 N	81.18^0 E	Hanamkonda	18.01 ^{0}N	79.56 ^{0}E	1871-2000	1901-2003
				CRU	17.8^0 N	80.75 ^{0}E	1901-2011	1901-2011
3	Allapalli	19.43^0	80.06^0 E	Chandrapur	20.21 ^{0}N	79.56 ^{0}E	1871-2000	1901-2003
				CRU	19.3^0 N	80.35 ^{0}E	1901-2011	1901-2011
4	Nagzira	21.25^0	79.99^0 E	Nagpur	21.15 ^{0}N	79.09 ^{0}E	1871-2000	1901-2003
				CRU	21.3 ^{0}N	79.75 ^{0}E	1901-2011	1901-2011

According to IMD seasons is divided into winter (DJF), Pre-monsoon (MAM), Monsoon (JJAS) and Post-monsoon (ON). The climatology of rainfall is calculated using rainfall data for 130 years (AD 1871 to 2000) and temperature is calculated using temperature data for 100 years (AD 1901 t0 2000).

3.5.3 Climate Trends

Apart from monthly climatology, trend analysis of temperature and rainfall on seasonal and annual timescale are also required to understand the response of these climatic parameters to tree growth in the perspective of climate change. Towards this, trend analyses data are presented on seasonal and annual time scale. Mean, standard deviation and trend of these aforementioned datasets for all four observatories are calculated.

In order to study closely the multi-decadal climate changes, trend analyses are carried out in 30 (~1902-1931; ~1932-1961), 40 (~1962-2001) and 100 years (~1902-2001) time windows. All trends (>95 percentage confidence level, marked as * and >99 percentage confidence level, marked as **) have been analyzed using non parametric Men–Kendall test.

3.6 TREE GROWTH - CLIMATE RELATIONSHIP

Relationship between tree growth and climatic parameters can be assessed by various methods. A simple method is the correlation between tree growth and climatic parameters or a simple linear regression model with only two variables: growth indices and climatic parameters. However, this model requires an over-simplified assumption that the climatic variable selected is the only one accounting for most of the variance in the tree growth record; therefore, it has a very limited scope as it does not represent the exact relationship between tree growth and climatic parameters. As the tree growth is a very complex process encompassing several climatic interactions, a more objective approach is the use of multiple regression techniques. Such techniques help in selecting from a variety of climatic variables those which are primarily responsible for the variance in the tree growth record. In a multiple regression analysis, when the climatic parameters such as the monthly temperature and precipitation are used as the *predictors* and tree growth parameters as the *predictands* the analysis is termed as response function analysis. When the tree growth parameters are *predictors* and climate is the *predictand,* then the equation is referred to as a transfer function analysis. The coefficients of the regression equation are applied to pre-instrumental tree-ring data to obtain estimates or reconstruction of climate.

In case of correlation analysis, only the association between variables in the ring-width indices and particular climatic parameter is explained without regard to the cause and effect. However, it gives some indication of the nature of the relationship between tree growth and the climate. It is more appropriate to correlate ring width parameters with average condition of climate of group of months or seasons throughout the year rather than to correlate with a specific period.

3.7 RESPONSE FUNCTION ANALYSIS

A precise quantitative analysis of climate-tree growth relationship can be obtained by response function analysis (Fritts et al, 1971; Fritts, 1976). It is basically a multiple regression analysis in which monthly or seasonal climatic parameters (temperature and precipitation) are predictors and the tree-ring parameters are predictands. Previous year's growth values are also included in the regression scheme to account for the persistence in the tree-ring series. Both climate and prior growth variables are generally used to calculate the amount of chronology variance explained and to quantify the relative importance of the individual climatic variable. The total amount of chronology variance is taken to be a measure of the strength of the climate forcing signal. The sign and magnitude of the regression coefficients of individual monthly climate variables indicate the nature of tree growth-climate link. The response function analysis can also be carried out using RES chronologies (ARSTAN approach;

Holmes *et al.*, 1986) in which the persistence i.e. influence of autocorrelation between the adjacent rings is minimized by autoregressive modeling. The use of RES version of the chronology in the response function analysis is more effective when the common variance and mean sensitivity is more than that of the STD version (persistence not removed). In such a case, there is no need to account for the effect of prior year's growth as the autocorrelation structure is removed from the series (Serre and Tessier, 1990).

One of the important problems in the multiple regression analysis is that the climatic variables are themselves often highly correlated. A way round this problem is to express the variance of climatic data in terms of principal components or eigenvectors and to use these as predictors in the regression procedure. Principal component analysis involves statistical transformation of the original (inter-correlated) data set to produce a set of orthogonal (uncorrelated) eigenvectors (Fritts, 1976; Pant *et al.*, 1988). This new set of principal components (PCs) is employed in the stepwise multiple regression analysis as a predictor set. The resultant regression equation is then reconverted back in terms of the original climatic variables using the corresponding weights of PCs. These weights or coefficients of the regression equation are the elements of the response function, representing the response of the tree to the combination of climatic conditions represented in the eigenvector.

There are several approaches in calculating the response functions with slight modifications depending upon the requirements. Berger *et al.* (1979) proposed the removal of persistence from the whole chronology before obtaining the response functions. Introducing the climate of prior growth seasons is another possibility which can give better results if there are any lag effects on the tree growth. Fritts and Wu (1986) tested response functions using different approaches such as all step multiple regression, stepwise multiple regression, ridge regression and simple correlation analysis in which they noted more or less similar relationship with slight differences due to the characteristics of individual method. They also tested the response structure before and after the autoregressive modeling was applied.

In response function analysis, selection of predictor variables to enter into the regression is very important. The entry of the predictor variable should confirm that the variance explained by the entered variable is more than the error variance. There are various ways to select the predictors to enter into the regression scheme (Lofgren *et al.*, 1982). Fritts (1976) suggested that when the F ratio (where, F= variance explained by the predictor/ error variance.) falls below unity, the regression may be terminated. Another method of termination of regression is the PVP criterion (Berger *et al.*, 1979; Guiot, 1985). This retains those principal components whose cumulative eigenvalue product (CEP) is greater than one. The scree line approach (Tatsuoka, 1974) is also useful in selecting the PCs into the regression equation. In this method, the eigenvalue is plotted as a function of their order and the number of eigenvalue above the point where the change in slope becomes nearly constant is only selected. The number of PCs can also be selected in the regression process until they together explain more than a certain percentage of the total variance (Fritts *et al.*, 1979). The value of 90 to 95 percentages is generally a reasonable cutoff level.

The growth period of Teak is from March to October. After that the growth ceases. Growth remains dormant during winter (November to February). Therefore, thirteen variables, each of monthly temperature and precipitation of these stations from the previous October (ending month of prior growth period) to current October (ending month of the current growth period) have been chosen as a set of predictor variables in stepwise multiple regression analysis to obtain the respective response function coefficients. The set of predictor variables has been transformed into an equal number of uncorrelated variables using principal components analysis before employing in the stepwise multiple regressions. In following sections various response functions have been presented based on the grouping of the tree-ring chronologies and their station data as shown in Table 5 and corresponding grid point CRU data.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 CROSS DATING

During the analysis, we have observed a good cross matching among the samples for almost all the sites except Thatibanda. Nagzira, Allapalli samples comparatively have better cross matching than the Edugurapalli samples. Rings and ring boundaries are clear. Occurrence of false or double rings has been observed only in a few cases. Earlier portions of most of the samples show prominent juvenile effect. Occurrence of false or double rings is relatively less in Allapalli samples. In case of Thatibanda site, due to narrowness of rings and association of vessels with ring boundaries, it has been found very difficult to cross match all samples.

Since these plots are prepared by visual analysis, it provides a preliminary judgment of the suitability of these samples for further studies.

4.2 STANDARDIZATION

Master chronology for Thatibanda (Fig. 13), Edugurapalli (Fig. 14), Allapalli (Fig 15), and Nagzira (Fig. 16) has been developed. This site chronology represents the average characteristic yearly growth of trees from a site in response solitary by climate, since the growth trend of individual trees has been already removed by cubic spline (Thatibanda, Edugurapalli, Allapalli) and negative exponential curve (Nagzira). Tree ring width measurement has been replaced by unit less quantity ring width index (RWI), which is amenable for comparison with any chronology from any site and at any age group.

Various statistics in Table 6 indicate good performance of all four tree-ring chronologies. It is believed that high values of standard deviation and mean sensitivity indicate good dendroclimatic potential of the species and situation.

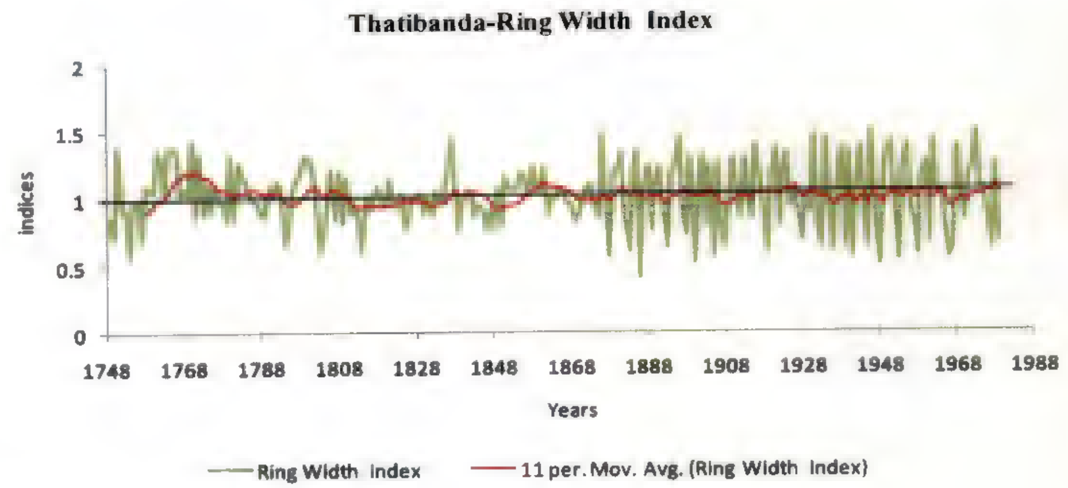


Fig. 13 Ring width index of Thatibanda

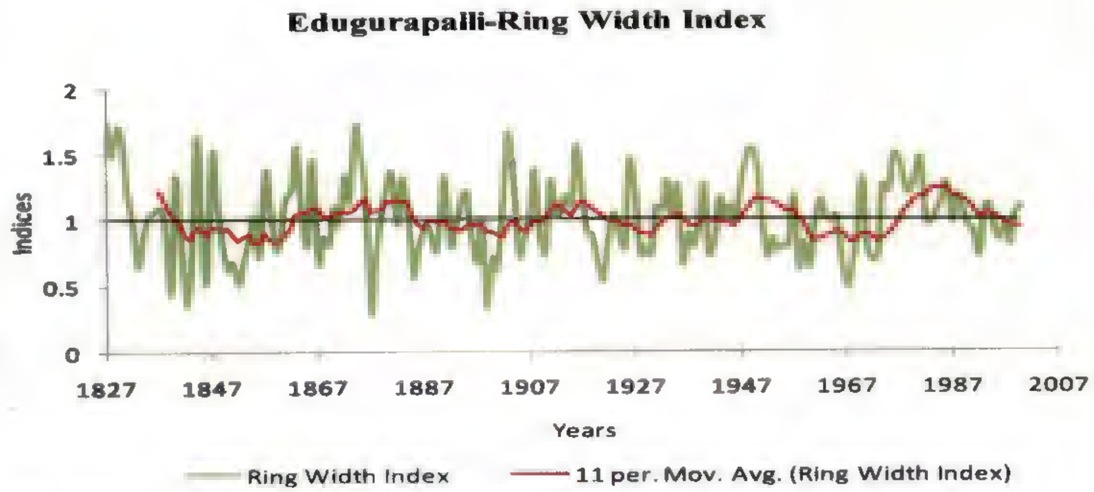


Fig. 14 Ring width index of Edugurapalli

71

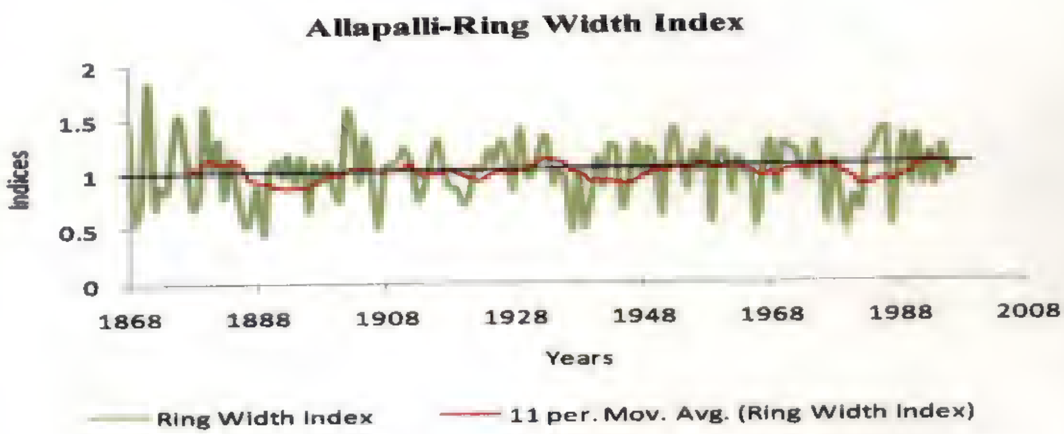


Fig. 15 Ring width index of Allapalli

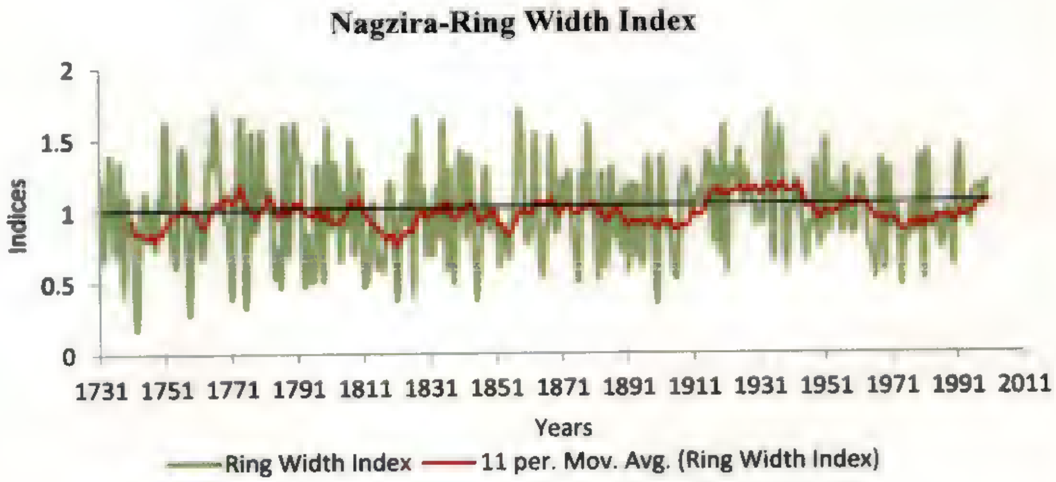


Fig. 16 Ring width index of Nagzira

Nagzira and Edugurapalli chronologies show moderately high values of these statistics followed by Allapalli. Thatibanda shows the least value of standard deviation and mean sensitivity among the four. Lag 1 auto correlation is significant in all the chronologies except Thatibanda. It indicates that Thatibanda chronology is more influenced by year to year local climate variations. Low frequency variation is minimal, whereas other three chronologies exhibit noticeable low frequency variations. Performance of common period statistics is good in all the four chronologies. Mean correlations and signal to noise ratios shows high dendroclimatic potential.

