High resolution monsoon reconstruction using oxygen isotopes in teak trees

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By

Shreyas R. Managave

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Planetary and Geosciences Division
Physical Research Laboratory,
Navrangpura, Ahmedabad-380 009, India

Certificate

I hereby declare that the work presented in this thesis is original and has not formed the basis for the award of any degree or diploma by any university or institution.

Shreyas R. Managave (Author)
Planetary and Geosciences Division
Physical Research Laboratory
Navrangpura, Ahmedabad, 380009
India

Certified by:

Prof. R.Ramesh (Guide)
Planetary and Geosciences Division
Physical Research Laboratory
Navrangpura, Ahmedabad-380 009
India

Prof. L.S.Chamyal (Co-guide)
Department of Geology
The Maharaja Sayajirao University of Baroda
Vadodara -390 002
India

This Thesis is Dedicated

to

My Dear Parents

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ABSTRACT

Among various terrestrial climate proxies used for reconstruction of the past climate, it is advantageous to use trees for climate reconstruction as they have a wide geographic distribution, are annually resolved, show a continuous record, and are easily dated by ring-counting. Numerous dendroclimatological investigations have shown the efficacy of the ring-width and its isotopic composition ($\delta^{18}O$, $\delta^{13}C$ and δD) studies in reconstruction of past climate. It is further believed that the isotopic records of trees, especially from the tropical area, are more useful than ring-width records in reconstructing past climate.

Unlike stable isotope-based dendroclimatological investigations of temperate trees, the potential of tropical trees is yet to be fully realized, as only a few tropical species, such as teak (*Tectona grandis*), exhibit distinct and clearly datable growth rings. Wide geographical distribution of teak, especially in south and south-east Asia – India, Java, Sumatra, Burma, and Thailand – a region important for tracking the past history of El Nino- Southern Oscillation phenomenon, makes it an important candidate for dendroclimatology. Preliminary isotope studies had shown potential of teak in reconstructing past climate, especially rainfall.

To exploit the climatic potential of teak, it is thus important to know what governs its isotopic composition on annual as well as sub-annual scales. Recently developed plant physiological models help in constraining the isotopic composition of photosynthates produced during the growing season, which, coupled with newly developed, faster cellulose extraction techniques makes sub-annual isotope studies increasingly significant.

In the present study, teak from western, central and southern India were analysed for the oxygen isotopic composition ($\delta^{18}O$) for understanding what governs their $\delta^{18}O$ on annual and sub-annual scales. The understanding of this formed the basis for reconstruction of past rainfall.

The first chapter introduces the field of isotope dendroclimatology. It starts with stating importance of trees in reconstructing past climate and how isotope studies in general and $\delta^{18}O$ studies in particular are more advantageous than ring-width studies for deciphering past climate. The importance of a tropical tree species, teak, in understanding past tropical climate is then described. This is followed by a general discussion regarding processes governing $\delta^{18}O$ of trees, described under the atmospheric, soil water and plant physiological processes. This is followed by a brief review of experimental isotope dendroclimatology in which details regarding cellulose extraction and its isotope measurement using mass spectrometer is given. Subsequently, previous isotope dendroclimatological investigation in the tropical region is reported. The chapter ends with describing the statement and rationale behind the present study.

The second chapter describes experimental procedure followed in the present study. Initially, information about climatic setting of the sample sites has been described. An account of $\delta^{18}O$ data of rainwater observed at various stations in the peninsular India is also reported. This is followed by a detailed description of individual samples and their chronology. Method of cellulose extraction followed in the present study is described. Details of the mass-spectrometric measurements of the cellulose samples have been dealt with subsequently.

For sub-annual studies selected rings of various widths were manually sub-divided into various equal parts along a radial direction; the separated parts represent wood formed during various times of the growing season. The sub-annual cellulose $\delta^{18}O$ record of the separated parts was used to constrain factors governing $\delta^{18}O$ of cellulose during the growing season.

Cellulose was extracted using the recently developed faster cellulose extraction techniques with some modifications. The modification introduced in the present study helps to solve the problem of acetylation of cellulose reported in the literature.

The results of the sub-annual $\delta^{18}O$ analysis are described in Chapter 3. For sub-annual analysis, 10 to 17 rings from trees from central and southern India were selected and further divided into various equal parts. To identify what governs the $\delta^{18}O$ of photosynthates during growing season, a plant physiological model was employed and sub-annual $\delta^{18}O$ profiles were constructed using available local meteorological data. The comparison of modeled and actually observed values was done to understand relative importance of rainfall amount and its $\delta^{18}O$ and relative humidity in deciding $\delta^{18}O$ values of tree rings.