Table 6 yields the inter-correlations among the four chronologies. Only Nagzira and Allapalli have some significant relationship (95 percentage significant). Other chronologies have very poor correlation with each other. It indicates that the local climate has a strong impact on chronologies. Thatibanda is close to the east coast and region is influenced by South-west as well as North-east monsoon. Edugurapalli also have some impact of the North-east monsoon. In case of Allapalli and Nagzira, the region is a core region of the South-west monsoon and hardly any influence of North-east monsoon. They also show the significant relationship with each other.

The mean sensitivity, which is the measure of the relative difference in the width from one ring to the next, is least for Thatibanda chronology and maximum for Nagzira chronology. The standard deviation is also least for Thatibanda and highest for Nagzira chronology. Perseverance in the series, defined by lag-1 autocorrelation values, is highest in Nagzira and lowest for Thatibanda series. The autocorrelation is the correlation or linkage of each value with the immediately preceding value in the series. The large value of the autocorrelation and low value of mean sensitivity indicate the presence of lower frequency variance in the series. When the case is reversed, the high

Table 5 Statistics of chronology of overall stations

	Allapalli	Edugurapalli	Nagzira	Thatibanda
Full chronology period	1866 -1997 (132 yrs.)	1827 - 2000 (174 yrs).	1728 - 2000 (273 yrs.)	1747 - 1979 (233 yrs.)
1. No. of cores(trees)	40(30)	18(10)	26(14)	26(10)
2. Mean	0.999	0.985	0.985	0.995
3. Standard deviation	0.269	0.285	0.314	0.242
4. Mean sensitivity	0.325	0.352	0.380	0.289
5. Lag-1 Auto Correlation	0.3625	0.2612	0.450	0.131
Common period	1936 - 1997 (62 yrs.)	1911 - 2000 (90 yrs.)	1875 - 1997 (123 yrs.)	1875 - 1960 (86 yrs.)
6. No. of cores(trees)	32(32)	14(10)	18(11)	23
7. Mean correlation (variance)	0.363	0.347	0.270	0.366
8. Signal - noise ratio	18.253	7.441	4.060	13.284
9. Expressed population signal (EPS)	0.948	0.882	0.802	0.930

Table 6 Correlations among the four chronologies over a common time period 1868-1979 (112 years)

	Nagzira	Allapalli	Edugurapalli	Thatibanda
Nagzira	1.000	0.20*	0.010	0.039
Allapalli	---	1.000	0.062	0.116
Edugurapalli	---	---	1.000	0.036
Thatibanda	---	---	---	1.000

frequency variations in the series is more. The high frequency variance is of more interest for dendroclimatic studies.

4.3 VALIDATION OF METEOROLOGICAL DATA SETS

Table 8 shows strong (>99 percentage significant) positive correlation between observed and CRU among all observatories for both temperature and rainfall. Pearson Correlation coefficient (r) for rainfall varies from 0.937 (Hanamkonda) to 0.988 (Nagpur) and for temperature varies from 0.983 (Masulipatnam) to 0.996 (Nagpur). These strong correlations show the reliability of the extracted data over the observatories.

Table 9 indicates a strong positive (>99 percentage confidence) correlation between temperature between the data extracted from the tree ring sites and observed data from nearby observatories. The correlation between varies from 0.946 (Edugurapalli- Masulipatnam) to 0.996 (Nagzira-Nagpur). The correlations are, however, slightly lower for rainfall. The correlation between rainfall varies from 0.713 (Edugurapalli- Masulipatnam) to 0.917 (Nagzira-Nagpur). It is important to note that the distances between the sample locations and observatories vary from site to site. For an example Nagzira (tree ring site) and Nagpur (observatory) are ~110 km apart but Edugurapalli (tree ring site) and Masulipatnam (observatory) are ~350 km apart. These distances may partly affect the rainfall distribution, but not temperature distribution very much, Dash *et al.* (2002) has quantified the spatial variations of Indian rainfall from region to region.

By virtue of high coherency between observed meteorological data and CRU data, both the data sets have been used in the development of tree growth and climate relationship (response function analysis). As all correlations are >0.7, climatology and trend diagrams are prepared with the observed data sets in order to

Table 7 Correlation between CRU gridded data extracted over observatories and corresponding observed data from observatories.

SI. NO.	NAME OF STATION	LATITUDE	LONGITUDE	Correlation between STATION DATA vs. CRU DATA (Rainfall)	Correlation between STATION DATA vs. CRU DATA (Temperature)
1.	Chandrapur	20.21^0 N	79.56^0 E	0.966**	0.991**
2.	Hanamkonda	18.01^0 N	79.56^0 E	0.937**	0.989**
3.	Masulipatnam	16.19^0 N	81.14^0 E	0.966**	0.983**
4.	Nagpur	21.15^0 N	79.09^0 E	0.989**	0.996**

Table 8 Correlation between CRU gridded data extracted from tree ring site and corresponding observed data from nearby observatorie.

SI. No.	Area from which CRU gridded data are collected	Meteorological station	Correlation between CRU and station data (rainfall)	Correlation between CRU and station data (Temperature)
1	Allapalli	Chandrapur	0.904**	0.991**
2	Edungurapalli	Hanamkonda	0.837**	0.979**
3	Nagzira	Nagpur	0.917**	0.996**
4	Thatibanda	Masulipatnam	0.780**	0.954**

understand the local climate of the regions and to decipher the tree growth climate relationship under the perspective of local as well as global climate change.

4.4 CLIMATOLOGY OF STATIONS

The distribution of rainfall over Masulipatnam, Hanamkonda, Nagpur, and Chandrapur observatories during monsoon (SW) and winter (NE) monsoon in the study area largely depends on the availability of the moisture flux from Bay of Bengal which considerably varies along the east coast (Fig.18 (a, b)). Therefore, a gradual decrease of summer monsoon rainfall from coast to inland may not be applicable for the present study. Interestingly, Fig. 18 shows a gradual increase in summer monsoonal rainfall from the coast (Masulipatnam) to inland (Nagpur) (from 107 to 197 mm in June, 177 to 352 mm in July, 166 to 284 mm in August and 169 to 194 mm in September). This observation is at par with the IMD long term average distribution of summer monsoon rainfall presented in Fig. 17. This increase in rainfall from coast to inland may be attributed to an additional moisture sources (possibly from Arabian Sea). Except Masulipatnam all other stations receive maximum rainfall during July, whereas Masulipatnam receives maximum rainfall during October (Fig. 18 (a)). During October and November rainfall is decreasing from east coast to inland, i.e. it decreases from 221.69 to 55.91 mm in October and 128.94 to 17.3 mm in November. It possibly suggests that North East monsoon is the driving force for increasing (decreasing) rainfall in coast (inland) (Fig. 18 (a-d)). All stations receive minimal (5.22 mm to 22.9mm) rainfall during winter season.

The mean monthly temperature decreases from the coast (Masulipatnam) to inland (Nagpur) during the winter season. It is evident from the Fig.4.6 (a-d) that during December mean monthly temperature decreases from 23.9°c to 20.3°c, January mean monthly temperature decreases from 23.8°c to 20.9°c and during February it decreases from 25.4°c to 23.4^{0}°c from coast to inland. It is clear that the gradient between the mean temperature between coast and inland is decreasing as it proceeds

RAINFALL (cm)

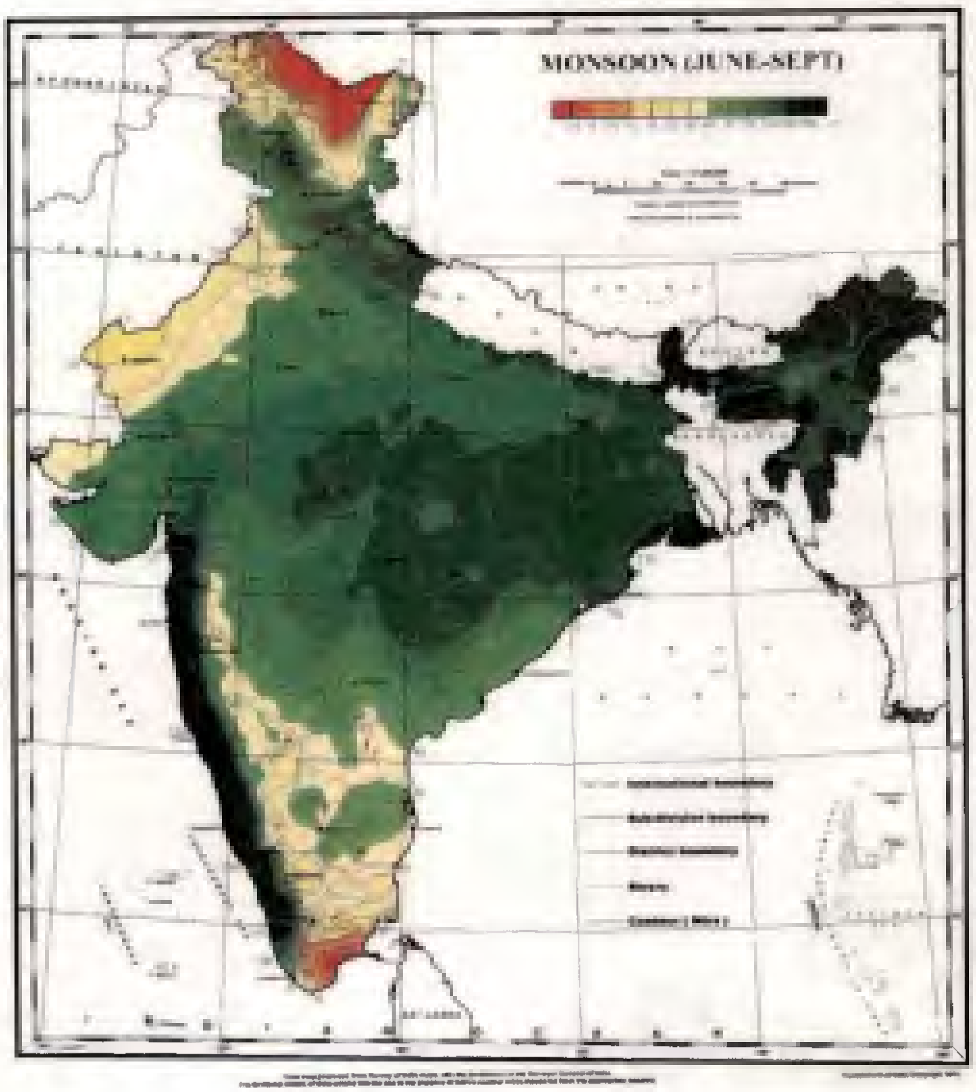


Fig. 17 IMD long term average distribution of summer monsoon rainfall map

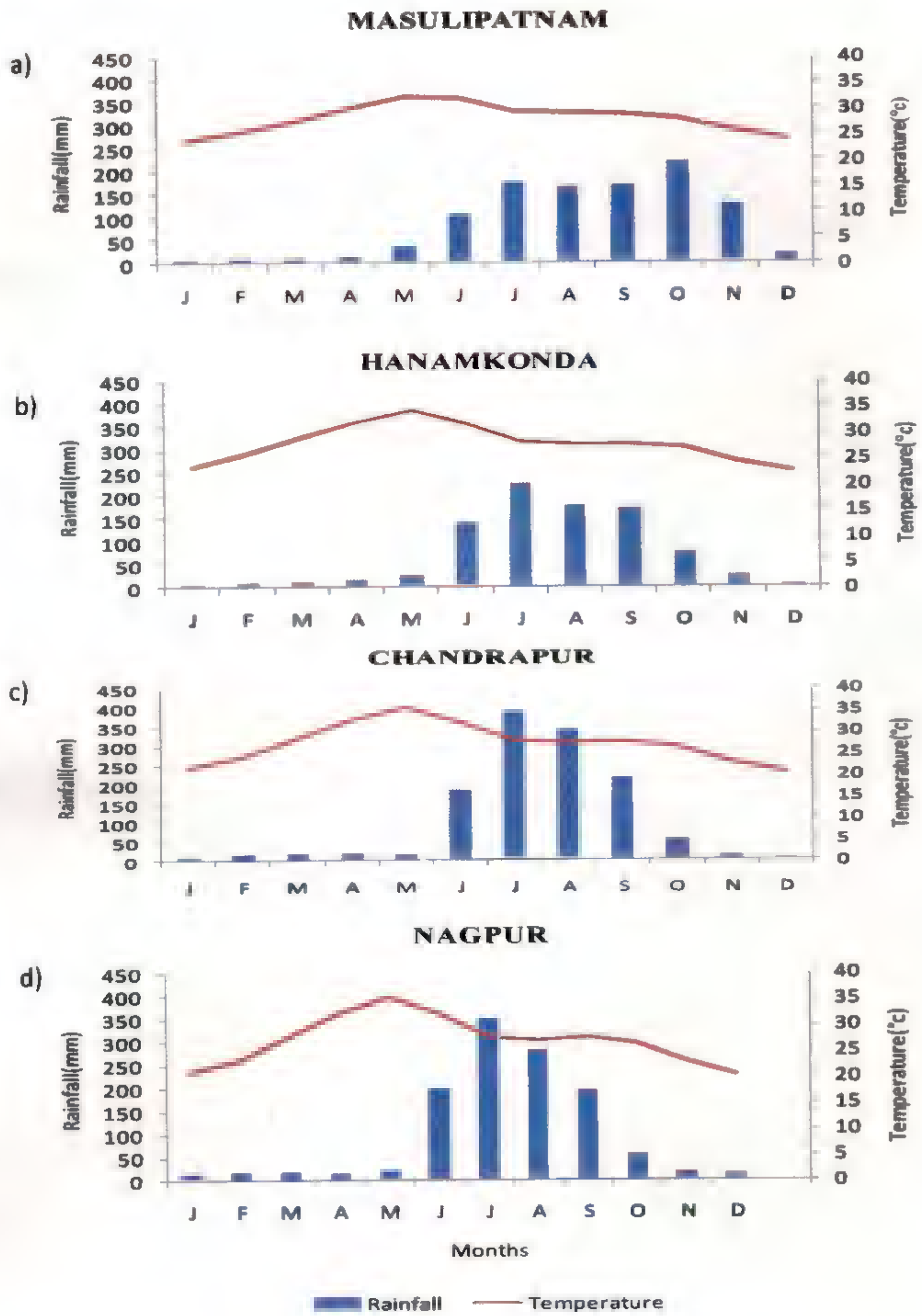


Fig.18 (a, b, c, d). Climatology of Masulipatnam, Hanamkonda, Chandrapur and Nagpur

from winter to pre-monsoon and monsoon period and further increasing during the post monsoon season.

4.5 CLIMATE TRENDS

Trend analysis of climate data from aforementioned meteorological stations was calculated to understand more about tree growth, climate relationships in the perspective of climate change. Towards this, trend analyses data are presented on seasonal and annual timescale in Tables 9-12. The tables show mean, standard deviation and trend of these aforementioned datasets for all six observatories. In order to study closely the multi-decadal climate changes, trend analyses are carried out in 30 (~1902-1931; ~1932-1961), 40 (~1962-2001) and 100 years (~1902-2001) time windows. All trends (>95 percentage confidence level, marked as * and >99 percentage confidence level, marked as **) are analyzed using non parametric Men–Kendall test and presented in the Tables 9-12. Figs 19 (a, b) to 22 (a, b) indicate seasonal and annual temperature (a) and rainfall series (b) for Masulipatnam, Hanamkonda, Chandrapur and Nagpur stations.

All stations show positive trends in most of the season and annual basis. In winter temperature, all the stations show positive trends (1°C to 2.2°C) on centennial time scale. However, trend values (except for the station, Chandrapur, 2.2°C) increase gradually from the coast (0.1°C; Masulipatnam) to inland (0.8°C; Nagpur). These observations are at par with earlier findings of Pant and Kumar (1997). Interestingly; these warming trends are not always visible on the multi decadal time scale. For example, in the time window of 1902-1931, Nagpur temperature shows the negative non-significant trend in monsoon, post monsoon and centennial scale. Masulipatnam, Chandrapur exhibits a positive temperature trend during 1962-2001.

Warming trends are noticed only at Masulipatnam and Chandrapur during pre-monsoon on centennial time scale, although no significant changes, unlike winter, are observed from the coast to inland. In the multi-decadal time scales, no notable trend is observed among the stations except Masulipatnam which exhibits an abrupt warming for the period 1932-1961. Temperature during monsoon season over Hanamkonda shows comparably small increase during 1902-2001 (0.6°C). On multi decadal time scale, Masulipatnam and Hanamkonda showed an increase in temperature only during 1962-2001. This suggests no overall warming during monsoon period although some local trends are visible. Like winter, all stations show warming trends (0.5°C to 2°C) in post-monsoon temperature on centennial time scale. Magnitude of positive trend in temperature (warming) increases from the coast to inland (not linear) during 1902-2001, very similar winter. In multi-decadal time scale, Masulipatnam and Hanamkonda show warming trends only during 1962-2001.

From the above study, it is clear that there is a significant warming over all stations in annual and some seasonal (winter and post-monsoon) time scale. Unlike temperature, seasonal rainfall does not have a common trend for all situations, both in multi-decadal and centennial time scale. But locally some significant trends are visible. For instance, winter rainfall shows a significant decreasing trend at Masulipatnam during 1901-1930 and at Hanamkonda during 1931-1960. Monsoon rainfall during 1931-1960 shows a significant increase at Masulipatnam and a significant negative trend in Nagpur during 1901-2000. This shows that the change in climate over station due to rainfall is driven by local factors. With this backdrop of climate information, ring width-climate response would be discussed in the next section.

Table 9 Statistics of Masulipatnam climate. (a) Statistics of Masulipatnam Temperature, (b) Statistics of Masulipatnam Rainfall

a)

STATISTICS OF MASULIPATANAM RAINFALL												
	100 years(1901-2000)			30 years(1901-1930)			30 years(1931-1960)			40 years(1961-2000)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	3.4	4.9	0.6	4.2	5.8	*-31.2	2.8	4.8	-5.6	4	5.3	4.9
MAM	5.9	5.9	-0.4	7.2	6.5	23.5	6.3	4.5	-7	5.1	6.7	1.6
JJAS	61.8	19.6	7.6	61.4	19.3	-11.9	61.2	15.9	**109.9	64.8	22.1	26.6
ON	35.1	19.6	-1.1	35.8	21.3	59.4	37	17.2	-28.7	33.4	20.3	-3.5
Annual	106.1	28.1	6.8	108.5	32	40.6	107.4	23.3	67.9	107.3	26.9	29.1

b)

STATISTIC OF MASULIPATANAM TEMPERATURE												
	100 years(1902-2001)			30 years(1902-1931)			30 years(1932-1961)			40 years(1962-2001)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	24.3	0.9	**1.3	23.9	1.4	4.6	23.9	1.6	*8	24.4	1.4	**5.6
MAM	30	0.6	**0.6	29.9	0.4	-1	29.8	0.5	1	30.1	0.8	**4.1
JJAS	29.8	0.6	0.1	30	0.6	-0.5	29.7	0.4	-0.1	29.9	0.8	**3.5
ON	26.8	0.6	**0.5	26.7	0.5	*2.4	26.7	0.4	1	26.9	0.6	**2.9
Annual	28	0.5	**0.5	28	0.3	-1	27.8	0.3	1	28.1	0.6	**3.5

84

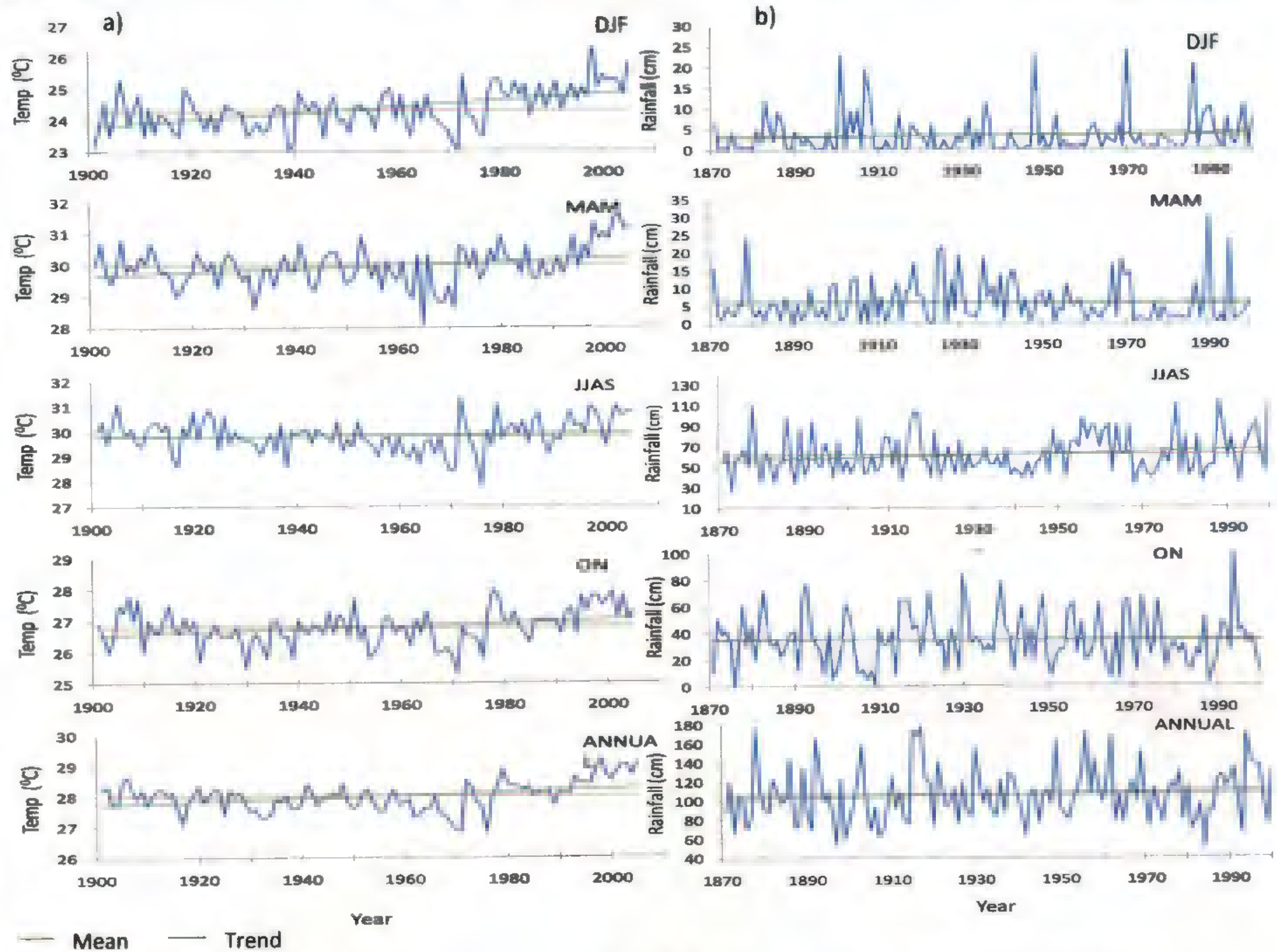


Fig. 19 (a, b) Temperature (100 years) and Rainfall (130 years) trend over Masulipatnam

Table 10 Statistics of Hanamkonda climate. (a) Statistics of Hanamkonda Temperature, (b) Statistics of Hanamkonda Rainfall

a)

STATISTICS OF HANAMKONDA TEMPERATURE												
	100 years(1902-2001)			30 years(1902-1931)			30 years(1932-1961)			40 years(1962-2001)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	23.9	1	**1.1	23.5	1.5	7.5	23.7	1.5	6.3	24	1.3	3.3
MAM	31.9	0.7	0.4	31.8	0.8	1.3	31.8	0.7	0.4	32	0.7	1.2
JJAS	28.8	0.6	**0.6	28.7	0.6	1.2	28.6	0.5	1.2	29	0.6	*1.7
ON	25.7	0.8	**0.9	25.5	0.8	-0.1	25.5	0.7	0.6	26	0.8	*2.5
Annual	27.8	0.4	**0.6	27.7	0.4	1.3	27.7	0.4	1	28	0.5	**1.5

b)

STATISTICS OF HANAMKONDA RAINFALL												
	100 years(1901-2000)			30 years(1901-1930)			30 years(1931-1960)			40 years(1961-2000)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	2.2	2.8	0.3	2.7	2.8	2.7	1.9	2.9	*-14.3	2.4	3.2	-3.2
MAM	5.4	4.6	0.7	5.8	5	8.4	6.8	5	-9	5	4.7	-0.8
JJAS	72	22	1	75.2	26.2	2.2	74.4	14.7	32.4	70.4	23.9	-36.6
ON	10.4	7.8	2.6	8.6	7	23.7	11.3	6.2	-2.2	11.8	9.8	-11.2
Annual	90	25.4	4.8	92.4	29.1	39.4	94.4	18.1	7.3	89.7	27	-50.8