Sub-annual $\delta^{18}O$ analysis of several annual growth rings of three teak trees from central India revealed a seasonal cycle with higher values in the early and late growing seasons and lower values in the mid growing season, with amplitudes of 1.9 to 5.0 ‰ and upto 6.8 ‰ in coarse and fine resolution samplings, respectively. Relative humidity rather than the amount of rainfall appears to control the sub-annual $\delta^{18}O$ variations. Further, a comparison of the $\delta^{18}O$ profile of a ring (year 1971 A.D.), analyzed with the highest resolution, and a model profile based on concurrent local meteorological data reveals the possibility of achieving a resolution of ~20 days in monsoon reconstruction by sub-annual $\delta^{18}O$ measurements.

High and coarse resolution sub-annual analyses of $\delta^{18}O$ of teak cellulose from southern India, receiving both rains, the south-west (SW) (summer) and the north-east (NE) (winter, more depleted in ^{18}O) monsoons, show a seasonal cycle, with some degree of incoherence. The amplitudes vary between 1 to 3 ‰, with lower $\delta^{18}O$ values at the early and late growing seasons and higher values at the middle. The observed pattern is opposite to that reported for teak trees from central India, where the annual rainfall is unimodal, with much less NE monsoon rains. Comparison of the observed and modeled profiles reveals that the observed pattern of sub-annual $\delta^{18}O$ variation can be explained only if the tree sampled rainfall from both the monsoons. Thus it appears possible to detect excess NE monsoon years in the past by analyzing the $\delta^{18}O$ of cellulose from latewood of teak trees.

The fourth chapter deals with inter-annual $\delta^{18}O$ variations observed in various teak trees analyzed in the present study. The relationship observed between rainfall and cellulose $\delta^{18}O$ of the corresponding years depends upon the location within India. The trees from western and central India show a positive relationship (r ~0.4) with the amount of rainfall while teak tree from southern India shows a negative relationship (r ~ -0.5). The former could be explained by invoking lengthening of the growing season as a consequence of higher rainfall. The plausible reasons for the negative correlation in the case of the latter could be the presence of relatively strong amount effect in rainfall in the region, higher rainfall during the north-east (NE) monsoon, one depleted in ^{18}O, and relatively lesser effect of lower relative humidity conditions in deciding tree $\delta^{18}O$.

Based on the relationship observed between $\delta^{18}O$ record of teak from southern India and rainfall record, past rainfall record of Palakkad, Kerala and southern India was reconstructed back to A.D. 1743. The cellulose $\delta^{18}O$ based rainfall record extends the existing record back in time by 128 and 70 years for Palakkad and southern India, respectively. One of the conspicuous features of the extended record is higher precipitation during 1743-1830 as compared to the later period.

The fifth chapter summarizes the present work, discusses its implications and ends with recommendations regarding possible future work. To deconvolute climate signal from non-climate noise in cellulose $\delta^{18}O$ record, better understanding of physiological processes of teak is felt necessary.

Chapter 1　　Introduction

1.1 Introduction

Climate of the earth is continuously changing due to natural as well as anthropogenic reasons. For predicting future climate, it is imperative to know how climate changed in the past, especially during the past few centuries. Even though limited-span instrumental climate records are available, they are restricted to a few places and cover relatively a short period of time (e.g. about 100 years). Dearth of high resolution climatic data for longer periods necessitates finding proxies for the past climate.

Terrestrial proxies available for climate reconstruction are ice cores, lake sediments, corals, speleothems and tree rings. Among these, tree-rings have specific advantages: they have a wide geographic distribution, are annually resolved, show a continuous record, and are easily dated by ring-counting. Seasonality in the growth rate of trees driven by seasonality in the climatic factors can result in well-defined annual growth rings in trees. Individual tree-rings faithfully record contemporary climatic signatures hence provide an opportunity to decipher the variation in climatic parameters for a duration equivalent to the life-span of the tree. Using a technique called cross-dating, a procedure of matching ring patterns among trees and wood fragments in a given area (Fritz, 1976), it has been possible to stretch back tree ring record for thousands of years. Leuschner et al., (2002) and Spurk et al., (2002), for example, have constructed a tree ring record extending more than 8000 years. In the early years, only the width of the rings was used for climate reconstruction; wider (narrower) ring denoting higher (lower) temperature/precipitation. However, this simple relationship between width and climate is complicated by a variety of non-climatic factors (Fritz, 1976). For example, the site specific factors such as topography, soil type, forest thinning and ecological parameters like pest/insect infestations on trees can modify the climate- ring-width relationship. Isotopic composition (e.g., $\delta^{18}O$) of tree cellulose is believed to be less influenced by biological and ecological parameters in relation to ring-widths and can be used effectively in climate reconstruction. It has been shown by previous studies (Schiegl, 1974; Gray and Thompson, 1976; Epstein and Yapp, 1977; Burk and Stuiver, 1981;

Ramesh et al., 1985; Edwards et al., 1985; Lipp et al., 1991; Feng and Epstein, 1994) that isotopic record of oxygen and hydrogen from individual tree-rings can be successfully used as proxies to decipher climatic parameters such as rainfall, humidity and temperature.