86

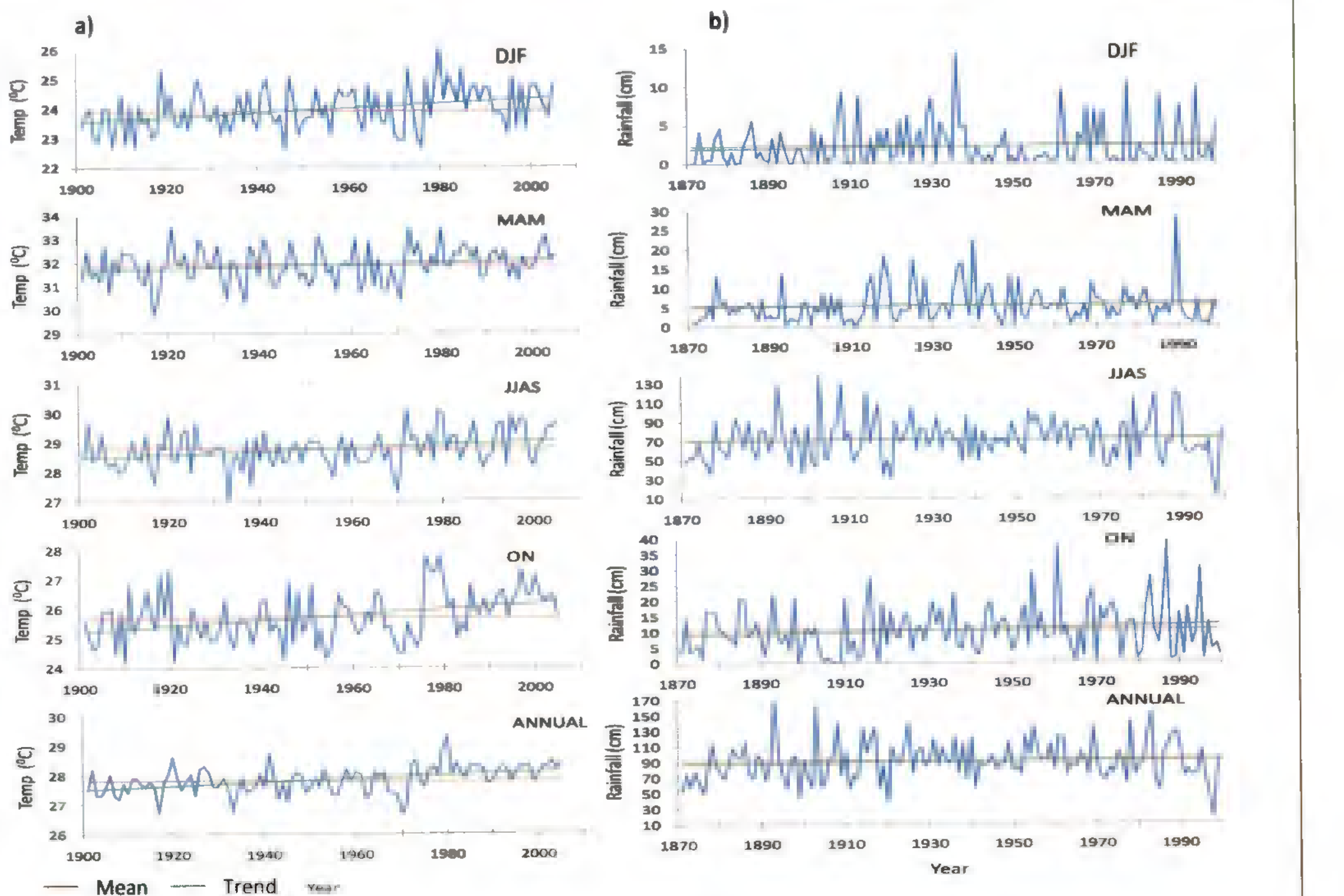


Fig. 20 (a,b) Temperature(100 years) and Rainfall (130 years) trend over Hanamkonda

Table 11 Statistics of Chandrapur climate. (a) Statistics of Chandrapur Temperature, (b) Statistics of Chandrapur Rainfall

a)

STATISTICS OF CHANDRAPUR TEMPERATURE												
	100 years(1902-2001)			30 years(1902-1931)			30 years(1932-1961)			40 years(1962-2001)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	22.2	1.1	**2.2	21.4	1.3	5.8	21.7	1.3	5.7	22.7	1.4	*4.1
MAM	32.3	0.9	**1.0	32	0.9	1.4	32.1	0.9	0.8	32.7	0.8	0.5
JJAS	28.8	0.6	0.2	28.8	0.6	1.1	28.6	0.5	0.9	28.9	0.6	0.1
ON	24.6	1	**1.7	24.2	0.8	0.8	24.2	0.7	0.5	25.3	1.1	2.3
Annual	27.4	0.5	**1.1	27.1	0.4	1.3	27.1	0.4	0.8	27.7	0.5	1.1

b)

STATISTICS OF CHANDRAPUR RAINFALL												
	100 years(1901-2000)			30 years(1901-1930)			30 years(1931-1960)			40 years(1961-2000)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	3.1	3.5	0.4	3.6	3.7	6.6	2.9	3.4	-9.1	3.2	3.4	1.4
MAM	5.5	5.4	-0.2	5.0	3.5	1.8	4.9	5	-0.3	5.8	4.5	-3.1
JJAS	113.6	26.5	-3.5	106.9	21.2	-5.8	118.2	27.5	-6.8	111.1	26.8	-1.5
ON	6.8	6.7	1.7	5.7	6.3	13.5	8.6	7.6	-18.4	7	7.1	12.7
Annual	129	29.5	-1.6	121.2	22.1	16.6	134.5	32.2	-35.8	127	30.9	9.7

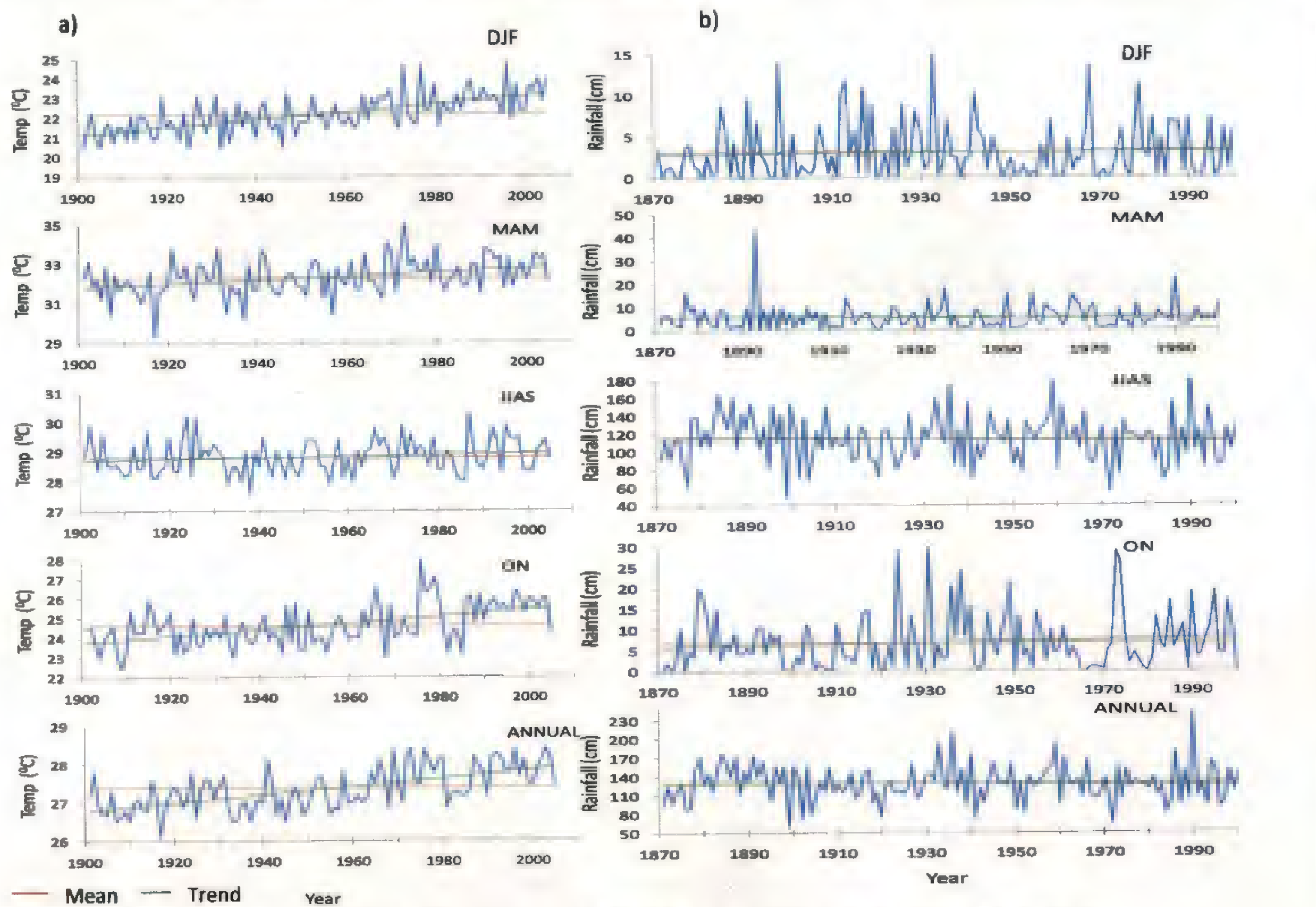


Fig. 21 (a, b) Temperature (100 years) and Rainfall (130 years) trend over Chandrapur

89

Table 12 Statistics of Nagpur climate. (a) Statistics of Nagpur Temperature, (b) Statistics of Nagpur Rainfall

a)

STATISTICS OF NAGPUR TEMPERATURE												
	100 years(1902-2001)			30 years(1902-1931)			30 years(1932-1961)			40 years(1962-2001)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	21.5	0.9	*0.8	21.1	1.3	5.3	21.5	1.2	4.2	21.4	1.2	3.2
MAM	31.8	0.9	0	31.8	1	0.1	31.8	0.9	-0.1	31.7	0.8	0.6
JJAS	28.6	0.5	0.2	28.5	0.6	-0.7	28.4	0.5	1.5	28.6	0.5	0.5
ON	24.6	0.8	*0.5	24.5	0.6	-1.1	24.4	0.8	-2.6	24.8	0.8	1.8
Annual	26.9	0.4	*0.2	26.9	0.4	-0.2	26.9	0.4	-0.1	27	0.4	0.9

b)

STATISTICS OF NAGPUR RAINFALL												
	100 years(1901-2000)			30 years(1901-1930)			30 years(1931-1960)			40 years(1961-2000)		
	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend	Mean	Standard deviation	Trend
DJF	4.3	5	2	4.4	4.2	2.7	3.5	4	-7.3	5.6	6.4	3.1
MAM	4.9	4.4	0.6	5.2	4.9	-7.9	5.8	4.9	-5.6	4.7	3.5	1
JJAS	102.7	22.5	**-14	103.1	22	-47.4	107.5	22.1	-94.4	94.6	19.6	-23.8
ON	7.3	7	0.8	6.5	7.2	17.2	8.2	6.8	-19.1	7.4	7	11.6
Annual	119.1	26.2	-10.7	119.3	26.7	-36.4	125.1	27.9	-123.6	112.2	22	-10.9

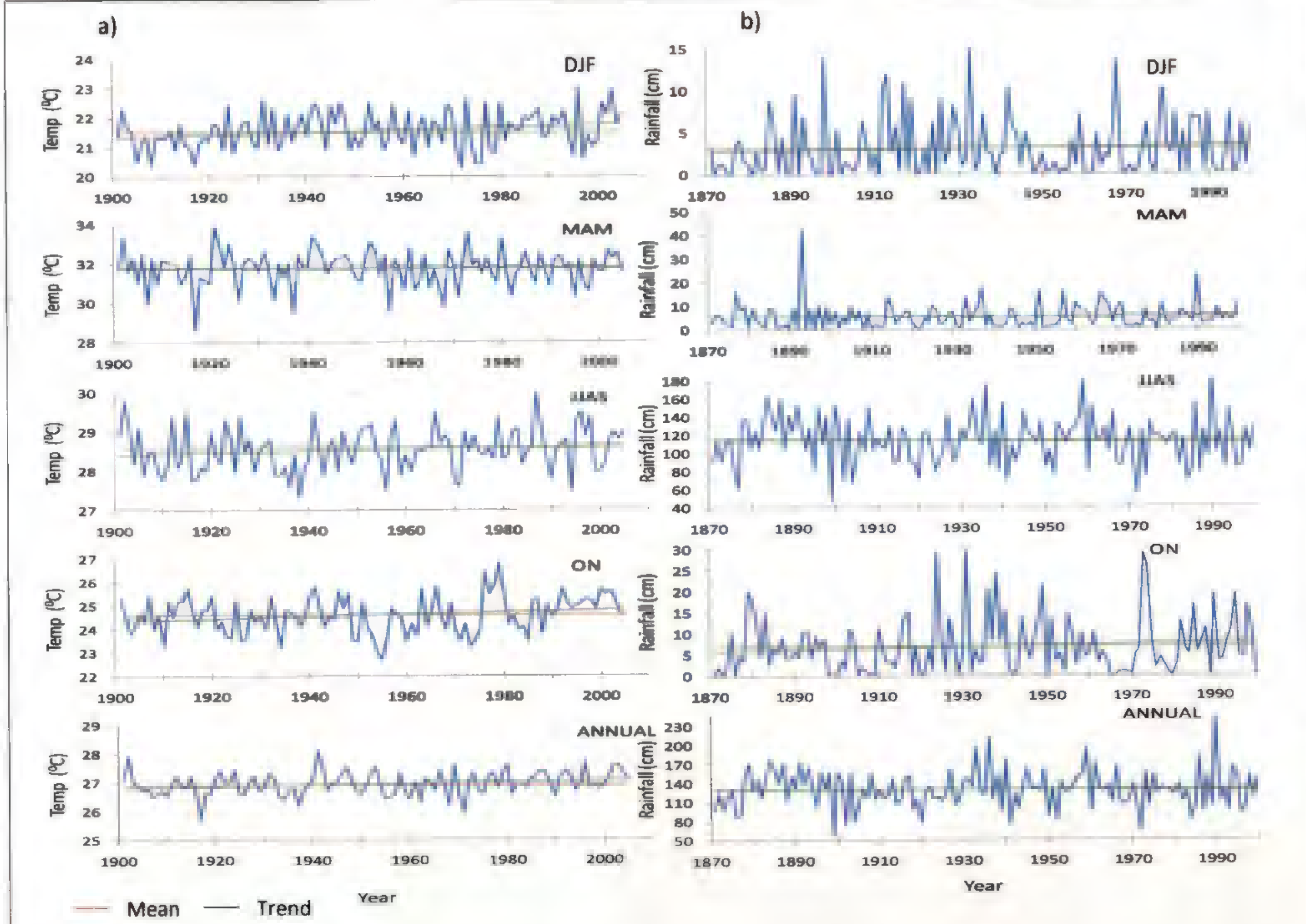


Fig. 22 (a,b) Temperature (100 years) and Rainfall(130 years) trend over Nagpur

4.6 RESPONSE FUNCTION ANALYSIS

Response of tree growth to climate has been calculated by multiple regression analysis using Nagzira site chronology (NAGZ chronology), Allapalli site chronology (ALLA chronology), Edugurapalli site chronology (EDUG chronology), and Thatibanda site chronology (THAT chronology) along with meteorological data (IMD and CRU data). Response function was calculated one by one for each tree ring site and the relationship has been built. Response of individual site to climate is discussed below:

4.6.1 NAGZ Chronology and Nagpur Climate Data

Monthly climatic record (temperature and precipitation) of Nagpur and corresponding CRU data along with NAGZ chronology used in the process of response function analysis. A continuous record of monthly precipitation of Nagpur is available for 1871-2002 whereas temperature data available from 1901-2003. The grid point of the CRU data (monthly temperature and rainfall) is close to sapling site. As discussed earlier in the chapter, the correlation between Nagpur and CRU data is highly significant .001 percent level. Response functions of NAGZ in relation to monthly temperature and rainfall of Nagpur and CRU data are shown in Fig. 23 (a and b) respectively. Vertical bars give significant response function.

Pre-monsoon (March-April-May) temperature shows significant negative response while the precipitation during the same months shows positive response in both Nagpur and CRU data. However, June and July rainfall shows a significant positive relationship. During other months (e.g. winter) there is no any pattern of significant relationship.

4.6.2 ALLA Chronology and Chandrapur Climate Data

ALLA site is close to the Chandrapur Met station and also comparatively closer to NAGZ tree-ring site than EDUG and THAT site. Fig. 24 (a, b) indicates the response function of ALLA with Chandrapur station data and corresponding CRU grid data respectively. The climatology of Chandrapur is very much similar to the Nagpur Climatology. Correlation between ALLA and NAGZ chronologies is also positively significant (Table 6). Hence the pattern of the response function is more or less similar to that of NAGZ with Nagpur. Chandrapur temperature during summer months shows more significant negative relationship as compare to the CRU temperature. Positive relationship with summer months (March-July) rainfall is more substantial than the CRU rainfall.

4.6.3 EDUG Chronology and Hanamkonda Climate Data

EDUG tree-ring site is more eastward to NGZ and ALLA tree-ring sites. The nearest observatory station selected for the response function analysis is Hanamkonda. As discussed in Chapter-4, climatology of the station is very similar to Nagpur and Chandrapur. However, post-monsoon month (October) rainfall is comparatively slightly more. In case of temperature, trend in seasonal and annual surface mean temperature has been increased from west to east (From Nagpur to Masulipatnam). This pattern is more significant during recent 40 years. The response functions, pattern with Hanamkonda climate (Figure 25 (a, b)) is similar to that of NAAGZ and ALLA. However, July and August temperatures show significant negative relationship with tree growth. A decreasing trend is evident in the recent 40 years overall rainfall. Temperature shows a significant increasing trend in all the season except pre-monsoon (Table 10). This may impact on moisture availability, more significantly during these months,

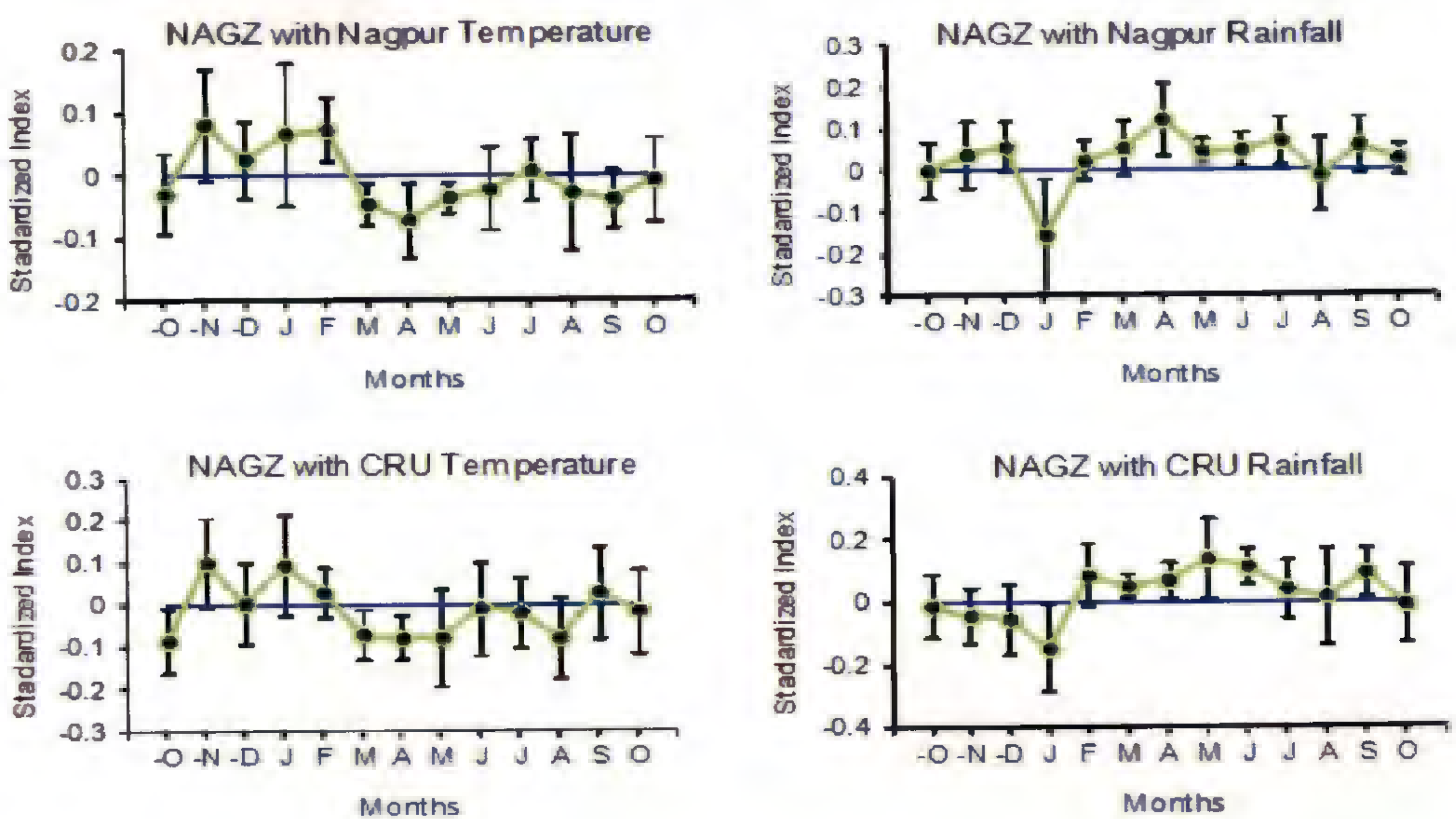


Fig. 23 Response of NAGZ with Nagpur meteorological station data and CRU data (Temperature and Rainfall)

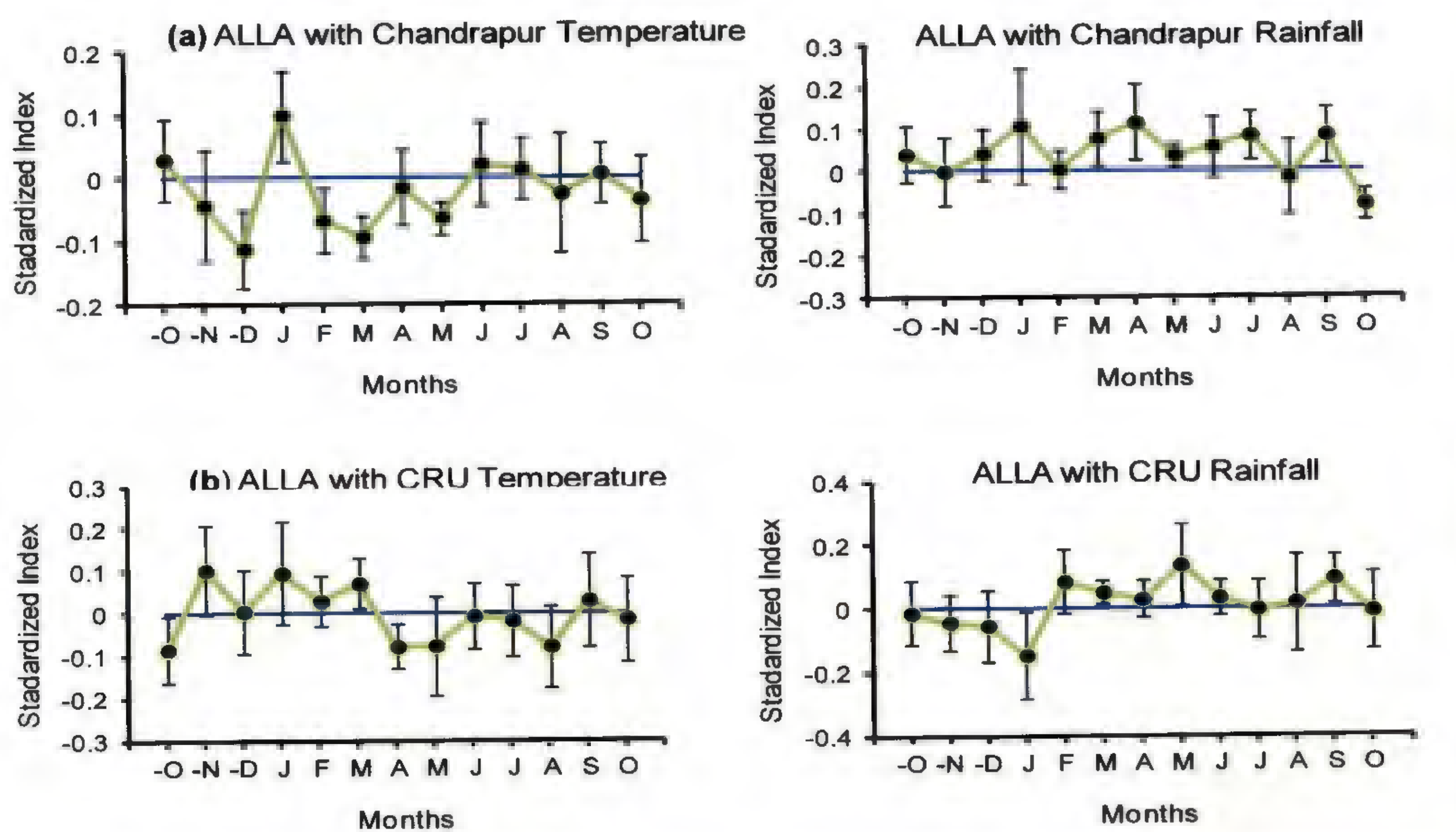


Fig. 24 Response of ALLA with Chandrapur meteorological station data and CRU data (Temperature and Rainfall)

hence the negative relationship. However, the general pattern of negative response of temperature during summer months and positive response of rainfall during the summer and monsoon month is important in the analysis. Similar patterns of relationship with CRU data are also evident, but the signal is weak (Fig. 25 .b)

4.6.3 THAT Chronology and Masulipatnam Climate Data

Site location of THAT is far eastward to NAGZ, ALLA and EDUG tree-ring sites. The nearest observatory station selected for the response function analysis is Masulipatnam. CRU grid point selected for THAT is comparatively closer than observatory station Masulipatnam. Significant at the .001 percent level. Masulipatnam is coastal station and strongly influenced by South-west as well as North-east monsoon. Therefore, the amount of rainfall is significantly higher during monsoon (JJAS) and post-monsoon (ON) months compared to the other months. Temperature shows a significant increasing trend which is more significant during recent few decades. Fig. 26 a and b represents the response of station data and CRU data respectively on THAT chronology. The relationship of THAT with climate is somewhat similar to the relationship observed in other three tree-ring chronologies. It is observed that significant positive response with rainfall of summer monsoon is extended till October due to additional rains of the North-east monsoon. CRU data signals are slightly better than signals of observed data in THAT chronology

4.7 COMMONALITY IN TREE GROWTH - CLIMATE RELATIONSHIP

The various response function analyses carried out over different regions of central India clearly indicate the crucial role played by the summer climate in tree growth. All the four cases, for which the relationships between tree growth and climate have been studied, show more or less similar behavior of the growth responses to summer climate. The significant negative response of summer temperature associated with the positive response of summer rainfall is mainly related to the availability of moisture which is a function of both temperature and rainfall. As observed in the earlier section, the climatology of the sampling sites based on the long-term records shows similar patterns of annual variation of monthly temperature and rainfall. These patterns are slightly different at a coastal region (Masulipatnam) where North-east monsoon influence is also significant. Hanamkonda also shows some influence of North-east monsoon. Temperature over most part of the region gradually increases above the annual average from March. May is the hottest month of the pre-monsoon (March-April-May) season. This result in an increase in the rate of evaporation of available moisture received from the small amount of rainfall during the season. As this season coincides with the early part of the active growth period (March-June) of the teak, a loss of moisture due to extensive heating affects tree growth. Therefore, though the higher temperature accelerates the photosynthesis, significant moisture deficiency occurs due to high rate of evaporation and evapotranspiration. This may largely explain the negative relationship with temperature of pre-monsoon (March-April-May) season as observed in the analysis. More than average rainfall during the season is very useful in maintaining the minimum requirement of moisture and is found to be conducive for tree growth. Rainfall increases by June. About 75 percentage of the total rainfall occurs during the monsoon (June-July-August-September) season. Therefore, during this period, moisture stress condition does not persist for prolonged periods, though the temperatures during the season are maintained at relatively higher level. In case of Thatibanda and Masulipatnam relationship the significant positive relationship with summer month's rainfall extends till October, mainly due to North-east monsoon rainfall.