1.2 Tropics and Teak (*Tectona grandis*)

Tropical area appears to play a crucial role in global climate through El Niño-Southern Oscillation (ENSO), a coupled atmospheric-ocean phenomenon affecting climate of tropical, subtropical and mid-latitude areas (Diaz and Markgraf Eds. 2000). In India, the relationship between ENSO and monsoonal rainfall has been established (Pant and Parthasarathy, 1981; Krishna Kumar et al., 1995). Limited time span covered by instrumental rainfall record demands finding proxies to understand past variations in ENSO. Corals have been used to reconstruct past variation in ENSO (Cole et al., 1993 and 2000; Tudhope et al., 2001). Tree rings provide excellent terrestrial archives for the past variation in ENSO related rainfall (Stahle et al., 1998; D'Arrigo et al., 2005, Christie et al., 2008). As there is no pronounced seasonality in temperature, a factor responsible for growth rings in temperate regions (Fritts, 1976), tropical trees rarely exhibit well developed annual growth rings. Nevertheless, seasonality in precipitation and relative humidity in some tropical areas does result in the development of annual growth rings in a few species. Teak is one such species with reliable growth rings and is distributed throughout tropical Asia, parts of Africa and Latin America. Several regional chronologies have been developed using teak trees (e.g. Berlage, 1931; Pumijumnong et al., 1995; Borgaonkar et al., 2007; Buckley et al., 2007).

1.3 Oxygen isotopes in tree cellulose

Stable isotope ratios of carbon ($\delta^{13}C$), hydrogen (δD) and oxygen ($\delta^{18}O$) in tree rings have been used to get information about past climate. Although $\delta^{13}C$ of the tree rings have been used to understand past variations in $\delta^{13}C$ of atmospheric CO_2 and climatic parameters such as temperature and relative humidity, its interpretation is complicated by variety of environmental effects. These effects include juvenile effect (rings corresponding to the early years of growth are depleted in ^{13}C as they ingest ^{13}C depleted CO_2 released by respiration of other plants and soil, and the degradation of organic matter) and pollution/anthropogenic effect (tree rings since the industrial era, i.e. from around AD 1850 are progressively depleted in ^{13}C due to introduction of ^{13}C depleted CO_2 in the atmosphere produced by fossil fuel burning, and a plant's response to increasing CO_2 concentration in atmosphere; also known as the 'Suess Effect'. In addition, different levels of solar radiance and nutrients available to plants, and water stress cause variations in $\delta^{13}C$ around the circumference of a ring (intra-ring variation, Francey and Farquhar, 1982). $\delta^{18}O$ of tree cellulose, on the contrary, is directly related to the oxygen isotopic ratio of the plant's source water (and hence that of precipitation) and relative humidity (e.g. Roden et al., 2000). Since oxygen isotope ratio of precipitation is directly related to temperature (Dansgard, 1964) and/or amount of precipitation (Dansgard, 1964; Rozanski et al., 1993, Yadava et al., 2007), it is conceivable that $\delta^{18}O$ signature of tree cellulose is a more powerful tool in reconstructing past climate.

1.4 Factors influencing $\delta^{18}O$ of tree ring cellulose

Oxygen isotope composition ($\delta^{18}O$) of plant material depends upon $\delta^{18}O$ of the source water, the level of evaporative enrichment of the source water in the leaf during transpiration, biochemical fractionation associated with the synthesis of sucrose in the leaf and the extent of exchange between sucrose and xylem water during cellulose synthesis. A brief description of processes that govern the above mentioned factors is discussed below.

1.4.1 Atmospheric processes

$\delta^{18}O$ of precipitation and atmospheric water vapor, and relative humidity are important in determining $\delta^{18}O$ of the cellulose. $\delta^{18}O$ of the precipitation primarily determines the $\delta^{18}O$ of the source water trees use for photosynthesis in areas of no permanent ground water, whereas $\delta^{18}O$ of water vapor and relative humidity modify the source water $\delta^{18}O$ during transpirational process. It is the transpirationally modified water that is actually used for photosynthesis. In this context, a good knowledge of what decides $\delta^{18}O$ of precipitation and atmospheric water vapor, and changes in relative humidity during growing season are necessary.

A detailed account of variation in the isotopic composition of rainfall over the world since 1961 is maintained by IAEA/WMO Global Network "Isotopes in Precipitation" (GNIP) and is available at http://isohis.iaea.org/.