In this thesis work, the reconstruction of the past climate based on the tree growth, climate relationship has not been done due to limited network of tree-ring data in space and time as well as the lack of significant correlation between 4 chronologies developed for sites (Table 6). The study has deciphered the significant impact of local climate on tree growth. As already discussed in chapter 3, local climate of the study sites are varying from Maritime climate to continental climate. Significant correlation between chronologies is available only at Nagzira and Allapalli which may be attributed to the closeness of the sites and similarity of local climate persisting in these regions (Continental climate). Thatibanda and Edugurapalli chronologies are not showing good correlation despite of their influence from maritime climate, which can be attributed to the huge difference in elevation (Table 3). Even though individual chronologies are showing promising results about the potential for reconstruction of local climate, results uncloaks the inadequateness of these chronologies for the reconstruction of past climate from central India. These site chronologies are insufficient to reconstruct the central India climate. However, with longer chronologies over a wider area; reconstruction of Indian monsoon climate can be extended back to cover the entire Little Ice Age Period.

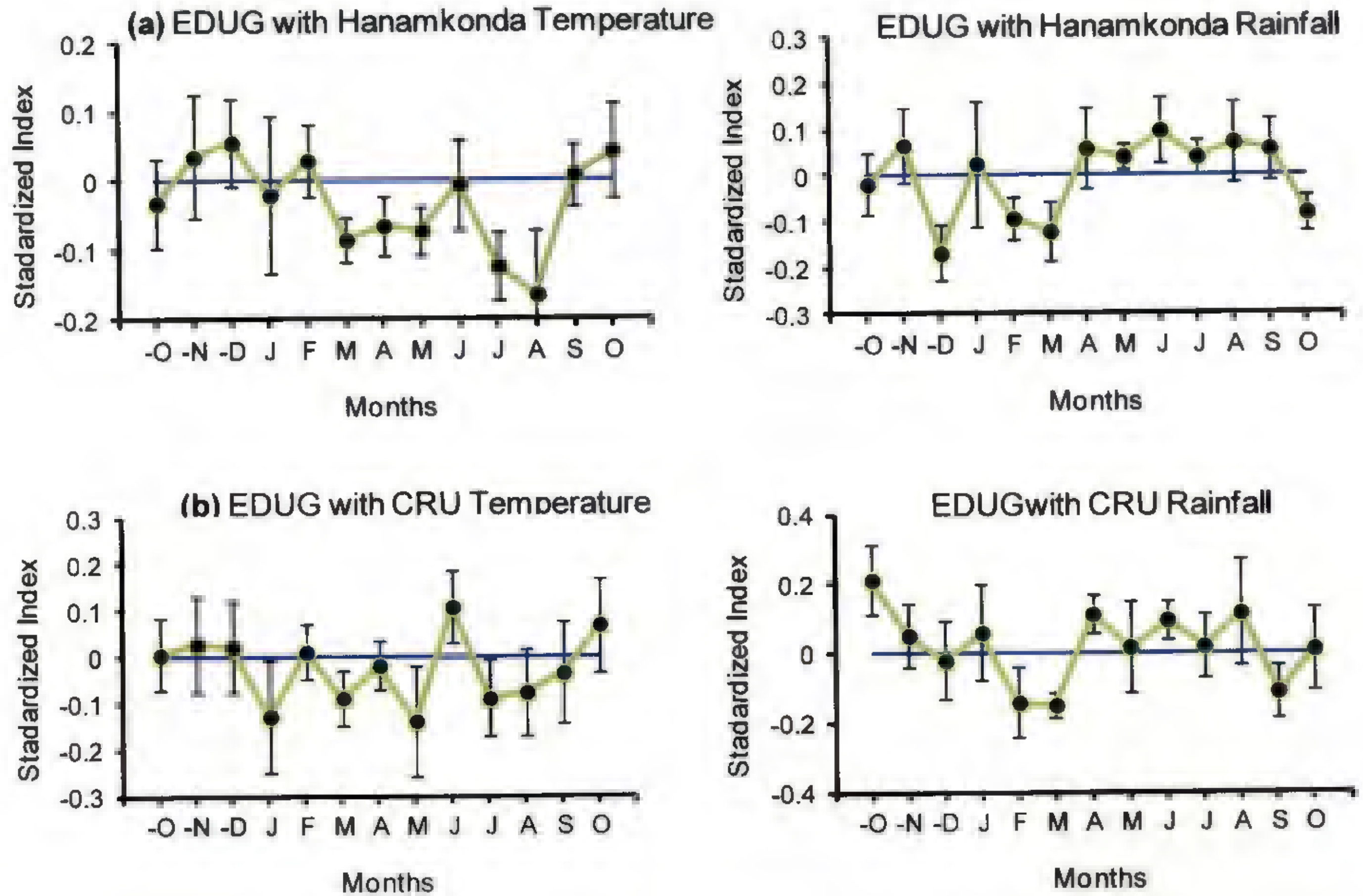


Fig. 25 Response of EDUG with Hanamkonda meteorological station data and CRU data (Temperature and Rainfall)

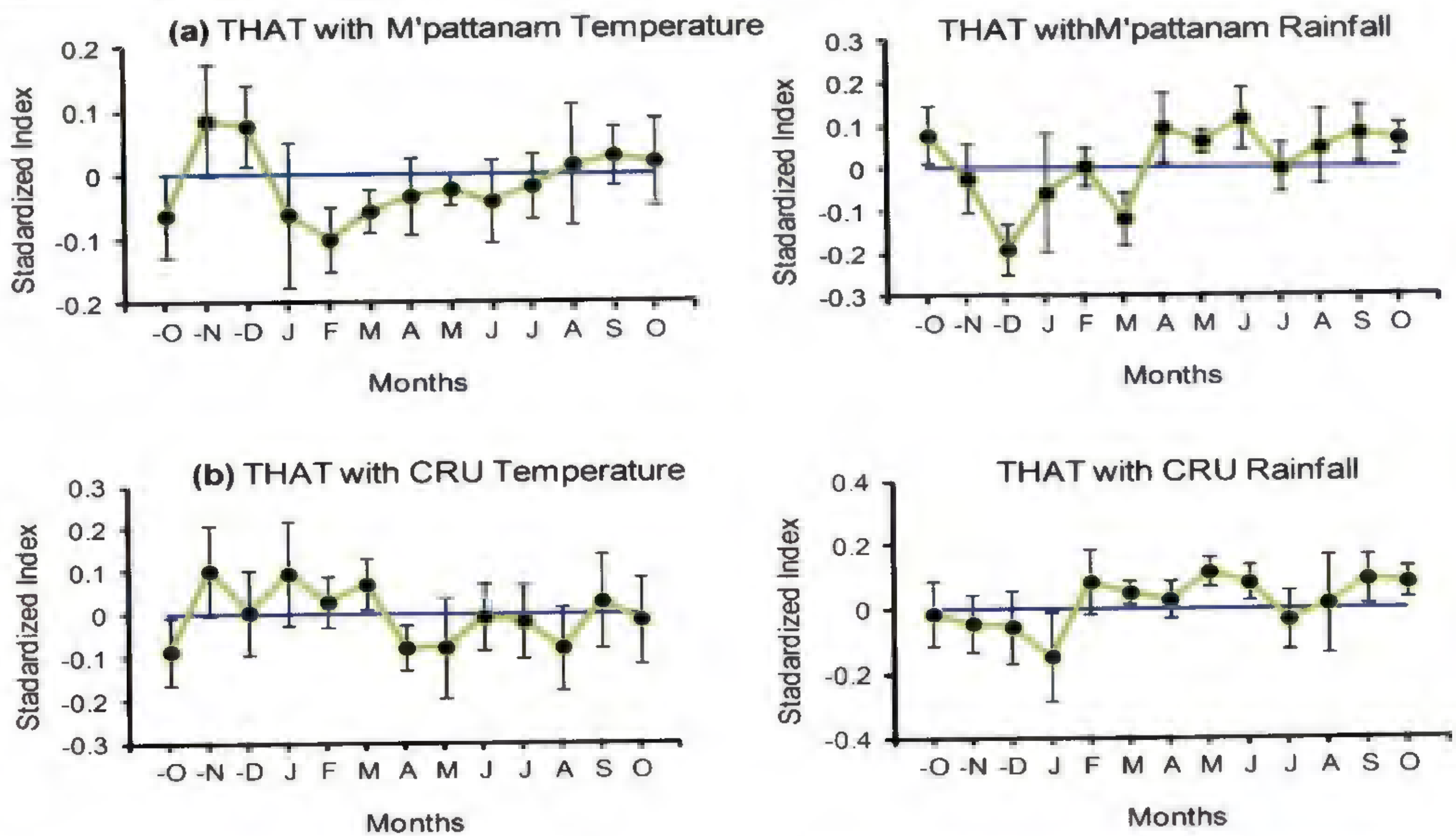


Fig. 26 Response of THAT with Masulipatnam meteorological station data and CRU data (Temperature and Rainfall)

CHAPTER 5
SUMMARY AND CONCLUSIONS

The primary interest of the project was to develop tree-ring data base of four different tree-ring sites over the central India and study their climate response to understand the tree growth - climate relationship.

During the project activity, Teak (*Tectona grandis* L. f.) tree-ring data from four sites from central India have been used. The sites are selected along the east-west transect from the east coast region (Thatibanda tree-ring site) to the Central India covering tree-ring sites Edugurapalli, Allapalli to Nagzira of central India. Thatibanda site is close to east coast and receives good rainfall during southwest (JJAS) as well as northeast (ON) monsoon season. Remaining three tree-ring sites, mostly receive rainfall during southwest monsoon season. Edugurapalli also receives a small amount of northeast monsoonal rains but comparatively less than the Thatibanda. Maximum rainfall is received during monsoon (June to September). However, during pre-monsoon (March-May) season rainfall is very less and season is the warmest. To understand the climatic impact on teak tree growth along the east west transact, I have selected four tree-ring sites. All the sites are influenced by southwest monsoon and in addition to that one costal site is also influenced by northeast monsoon rainfall. Another important purpose of the study is to get acquainted myself with dendrochronological and dendroclimatological procedures with hand on practical exercise.

5.1 TREE-RING DATA BASE

Tree core samples of teak (*Tectona grandis*) from four different sites of central India, which were collected by IITM, Pune have been used in the analysis. With this set of raw material, I did all dendrochronological analysis in the laboratory, including surfacing, skeleton plot, cross matching, dating, and ring width measurement. This was an important aspect of my project program to learn the basic dendrochronological techniques. Ring width measurement system has been used for efficient and accurate measurement of ring widths, with an accuracy of 10^{-3}cm. The samples have been microscopically examined at various stages of processing, cross-matching and examination of anatomical details of anomalous rings to detect the false and double rings. About 96 data series of ring widths from well dated samples have been used for further analysis.

5.2 CHRONOLOGY DEVELOPMENT AND ITS DENDROCLIMATIC POTENTIAL

Ring width series indicate the resultant annual growth patterns of the trees, representing the aggregate effect of many internal and environmental signals including climatic and non-climatic factors like biological aging, local endogenous disturbances due to competition among the trees and exogenous disturbances caused by fire, pests, disease, pollution etc. Appropriate detrending methods such as negative exponential, cubic spline smoothing, linear regression have been applied to the individual ring width series depending upon the nature of the series to minimize non-climatic signals. The ring width series, thus filtered out, are called the index series and contain large variance due to climatic influences. Site chronologies have been prepared by averaging all the index series from a particular site. Various statistics for four chronologies have been studied to evaluate their dendroclimatic potentiality. The chronologies suitable to use in climatic reconstruction are expected to have (i) high values of mean sensitivity, (ii) low persistence (auto-correlation), (iii) high standard deviation and (iv) high values of common variance and signal to noise ratio (Fritts, 1976). The present chronologies show more persistence (auto-correlation) in the series and moderate values of mean sensitivity. Common variance and signal to noise ratios based on common period show moderately high values.

5.3 CLIMATE DATA ANALYSIS

Analysis of surface mean air temperature of four stations namely Nagpur, Chandrapur, Hanamkonda and Masulipatnam which are widely distributed over the study area indicates increasing trend in most of the seasons during 20th century. More warming during recent four decades is noticed in Hanamkonda and coastal station Masulipatnam. The overall increasing tendency in temperature in all the seasons over the study area indicates a definite warming during 20th century and recent four decades. Similar patterns were observed over entire Indian region (Kothawale and Rupa Kumar, 2005), Northern Hemisphere (Mann et al. 1999) and in many other parts of the globe (Jones *et al*. 1999; Jones and Moberg,2003). However, rainfall series of the four stations does not show any definite increasing or decreasing tendency.

5.4 TREE GROWTH-CLIMATE RELATIONSHIPS

The standardized index series contain large climate signal compared to those of raw ring-width series. These index chronologies are correlated with regional climatic parameters to study the association between tree growth and climate. The main purpose of the study is to find out reliable relationship between tree-ring variations and various climatic parameters which are statistically significant, to establish the equations which can be used for the reconstruction of these parameters over the earlier period to the instrumental record.

In the development of the relationship between climate and tree growth, the response function analyses have been used. For this purpose, data of monthly mean surface temperature and precipitation of four stations, namely Nagpur, Chandrapur, Hanamkonda and Masulipatnam along with the corresponding tree-ring chronologies namely NAGZ, ALLA, EDUG and THAT respectively have been used. I have also used CRU grid point data of monthly mean temperature and rainfall index. Many times observatory station data are far away from the tree-ring site location, in such cases, the data of CRU grid close to tree-ring site is can be used for comparison and better understanding of tree growth climate relationship.

Tectona grandis has active growth period from March to October and November to February is the dormant period. Therefore, climate variables from the previous October (ending month of prior growth period) to current October (ending month of the current growth period) have been used in the analysis. Response function analyses suggest the importance of the critical role played by summer climate of the respective region in tree growth. Significant negative relationship of tree-ring chronologies with summer temperatures and positive relationship with summer and monsoon precipitation is the characteristic feature of the analyses.

Central India is the core region of the Indian southwest monsoon. More than 70 percentage of total annual rainfall have received in these months. Some east coast regions have also received a good amount of northeast monsoon rainfall. Temperatures over the region gradually increase above the annual average from March resulting in the increase of the rate of evaporation of the available moisture obtained from the small amount of precipitation during the season. Therefore, though at higher temperature photosynthesis accelerates, significant moisture deficiency occurs due to high rate of evaporation and evapotranspiration. This may largely explain the significant negative relationship with pre-monsoon (MAM) summer temperature as observed in the response function analysis. More than average precipitation during the pre-monsoon is very useful in maintaining the minimum requirement of moisture and is found to be conducive for tree growth, hence the significant positive relationship. In general, precipitation has a positive influence on tree growth. Summer months (May-September) show a relatively more significant and consistent positive influence on all tree-ring chronologies, however, in case of THAT chronology, which is close to the east coast, influence of precipitation is extended to October due to a good amount of northeast monsoon rainfall. This possibly represents the same physiological response of the tree to climate variations, particularly in view of the negative relationship between summer temperature and precipitation.

In this thesis work, reconstruction of the past climate based on the tree growth, climate relationship has not been attempted due to limited network of tree-ring data in space and time. However, with longer chronologies over a wider area, reconstruction of Indian monsoon climate can be extended back to cover the entire Little Ice Age Period.

5.5 CONCLUSIONS

A brief summary of the subject under study has been presented in the above section. Some important conclusions based on the observations, data analysis, statistical analysis carried out during the different stages of preparation of the thesis are listed below. These conclusions may be useful and could provide some directives for further studies in the discipline.

- *Tectona grandis* from a wide area of central India show high dendroclimatic potential and would be useful in past climate reconstruction.
- The seasonal and annual mean temperature pattern over the four stations, namely Nagpur, Chandrapur, Hanamkonda, Masulipatnam of central and east coast region indicate a general increasing trend during the past hundred years.
- An average anomalous feature of seasonal and annual rainfall of these four stations distantly located to each other do not show any significant increasing or decreasing tendency during last more than 100 years.
- Common period statistics show moderately high values of common variance and signal to noise ratio for each chronology, which suggests the high dendroclimatic potentiality of the chronologies.
- The results of response function analyses indicate a more or less similar relationship between regional climate and tree growth. Summer temperature and rainfall play an important role in tree growth - climate relationship. Higher

temperature and lower precipitation during the summer months create unfavorable conditions for tree growth.

REFERENCES

Anish, M. C., Anoop, E. V., Vishnu, R., Sreejith, B. and Jijeesh, C. M. 2015. Effect of growth rate on wood quality of teak (*Tectona grandis* L. f.): a comparative study of teak grown under differing site quality conditions. *J. Indian Acad. Wood Sci.* 12(1): 81–88.

Baas, P. and Vetter, R. E. 1989. Growth rings in tropical trees. *IAWA Bull.* 10: 95-174.

Berger, A. L., Guiot, J., Mathieu, L. and Munaut, A. V. 1979. Tree-Ring and climate in Morocco. *Tree-Ring Bull.* 39: 61-75.

Berlage, H. P. 1931. On the relationship between thickness of tree rings of Djati (teak) trees and rainfall on Java. *Tectona* 24: 939–953.

Bhattacharyya, A., LaMarche, J., Valmore, C., Telewski and Frank, W. 1988. Dendrochronological Reconnaissance of the Conifers of Northwest India. *Tree-Ring Bull.* 48: 21–30.

Bhattacharyya, A., Shah, S. K. and Chaudhary, V. 2006. Would tree ring data of *Betula utilis* be potential for the analysis of Himalayan glacial fluctuations?. *Curr. Sci.* 91(6): 754–761.

Bhattacharyya, A. and Yadav, R. R. 1989. Dendroclimatic research in India. *Proc. Indian Nat. Sci. Acad.* 55: 696–701.

Bhattacharyya, A. and Yadav, R. R. 1999. Climatic reconstructions using tree-ring data from tropical and temperate regions of India - A review. *IAWA Bull.* 20:311–316.

Bhattacharyya, A., Yadav, R. R., Borgaonkar, H. P. and Pant, G. B. 1992. Growth-ring analysis of Indian tropical trees: dendroclimatic potential. *Curr. Sci.* 62(11): 736–741.

Bilham, R., Pant, G. B. and Jacoby, G. C. 1983. Dendroclimatic potential of juniper trees from the Sir Sar range in the Karako-ram. *Man Environ.* 7: 45–50.

Borgaonkar, H. P. 1996. Ring-Width Variations in *Cedrus Deodara* and Its Climatic Response Over the Western Himalaya. *Int. J. Climatol.* 16:1409–1422.

Borgaonkar, H. P., Pant, G. B. and Rupa Kumar, K. 1994. Dendroclimatic reconstruction of summer precipitation at Srinagar, Kashmir, India, since the late-eighteenth century. *Holocene* 4(3): 299–306.

Borgaonkar, H. P., Sikder, A. B., Ram, S. and Pant, G. B. 2010. El Nino and related monsoon drought signals in 523-year-long ring width records of teak (*Tectona grandis* L.F.) trees from south India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 285: 74-84.

Bradley, R. S. 1985. Quaternary paleoclimatology: methods of paleoclimatic reconstruction. London and Boston: Boston: Allen & Unwin. ISBN 0-04-551067-9.

Brandis, D. 1879. Memorandum on the rate of growth of teak. *Indian Forest.* 4(3): 215-225.

Buckley, B. M., Anchukaitis, K. J., Penny, D., Fletcher, R., Cook, E. R., Sano, M. and Hong, T. M. 2010. Climate as a contributing factor in the demise of Angkor, Cambodia. *Proc. Natl. Acad Sci. U.S.A.* 107(15): 6748- 6752.

Buckley, B. M., Barbetti, M., Watanasak, M., Darrigo, R., Boonchirdchoo, S. and Sarutanon, S. 1995. Dendrochronological investigations in Thailand. *Iawa J.*, 16(4): 393–409.

Buckley, B. M., Cook, B. I., Bhattacharyya, A., Dukpa, D. and Chaudhary, V. 2005. Global surface temperature signals in pine ring-width chronologies from southern monsoon Asia. *Geophys. Res. Lett.* 32(20): 1–4.

Buckley, B. M., Duangsathaporn, K., Palakit, K., Butler, S., Syhapanya, V. and Xaybouangeun, N. 2007a. Analyses of growth rings of Pinus merkusii from Lao P.D.R. *For. Ecol. Manage* 253:120–127.

Buckley, B. M., Palakit, K., Duangsathaporn, K., Sanguantham, P. and Prasomsin, P. 2007b. Decadal scale droughts over northwestern Thailand over the past 448 years: Links to the tropical Pacific and Indian Ocean sectors. *Climate Dynam.* 29(1):63–71.

Chaudhary, V. and Bhattacharyya, A. 2002. Suitability of Pinus kesiya in Shillong, Meghalaya for tree-ring analyses. *Curr. Sci.* 83(8):1010–1015.

Chen, F., Yu, S., He, Q., Zhang, R., Kobuliev, Z. V. and Mamadjonov, Y. M. 2016. Comparison of drought signals in tree-ring width records of juniper trees from Central and West Asia during the last four centuries. *Arab. J. Geosci*. 9(4): 255.

Chowdhury, K. A. 1964. Growth rings in tropical trees and taxonomy. *J. Indian Bot. Soc.* 43: 334–342.

Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C. and Wright, W. E. 2010. Asian monsoon failure and megadrought during the last millennium. *Sci.* 328: 486-489.

Cook, E. R. and Holmes, R. L. 1986. Users manual for program ARSTAN. Laboratory of Tree-Ring Research, University of Arizona, Tucson, p.15.

Cook, E. R., Krusic, P. J., Anchukaitis, K. J., Buckley, B. M., Nakatsuka, T. and Sano, M. 2013. Tree-ring reconstructed summer temperature anomalies for temperate East Asia since 800 C.E. *Clim. Dyn.*, 41: 2957–2972.

Cook, E. R. and Peters, K. 1981. The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bull.*, 41:45–53.

Coster, C. 1927. Zur Anatomie und Physiologie der Zuwachszonen und Jahresringbildung in den Tropen I. *Ann. Jard. Bot. Buitenzorg* 37:49–161.

D'Arrigo, R., Barbetti, M., Watanasak, M., Buckley, B., Krusic, P., Boonchirdchoo, S. and Sarutanon, S. 1997. Progress in dendroclimatic studies of mountain pine in northern Thailand. *IAWA J.* 18(4):433–444.

D'Arrigo, R., Jacoby, G. C. and Krusic, P. J. 1994. Progress in Dendroclimatic studies in Indonesia. *TAO*, 5(3):349–363.

D'Arrigo, R., Palmer, J., Ummenhofer, C. C., Kyaw, N. N. and Krusic, P. 2011. Three centuries of Myanmar monsoon climate variability inferred from teak tree rings. *Geophys. Res. Lett.* 38(24): 705.

D'Arrigo, R. and Smerdon, J. E. 2008. Tropical climate influences on drought variability over Java, Indonesia. *Geophys. Res. Let.* 35(5): 707.

D'Arrigo, R. and Ummenhofer, C. C. 2015. The climate of myanmar: Evidence for effects of the pacific decadal Oscillation. *Int. J. Climatol.* 35(4):634–640.

Dahms, K. G. 1989. Das Holzportrait Teak (*Tectona grandis* L. f.). *Holz Als Roh-Und Werkstoff* 47(3):81–85.

Dawadi, B., Liang, E., Tian, L., Devkota, L. P. and Yao, T. 2013. Pre-monsoon precipitation signal in tree rings of timberline Betula utilis in the central Himalayas. *Quat. Int.* 283: 72–77.

De Boer, J. H. 1951. Tree-ring measurements and weather fluctuations in Java from A.D. 1514. *Kon Ned Akad Wetensch* 54:194–209.

Deepak, M. S., Sinha, S. K. and Rao, V. V. 2010. Tree-ring analysis of teak (Tectona grandis L. f.) from western ghats of india as a tool to determine drought years. *Emir. J. Food Agric.* 22(5):388–397.

Dié, A., De Ridder, M., Cherubini, P., Kouamé, F. N., Verheyden, A., Kitin, P., Beeckman, H. 2015. Tree rings show a different climatic response in a managed and a non-managed plantation of teak (*Tectona grandis* L. f.) in West Africa. *IAWA J.* 36(4): 409–427.

Döll, P. 2002. Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective. *Clim. Chang.* 54: 269–293.

Douglass, A. E. 1914. A Method of Estimating Rainfall by the Growth of Trees. *Bull. Am. Meteorol. Soc.* 46(5):321–335.

Douglass, A. E. 1935. Dating Pueblo Bonito and Other Ruins of the Southwest, National Geographic Society, p.76.

Esper, J., Cook, E. and Schweingruber, F. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Sci.* 295: 2250–2253.

Fritts, H. C. (1976). Tree Rings and Climate. Academic, San Diego, Calif., 567 p.

Fritts, H. C., Lofgren, G. F. and Gordon, G. A. 1979. Variations in climate since 1602 as reconstructed from tree rings. *Quat. Int.* 12:18–46.

Fritts, H. C. and Wu, X. 1986. A Comparision Between Response Function Analysis and Other Regression Techniques. *Tree-Ring Bull.* 46:31–46.

Gou, X., Deng, Y., Gao, L., Chen, F., Cook, E., Yang, M. and Zhang, F. 2015. Millennium tree-ring reconstruction of drought variability in the eastern Qilian Mountains, northwest China. *Clim. Dyn.* 45(7–8):1761–1770.

Graybill, D. A. 1979. Revised computer programs for tree-ring research. *Tree-Ring Bull.* 39: 77–82.

Guiot, J. 1985. The Extrapolation of Recent Climatological Studies with Spectral Canonical Regression. *J. Climatol.* 5: 325–335.

Gyi, K. and Tint, K. 1985. Management of natural teak forests in teak for future. In Proceeding of the second regional seminar on Teak for the Future, Myanmar, FAO, pp. 249.

Hlaing, Z. C., Teplyakov, V. K. and Thant, N. M. L. 2014. Influence of climate factors on tree-ring growth in teak (*Tectona grandis* L. f.) plantations in the Bago Yoma Range, Myanmar. *For. Sci. Technol.* 10(1): 40–45.