On the global scale, $\delta^{18}O$ of precipitation is largely governed by ambient temperature. Decreasing temperature results in the lowering of water holding capacity of air and drives the rainout process. As a result, the progressive precipitation associated with still lower temperatures becomes increasingly depleted in ^{18}O. Dansgaard (1964) demonstrated a linear relationship between surface air temperature (T_{annual}) and $\delta^{18}O$ of mean annual precipitation ($\delta^{18}O_a$) on the global scale as

$$\delta^{18}O_a = 0.695T_{annual} - 13.6\,‰$$

In tropical areas, typical relationship between $\delta^{18}O$ of rainfall and surface air temperature is overshadowed by the amount effect, an inverse relationship between $\delta^{18}O$ of rainfall and amount of precipitation on the monthly (Dansgaard, 1964; Rozanski et al., 1993) or individual rain event (Miyake et al., 1968; Yadava et al., 2007) scale. Dansgaard (1964) explained the amount effect in terms of 1) fractional removal of heavy isotopes in the rain; 2) equilibration of light rain (smaller drops) with enriched vapor below the cloud base; and 3) high relative loss of light isotopes when raindrop evaporates below the cloud base in arid region. Yurtsever and Gat (1981) analyzed rainfall and its isotopic composition of 14 island stations in equatorial belt, and found a linear relationship (r = 0.87) between mean monthly $\delta^{18}O$ of rainfall ($\delta^{18}O_m$) and mean monthly rainfall amount (P_m)

$$\delta^{18}O_m = (-0.015 \pm 0.002)P_m - (0.47 \pm 0.42),$$

The average rate of depletion in $\delta^{18}O$ of rainfall with increase in monthly rain amount was -1.5 ± 0.2 ‰ for 100 mm. Amount effect typically dominates south and south-east Asia (Araguás-Araguás et al., 1998). Yadava and Ramesh (2005) measured rainfall amount and its $\delta^{18}O$ for year 1999 at Jharsuguda (22°N, 84°E), central India and found the depletion rate of -9.2 ± 1.1 ‰ and -2.2 ± 0.8 ‰ for 100 mm rain per rain event and total monthly rain, respectively.

Rainout is another important process that determines isotopic composition of precipitation. It is a process by which moving air mass looses its water vapor through precipitation and remaining vapor becomes progressively depleted in ^{18}O. At each stage within the cloud there is isotopic equilibrium between rain and vapor. Mathematically, isotopic evolution of moving air parcel can be modeled by the Rayleigh fractionation equation

$$\delta^{18}O_{v(f)} = \delta o^{18}O_v + \varepsilon\ ^{18}O_{l-v} \,.\, \ln f$$

where $\delta^{18}O_{v(f)}$ and $\delta o^{18}O_v$ are the oxygen isotopic compositions of the residual fraction of water vapor at any point and isotopic composition of initial vapor, respectively; f is fraction of residual vapor remaining in cloud; and ε is the oxygen isotopic fractionation factor between the rain and vapor expressed in per mil (‰) units. $\delta^{18}O$ of accompanying rainfall is about 9 ‰ enriched than the $\delta^{18}O$ of vapor. An example of rainout effect in the Asian region is illustrated by Araguás-Araguás et al., (1998). They showed a progressive depletion of $\delta^{18}O$ of rainfall along the trajectory of Pacific monsoon from Haikou and Hong Kong (south of China) to Lhasa (Tibetan plateau) where $\delta^{18}O$ of rainwater changes from -7.2 ‰ to -18.3 ‰. This is known as 'continental' effect.

In addition to the amount and rainout (continental) effect, $\delta^{18}O$ of precipitation also changes with season. In India, the south-west and north-east monsoon have different isotopic signatures. Yadava et al., (2007) analyzed rains (2000 to 2002) at Mangalore which receives both the monsoons and showed that the NE monsoon precipitation is relatively more depleted in ^{18}O. This observation contrasts with observations elsewhere in South-East Asia, where summer rains are depleted in ^{18}O relative to winter rains (Araguás- Araguás et al., 1998).

1.4.2 $\delta^{18}O$ of atmospheric vapor

$\delta^{18}O$ of atmospheric water is one of the factors that decides the $\delta^{18}O$ of leaf water and its effectiveness increases with relative humidity (Roden et al., 2000). Higher relative humidity facilitates faster equilibration of atmospheric water vapor with leaf water. Unfortunately, in contrast to the measurement of isotopic composition of precipitation, isotopic composition of the atmospheric water vapor has not been monitored extensively. In general, atmospheric vapor is considered in equilibrium with local rainwater and its isotopic composition calculated using the corresponding equilibrium fractionation factor. It is known that $\delta^{18}O$ of atmospheric water vapor depends upon the moisture source and its interaction with the surface (Gat, 1996). In the Indian region, Srivastava et al., (2008) have found the atmospheric water vapor, in general, to be in equilibrium with ambient rain.

1.4.3 Soil hydrological processes

Isotopic composition of tree's source water is one of the important factors governing isotopic composition of tree. $\delta^{18}O$ of the rain water primarily decides $\delta^{18}O$ of the source water for plants. But various subsequent soil hydrological processes operating on the percolated rain water finally decides the $\delta^{18}O$ of water available for plant uptake. Understanding and quantification of soil hydrological processes (viz. water percolation in soil and its evaporation), however, has been largely ignored in dendroclimatological studies.

Isotopic composition of soil water primarily depends upon the isotopic composition of precipitation and ground water. In addition to this, environmental factors (viz. relative humidity, solar irradiance), through their effect on evaporation of soil water, also affect isotopic composition of soil water. Spatial and temporal heterogeneity in the isotopic composition of soil water has been reported. Barnes and Allison (1989) showed that an isotopic gradient exists in soil water due to evaporation in the upper part of the soil. The shape of this profile depends upon soil moisture content, soil texture and changing isotopic composition and amount of precipitation. They also found that the maximum heterogeneity in $\delta^{18}O$ and δD of soil water is observed at the soil surface and it gradually decreases with depth.

Tang and Feng (2001) conducted a detailed field investigation of the effect of soil hydrological processes in controlling the isotopic composition of soil water. In their study area, Hanover, NH, USA, precipitation is relatively evenly distributed throughout the year and with seasonally changing isotopic composition (isotopically enriched summer and depleted winter rainfall). They measured the temporal variation in the isotopic composition of rainwater, soils water at different depths and twig water from a maple tree. Their work demonstrated: 1) soil water isotopic composition is much less variable than that of precipitation implying mixing of various precipitation events; 2) soil water evaporation isotopically enriches the surface soil water; 3) water from summer rains gradually replaces water of winter precipitation; 4) extent of replacement of winter water with summer water depends upon intensity and frequency of summer precipitation, and its influence decreases with depth; 5) twig water samples soil water which has experienced evaporation.

Tsuji et al., (2006), in their study of oxygen isotopic composition of coexisting tree species in Hokkaido island, northern Japan, have shown the importance of rooting system of plants in controlling the plant's isotopic composition. Their work demonstrates water uptake characteristics of plants in the rhizosphere, an area of a soil affected by root system, in conjunction with the soil water processes ultimately decides tree cellulose isotopic composition. They found that shallow rooted tree species (spruce tree) respond to $\delta^{18}O$ of summer precipitation while deep rooted (oak) trees do not and explained it in terms of inability of deep rooted trees to sample summer precipitation.

Isotopic analysis of xylem water in conjunction with isotopic analysis of rain and ground water has yielded some important results in terms of water utilization by plants. White et al., (1985) have shown a single white pine (*Pinus Strobus*) tree can rapidly (within 3 days) switch its source water from shallower surface rain water to deeper groundwater. Dawson and Ehleringer (1991), on the contrary, showed that mature riparian trees growing close to perennial streams use little or no stream water, but instead prefer ground water. They explained this behavior in terms of mature trees preferring reliable ground water instead of unreliable surface or rain water. Age of the trees also decides which source water a tree samples. Dawson (1996), for example, showed older (larger) *Acer saccharum* trees have access to both shallow soil and ground water while younger (smaller) such trees depend on shallow soil water. Such results are important as different sources of water often have different isotopic compositions and decide the isotopic composition of tree ring cellulose.

1.4.4 Plant physiological processes

$\delta^{18}O$ of tree cellulose depends upon $\delta^{18}O$ of the source water, the level of evaporative enrichment of the source water in the leaf during transpiration, biochemical fractionation associated with the synthesis of sucrose in the leaf and the extent of exchange between sucrose and xylem water during cellulose synthesis. Plant physiological model for interpreting the isotopic composition of plant constituents (e.g. Flanagan et al., 1991; Saurer et al., 1997; Farquhar et al., 1998; Barbour and Farquhar, 2000; Roden et al., 2000, Barbour et al., 2004) can be used to understand the various processes outlined above.

Trees take up the soil water through roots without any isotopic fractionation (White et al., 1985) and transport it to the leaf through xylem. Analysis of xylem water/cellulose shows (Ehleringer and Dawson 1992, Lin et al., 1996, Schwinning et al., 2002, Evans and Schrag 2004) that plants record the isotopic composition of precipitation. The extent of isotopic enrichment of the leaf water depends upon temperature, relative humidity, $\delta^{18}O$ composition of atmospheric water vapor and leaf physiological parameters. Variation in isotopic composition of leaf water (and hence that of cellulose derived from it) depends upon isotopic composition of source water (therefore a function of ambient temperature or amount of precipitation) and the extent of isotopic enrichment of leaf water due to evaporation (therefore a function of relative humidity). In general, relative humidity is less effective during the peak growing season (monsoon) whereas its importance increases during the late growing season. Effect of relative humidity on the evaporative isotopic enrichment of the leaf water is lower at higher ambient humidity, a condition often characteristic of the main growing season in India. But at higher ambient humidity, isotopic composition of atmospheric water vapor through its exchange with the leaf water becomes important. During the late growing season, lower humidity creates higher vapor pressure gradients across the leaf which results in a higher evaporative isotopic enrichment of the leaf water.