Holmes, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull.* 43:69-78.

Huber, B. 1941. Aufbau einer mitteleuropäischen Jahrring -Chronologie. Mitteilung A Kad. *Dtsch. Forstwiss*. 1:110–125.

Huges, M. K. 1982. Climate from tree rings. Melbourne: Cambridge University Press.

Jacoby, G. C. 1989. Overview of tree-ring analysis in tropical regions. *IAWA j.* 10(2): 99–108.

Jacoby, G. C. and D'Arrigo, R. D. 1990. Teak (*Tectona grandis* L.f.), A tropical species of large-scale dendroclimatic potential. *Dendrochronologia* 8: 83–98.

Jones, P. D. and Moberg, A. 2003. Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Climate* 16(2):206–223.

Jones, P. D., New, M., Parker, D. E., Martin, S. and Rigor, I. G. 1999. Surface air temperature and its changes over the past 150 years. *Rev. Geophys.* 37(2):173–199.

Kang, S., Bräuning, A. and Ge, H. 2014. Tree-ring based evidence of the multi-decadal climatic oscillation during the past 200 years in north-central China. *J. Arid Environ.* 110: 53–59.

Kothawale, D. R., Munot, A. A. and Borgaonkar, H. P. 2008. Temperature variability over the Indian Ocean and its relationship with Indian summer monsoon rainfall. *Theor. Appl. Climatol.* 92:31–45.

Kothawale, D. R. and Rupa Kumar, K. 2005. On the recent changes in surface temperature trends over India. *Geophys. Res. Let.* 32(18):1–4.

Kumar, K., Rajagopalan, B. and Cane, M. 1999. On the weakening relationship between the indian monsoon and ENSO. *Sci.* 284:2156–2159.

Lamprecht, H. 1986. Waldbau in den. Tropen Die tropischen Waldo¨kosysteme und ihre Baumarten – Mo¨glichkeiten und Methoden zu ihrer nachhaltigen Nutzung. Paul Parey, Hamburg, p. 318.

Liese, W. 1986. To the memory of Sir Dietrich Brandis. *Indian For.* 112(8): 639–645.

Lofgren, G. R., Hunt, J. H. and Gray, B. M. 1982. Trasfer Functions. In: V. Hughes, M., Kelly, P. M., Pilcher, J. R. and LaMarche (ed.), Climate from Tree Rings. Cambridge: Cambridge University Press, pp. 50–58.

Mann, M. E., Bradley, R. S. and Hughes, M. K. 1999. Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations. *Geophys. Res. Let.* 26(6):759–762.

Murphy, J. O., and Whetton, P. H. 1989. Re-analysis of tree ring chronology from Java. *Proc. Kon. Ned. Akad. Wetensch* 92: 241–257.

Murphy, J. O., Whetton, P. H. and Ritsema, A. R. 1989. A re-analysis of a tree ring chronology from Java. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen Series B. Palaeontology, Geology, Physics, Chemistry, Anthropology, 92(3): 241–257.

Pachauri, R. K. and Reisinger, A. 2007. IPCC fourth assessment report. IPCC Fourth Assessment Report. Cambridge University Press, Cambridge, UK, 996p.

Pant, G. B. 1979. Role of tree-ring analysis and related studies in palaeo-climatology: preliminary survey and scope for Indian Region. *Mausam*, 30:439-448.

Pant, G. B. and Borgaonkar, H. P. 1983. Growth rings of teak trees and regional climatology (an ecological study of Thane region). *Environ. Manage.*, pp.153-158.

Pant, G. B., and Borgaonkar, H. P. 1984. Growth rate of Chir pines (Pinus roxburghii) trees in Kumaon area in relationship to regional climatology. *Himalayan Res. Dev.* 3:1-5.

Parthasarathy, B., Munot, A. A. and Kothawale, D. R. 1995. Monthly and Seasonal Rainfall Series for All-India Homogeneous Regions and Meteorological Subdivisions. *Indian Inst. Trop. Meteorol.* 1871 – 1994.

Pumijumnong, N. 1995. Dendrochrnologie mit Teak (*Tectona grandis* L. f.) in Nord-Thailand.

Pumijumnong, N. 2012. Teak Tree Ring Widths: Ecology and Climatology Research in Northwest Thailand. *Sci. Tech. Dev.* 31(2):165–174.

Pumijumnong, N. and Eckstein, D. 2011. Reconstruction of pre-monsoon weather conditions in northwestern Thailand from the tree-ring widths of Pinus merkusii and Pinus kesiya. *Trees Struct. Funct.* 25(1):125–132.

Pumijumnong, N., Eckstein, D. and Sass, U. 1995. Tree-Ring Research on Tectona grandis in Northern Thailand. *IAWA J.* 16(4):385–392.

Ram, S. 2012. On the recent strengthening of the relationship between Palmer Drought Severity Index and teak (*Tectona grandis* L. f.) tree-ring width chronology from Maharashtra, India: A case study. *Quat. Int.* 248:92–97.

Ram, S. and Borgaonkar, H. P. 2013. Growth response of conifer trees from high altitude region of Western Himalaya. *Curr. Sci.* 105(2):225–231.

Ram, S. and Borgaonkar, H. P. 2014. Climatic response of various tree ring parameters of fir (*Abies pindrow*) from Chandanwani in Jammu and Kashmir , western Himalaya , India. *Curr. Sci.* 106(11):1568–1576.

Ram, S. and Borgaonkar, H. P. 2016. Reconstruction of heat index based on tree-ring width records of western Himalaya in India. *Dendrochronologia*, 40:64–71.

Ram, S., Borgaonkar, H. P., Munot, A. A. and Sikder, A. B. 2011. Tree-ring variation in teak (*Tectona grandis* L. f.) from Allapalli, Maharashtra in relation to moisture and Palmer Drought Severity Index. *J. Earth. Syst. Sci.*120(4):713–721.

Ram, S., Borgaonkar, H. P. and Sikder, A. B. 2008. Tree-ring analysis of teak (*Tectona grandis* L.f.) in central India and its relationship with rainfall and moisture index. *J. Earth. Syst. Sci.* 117(5):637–645.

Ram, S., Borgaonkar, H. P. and Sikder, A. B. 2010. Varying strength of the relationship between tree-rings and summer month moisture index (April-September) over Central India: A case study. *Quat. Int.* 212(1):70–75.

Ram, S., Borgaonkar, H. P. and Sikder, A. B. 2011. Growth and climate relationship in teak trees from Conolly's plot, South India. *Curr. Sci.* 100(5): 630–633.

Sano, M., Buckley, B. M. and Sweda, T. 2009. Tree-ring based hydroclimate reconstruction over northern Vietnam from Fokienia hodginsi: Eighteenth century mega-drought and tropical Pacific influence. *Climate Dynam.* 33(2–3): 331–340.

Serre, F., and Tessier, L. 1990). Response Function Analyses for Ecological Study. In Cook, E. R. and Kairiukstis, L. A. (Ed.), Methods of Dendrochronology. Dordrecht: Kluwer Academic Publishers, pp. 247–258.

Singh, J. and Yadav, R. R. 2000. Tree-ring indications of recent glacier fluctuations in Gangotri, Western Himalaya, India. *Curr. Sci.* 79(11):1598–1601.

Yadav, R. R. and Park, W. K. 2000. Precipitation reconstruction using ring-width chronology of Himalayan cedar from Western Himalaya: Preliminary results; *Proc. Indian Acad. Sci.* 109:339–345.

Singh, J. And Yadav, R. R. 2005. Spring precipitation variations over the western Himalaya, India, since A.D. 1731 as deduced from tree rings. *J. Geophys. Res.* 110(1): 1–8.

Stokes, M. A.1996. An introduction to tree-ring dating. University of Arizona Press.

Stokes, M. A., and Smiley, T. L. 1968. An introduction to tree-ring dating. University of Chicago.

Venegas-González, A., Chagas, M. P., Anholetto Júnior, C. R., Alvares, C. A., Roig, F. A. and Tomazello, F. M. 2016. Sensitivity of tree ring growth to local and large-scale climate variability in a region of Southeastern Brazil. *Theor. Appl. Climatol.*, 123(1–2): 233–245.

White, P. S. 1979. Pattern, process, and natural disturbance in vegetation. *Bot. Rev.* 45(3):229–299.

Wigley, T. M. L., Briffa, K. R. and Jones, P. D. 1984. On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. *J. Clim. Appl. Meteorol.* 23: 201–213.

Williams, L. J., Bunyavejchewin, S. and Baker, P. J. 2008. Deciduousness in a seasonal tropical forest in western Thailand: Interannual and intraspecific variation in timing, duration and environmental cues. *Oecol.* 155(3):571–582.

Yadav, R. R. 2009. Tree ring imprints of long-term changes in climate in western Himalaya, *India. J. Biosci.* 34(5):699.

Yadav, R. R. 2011. Tree ring evidence of a 20th century precipitation surge in the monsoon shadow zone of the western Himalaya, India. *J. Geophys. Res. Atmos.* 116(2): 1–10.

Yadav, R. R., Braeuning, A. and Singh, J. 2011. Tree ring inferred summer temperature variations over the last millennium in western Himalaya, India. *Climate Dynam.* 36(7):1545–1554.

Yadav, R. R., Misra, K. G., Kotlia, B. S. and Upreti, N. 2014. Premonsoon precipitation variability in Kumaon Himalaya, India over a perspective of ~300 years. *Quat. Int.* 325:213–219.

Yadav, R. R., Park, W. K., Singh, J. and Dubey, B. 2004. Do the western Himalayas defy global warming?. *Geophys. Res. Lett.* 31:17201.

Yadav, R. R. and Singh, J. 2002. Tree-Ring-Based Spring Temperature Patterns over the Past Four Centuries in Western Himalaya. *Quat. Res.* 57(3):299–305.

Yadava, A. K., Bräuning, A., Singh, J. and Yadav, R. R. 2016. Boreal spring precipitation variability in the cold arid western Himalaya during the last millennium, regional linkages, and socio-economic implications. *Quat. Sci. Rev.* 144:28–43.

Yamazawa, K. 1929. Hida ni okeru kanei go nen irai no jumoku no seicho ni tsuite (On tree growth since A.D. 1628 in Hida province). *Kisho Shushi* 7(6): 86–190.

Yusef, A.A., Francisco, H., 2009. Climate change vulnerability mapping for Southeast Asia, Economy and Environment Program for Southeast Asia(EEPSEA) report, June 2009, 32p.

Zanon, M. L. B. and Finger, C. A. G. 2010. Relação de variáveis meteorológicas com o crescimento das árvores de Araucaria angustifolia (Bertol) Kuntze em povoamentos implantados. *Ciência Florestal* 20(3):467–476.

DENDROCLIMATIC ANALYSIS OF TEAK (*Tectona grandis* L. f.)

FROM CENTRAL INDIA

TO EVALUATE THE POTENTIAL FOR CLIMATE RECONSTRUCTION

by

REJI MARIYA JOY K.

(2011-20-122)

ABSTRACT OF THE THESIS

Submitted in partial fulfilment of the

requirements for the degree of

B. Sc. -M. Sc. (Integrated) CLIMATE CHANGE ADAPTATION

Faculty of Agriculture

Kerala Agricultural University

ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH

VELLANIKKARA, THRISSUR - 680 656

KERALA, INDIA,

2016

ABSTRACT

Paleoclimatology is the study of climate prior to the instrumental record. Instrumental records are available for a period nearly 100-150 years, which is inadequate for explaining the climate variability and climate change in past millennial time scale. Paleoclimatic data helps in testing the hypothesis about the causes of climate change. When the past climatic fluctuations are understood, the climatic variations in the future could possibly be anticipated. The science of reconstructing past climate by using tree rings is known as Dendroclimatology.

In the present dendroclimatic study, 96 teak core samples have been used from Allapalli (Ggadchiroli, 26 cores), Nagzira (Bhandra, 26 cores) of Maharashtra and Edugurapalli (Bhandrachalam, 18 cores), and Thatibanda (Visakhapattanam, 26 cores) of Andhra Pradesh by IITM. Samples were precisely cross dated and ring width was measured using stereo microscope and measurement setup along with the software 'TROPMET RINGS', after proper mounting, sanding, polishing and skeleton plotting. COFECHA program was used for checking the quality of cross-dating and measurement accuracy. Standardization of the tree ring series is an important aspect of dendroclimatology for removing the non-climatic signals from tree ring series and to improve the climatic signals. The computer program ARSTAN was used for this specific purpose. Common period statistics produced by ARSTAN show moderately high values of common variance and signal to noise ratio for each chronology, which suggests a high dendroclimatic potential of the chronologies.

Climate of site is very important to understand tree-growth climate relationship. Monthly, seasonal and annual climatic conditions over the sampling sites were analyzed by calculating climatology of stations using the data collected from nearby IMD stations. CRU TS (time-series) 3.20 data (0.5x0.5 degree resolution) of monthly gridded temperature and rainfall over a period of 1901-2011 was also used along with IMD data for analyzing the -growth climate relationship,

since the data showed good correlation with station data. Masulipatnam and Hanamkonda climate is influenced by both Southwest and Northeast monsoon whereas Chandrapur and Nagpur climate is influenced by South west monsoon only. Trend analysis of seasonal temperature data showed overall warming for all stations. Seasonal rainfall does not have a common trend for all stations.

The various response function analyses carried out over study sites in central India clearly indicate the crucial role played by the summer climate in tree growth. All the four cases, for which the relationships between tree growth and climate have been studied, show more or less similar behavior of the growth responses to summer climate (pre-monsoon). The significant negative response of summer temperature associated with the positive response of summer precipitation is mainly related to the availability of moisture which is a function of both temperature and precipitation. The study highlights the importance of moisture availability during beginning of tree growth and the potential of teak for the reconstruction of summer climate.