Various models have been proposed to calculate isotopic composition of the leaf water. Such models are based on detailed theoretical as well as laboratory experiments. Based on the Craig and Gordon (1965)'s model describing isotopic fractionation during evaporation from an open surface and then incorporating leaf boundary layer effects and diffusion through stomata, Dongmann et al., (1974) and Flanagan et al., (1991) wrote the isotopic composition of the leaf water (R_{wl}) as

$$R_{wl} = \alpha^* \left[\alpha_k R_{wx} \left(\frac{e_i - e_s}{e_i} \right) + \alpha_{kb} R_{wx} \left(\frac{e_s - e_a}{e_i} \right) + R_a \left(\frac{e_a}{e_i} \right) \right], \tag{1}$$

where R_{wl}, R_{wx} and R_a refer to isotopic ratios ($^{18}O/^{16}O$) of leaf water, xylem water and bulk air, respectively; water vapor pressure of intercellular leaf space is e_i, of leaf surface is e_s and of bulk air is e_a; α^*, α_k, and α_{kb} are respectively liquid-vapor equilibrium fractionation factor, kinetic fractionation factor and kinetic fractionation factor associated with leaf boundary layer.

The resultant isotopic composition of leaf water calculated using the above equation is observed to be more enriched than that of the bulk leaf water due to Péclet effect – an effect describing transpirational advection of ^{18}O depleted (xylem) water to the evaporating site opposed by the backward diffusion of ^{18}O enriched water into the leaf (Farquhar and Lloyd 1993). Barbour et al., (2004) have proposed a model considering the Péclet effect. To use this model, Péclet number for different tree species is required. This involves the measurement of effective path length; a model parameter that accounts for the discrepancy between the values predicted by the Craig-Gordon model and measured bulk leaf water measurements. In practice, detailed knowledge of the Péclet number for a given species and for a season is largely not available. Isotope dendroclimatologists circumvent this problem by either using an assumed value of the effective path length (and Péclet number) or using models (e.g. Roden et al., 2000) that ignore the Péclet effect. The results of the latter option are interpreted keeping in mind that the leaf water isotopic values obtained using such models could be more enriched in ^{18}O than the actual values. Clearly, more work needs to be done in quantifying Péclet number for each species during various times of the growing season.

Sucrose formed by photosynthesis in the leaf carries the isotopic composition of the leaf water. Complicated biochemical pathways are involved in synthesis of cellulose from sucrose, an account of which is given by Farquhar et al., (1998). Initially, it was thought (Epestein et al., 1977) that 2/3 and 1/3 of oxygen atoms of the tree ring cellulose is contributed by CO_2 and H_2O, respectively making overall enrichment of cellulose with respect to water at the evaporating site by 27 per mil. But later DeNiro and Epestein (1979) established that $\delta^{18}O$ of water determines $\delta^{18}O$ of cellulose. Sternberg (1989) based on review of available data in literature reported 27+/- 3 per mil enrichment of cellulose as compared to the water at site of synthesis. Further, it has been shown (Sternberg et al., 1986, and Saurer et al., 1997) that 45% of oxygen in cellulose is expected to exchange with (xylem) water during synthesis of cellulose from sucrose. This implies that 55% of oxygen atoms in cellulose carries the signature of evaporation processes (and hence relative humidity conditions) taking place in the leaf.

Roden et al., (2000) have outlined a mechanistic model for interpreting hydrogen and oxygen isotope ratios of tree cellulose. Their model considers exchange of oxygen atoms of sucrose with the medium (xylem) water during synthesis of cellulose. In their model, the final isotope composition of tree cellulose ($\delta^{18}O_{cx}$) is given by

$$\delta^{18}O_{cx} = fo \cdot (\delta^{18}O_{wx} + \varepsilon o) + (1 - fo) \cdot (\delta^{18}O_{wl} + \varepsilon o), \qquad (2)$$

where fo is the fraction of carbon-bound oxygen that undergoes exchange with medium water, $\delta^{18}O_{wx}$ is xylem water, $\delta^{18}O_{wl}$ refers to oxygen isotopic composition of the leaf water at the site of sucrose synthesis and εo indicates biochemical fractionation factor. The authors based on model and experimental results estimate fo to be 0.42.

It can be seen from the equations (1) and (2) that the e_a/e_i ratio, hence relative humidity plays a crucial role deciding isotopic composition of the leaf water and subsequently synthesized cellulose (Sheshshayee et al., 2005). In tropical areas, like the one in the present study, there is enough variation in relative humidity during growing season to leave its imprint on the isotopic composition of cellulose (Geeta Rajagopalan et al., 1999). Thus, by knowing relative humidity variation during entire growing season of a plant one can construct the expected tree cellulose $\delta^{18}O$ profile during that season.

1.5 A brief review of experimental isotope dendroclimatology

The components of wood viz. cellulose (~50%), lignin (~30%), hemicellulose (~15%), resin and lipids (~5%) have different isotopic ratios (Wilson and Grinsted, 1977) and their relative proportion in the ring changes with time during growing season and from year to year. In addition to this, lignin/cellulose ratios in trees are found to be climate independent (Gray, 1981). Further, resin is found to be mobile (Long et al., 1979) and lignin is shown to be deposited later than cellulose in the ring (Wilson and Grinsted, 1977). This prohibits use of isotopic composition of bulk wood for climate reconstruction and necessitates use of a specific component for climate reconstruction studies. In this context, cellulose is preferred in dendroclimatic investigations as it is durable and is a major component of wood. In addition, mechanistic models (e.g. Roden et al., 2000) used for interpreting climate are developed for the isotopic composition of cellulose. Cellulose $[(C_6H_{10}O_5)_n]$ is a long chained polysaccharide of $\beta(1 \rightarrow 4)$ linked D-glucose units where n can be several thousand to ten thousand units. Pure cellulose can not be extracted from the wood and always contains some traces of monosaccharides, lignin and other components (Corbett, 1963; White, 1983). Dendroclimatic investigations typically use α-cellulose, a part of cellulose that is insoluble in 17.5% NaOH, as the saponification removes some of the non-cellulosic components.

Various methods are available for extracting α-cellulose from wood samples and there is no consensus among isotope dendroclimatological community regarding use of a particular method. Moreover, investigators have modified the originally suggested methods to suite their specific needs. The extracted cellulose, as a result, often differs in its quality. Traditional techniques of extracting cellulose and measuring its isotopic composition have been laborious and time consuming leading to low sample throughput. Some recently suggested sample preparation techniques (Leavitt and Danzer, 1993; Loader et al., 1997; Brendel et al., 2000; Schulze et al., 2004; Rinne et al., 2005; Gaudinski et al., 2005) have enabled processing a large number of samples in less time leading to the analysis of number of chronologies, hitherto not considered feasible.

Traditional cellulose extraction methods (e.g. Green, 1963) involves 1) pretreatment involving extracting wood powder with organic solvent for removing components such as resins, gums and lipids; 2) bleaching stage where pretreated wood powder is delignified using glacial acetic acid and sodium chlorite; 3) purification stage where the delignified sample is immersed in 17% NaOH to obtain α-cellulose and removing wood components like mannan and xylan. As these methods are tedious and time consuming, processing of large a number of samples for isotopic measurements was difficult.

Interlaboratory comparison of different cellulose extraction methods followed by nine European stable isotope laboratories was conducted by Boettger et al., (2007). These laboratories extracted cellulose from oak and pine samples using their routine method which is either of the methods suggested by Sohn and Reiff (1942), Loader et al., (1997), Green (1963), Brenninkmijer (1983) and measured its isotopic ratio using different methods. The authors reported that the $\delta^{18}O$ values did not depend upon any specific method of cellulose extraction and recommended the elimination of a pretreatment of wood with organic solvents, inclusion of a purification step with 17% NaOH solution to produce α-cellulose, and isotopic measurements of oxygen isotopes under an argon hood.

Brendel et al., (2000)'s cellulose extraction method has become popular as it the fastest method (56 samples in 8 hours) of extracting cellulose and involves only standard laboratory chemicals and equipments. This method involves simultaneous removal of lignin and hemicellulose from the sample by treating it with a hot mixture of nitric acid and acetic acid. The other advantages of this method include the minimal use of chemicals and hence reduction of toxic waste disposal problems. Evans and Schrag (2004) scaled down the Brendel et al., (2000)'s method permitting the use of a very small amount of initial wood sample (~400 μg) and claimed α-cellulose can be extracted from 160 samples each day. Their protocol is useful to extract cellulose from tree-cores, especially when ring widths are smaller.

Gaudinski et al., (2005) pointed out that the Brendel's method adds carbon and nitrogen to the cellulose and left a residue that contains remnant lipids and waxes. In case of oxygen, the authors reported that cellulose extracted using Brendel's method is enriched in ^{18}O relative to the other methods and proposed a modification, MBrendel, involving the addition of a step to the Brendel method. This step treats the cellulose extracted by Brendel's method with 17% NaOH followed by water rinsing and acidification. The claims made by Gaudinski et al., (2005), were contested by Anchukaitis et al, (2008) who showed that the isotopic composition of cellulose extracted using the Brendel method is not statistically different from the traditional methods like Leavitte and Dansier and Gaudinski's MBrendel method.

Like traditional cellulose extraction methods, traditional techniques used for preparing gas (CO_2) from cellulose for mass-spectrometric analysis were also time consuming and laborious. These methods (Wilsen and Grinsted, 1977; Burk, 1979; Hardcastle and Friedman, 1974; Thompson and Gray, 1977) first pyrolysed the sample in presence of suitable catalyst (mercury or nickel) to produce C, CO and CO_2. The CO was then converted to CO_2 by electrical discharge and CO_2 thus recovered was used for mass-spectrometric ^{18}O analysis.

The advent of modern continuous flow IRMS (Isotope Ratio Mass Spectrometer) has revolutionized the isotopic analysis of cellulose samples; measurements today being fast and at reduced cost. Typically, the procedure involves online pyrolysis of cellulose sample in the presence of graphite and glassy carbon at ~1100°C to produce carbon monoxide (CO). In order to avoid isotopic interference of CO and nitrogen, CO is then separated from nitrogen by passing the mixture through a gas chromatograph (GC) (e.g. Farquhar et al., 1997; Saurer et al., 1998) with 5 Å sized seive. The sample gas is then introduced into the mass-spectrometer where analysis of a sample could be completed within 10 min. In this procedure a dry He gas (99.999% purity) is used as a carrier. Internal precision of the measurements is established using pure CO as a reference gas whereas external precision is measured with standards such as IAEA-C3 (32.6 ‰) and sucrose (ANU sucrose, 36.4‰). Typical reported internal and external precisions are less than 0.1‰ and 0.3‰, respectively.

1.5.1 Components of wood other than cellulose

Some pregress has been made in this direction of using oxygen atoms having specific positions in the cellulose structure rather than using all oxygen atoms for climate reconstruction. Sternberg et al., (2007) used the cellulose derived phenylglucosazone, a compound which lacks the oxygen attached to the second carbon of the cellulose-glucose moieties, instead of using bulk cellulose. These authors showed that phenylglucosazone is a better proxy for isotopic composition of the stem water and relative humidity than the bulk cellulose as the oxygen attached to the second carbon atom in cellulose can introduce isotopic ‘noise’ in the climate signal preserved by cellulose.

1.6 Previous isotope dendroclimatological investigations in the tropics

Relative to the extra-tropics, isotope based dendroclimatological work carried out in tropics is limited. The isotopic composition of rainfall in tropics is seldom related to temperature; it is rather affected by factors such as season, amount of rainfall and the rainout history, thus hampering meaningful interpretation of stable isotopic variations in tropical trees. To utilize tropical trees for climate reconstruction, a proper understanding of what governs isotopic composition of bulk as well as different parts of the ring is imperative. Most of the isotope dendroclimatological work being carried out in tropical area now involves high resolution/intra-ring sampling to understand driving forces that determine $\delta^{18}O$ of photosynthates produced during various times of the growing season. Recently developed models (e.g. Flanagan et al., 1991; Saurer et al., 1997; Farquhar et al., 1998; Barbour and Farquhar, 2000; Roden et al., 2000) can help in understanding parameters that govern the isotopic composition of photosynthates produced during various times of the growing season. This, coupled with newly developed cellulose extraction techniques (Brendel et al., 2000, Evans and Schrag 2004, Gaudinski et al., 2005 and Anchukaitis et al., 2008) has made intra-ring studies increasingly significant.

Ramesh et al., (1989) proposed a mechanism for using teak tree for climate reconstruction of tropical areas. They showed a positive correlation between δD of teak cellulose and amount of rainfall despite having no correlation between δD of precipitation and amount of rainfall in the area. The authors suggested increasing length of growing season as a result of higher rainfall as a possible explanation for observed positive correlation.

Evans and Schrag, (2004) demonstrated potential of tropical trees with or without growth rings in the reconstruction of past climate. Based on a protocol for rapid extraction of cellulose (Brendel et al., 2000), they extracted α-cellulose at high resolution from the sample. Based on the high resolution $\delta^{18}O$ record, they formulated an approach "tropical isotope dendrochronology" wherein seasonal cycles in (intra-ring) $\delta^{18}O$ variations are exploited to establish chronology within trees lacking annual growth rings. In their approach, wood corresponding to one seasonal cycle of $\delta^{18}O$ represents a 'ring'. Once such 'rings' are established, regular dating/counting methods can be used to assign calendar years to them. Past changes in rainfall, relative humidity and growth rate could then be reconstructed using the high resolution cellulose $\delta^{18}O$ record and a plant physiological model (Roden et al., 2000) developed for climatic interpretation of $\delta^{18}O$ of α-cellulose.

Poussart et al., (2004) studied trees from three different families from Thailand and Indonesia using an approach similar to that of Evans and Schrag (2004)'s. These authors have demonstrated reproducibility of climate signal between trees grown at the same locality as well as from wider geographical regions. Poussart and Schrag (2005) analyzed 11 different trees belonging to different families from Thailand for intra-ring $\delta^{18}O$ analysis. Their analysis of intra-ring $\delta^{18}O$ variations showed significant correlation between dry season rainfall and amplitude of intra-ring variation; and between wet season rainfall and minimum of intra-ring variation. This led them to propose a possibility of reconstructing dry and wet season rainfall using intra-ring $\delta^{18}O$ variations.

Verheyden et al., (2004) analyzed a mangrove tree *Rhizophora mucronata* Lam., for bulk wood high resolution oxygen and carbon isotope studies and found a remarkable annual cyclicity in them. Presence of ENSO related climate signal in the high resolution isotope record was also reported by them.

1.7 Rationale behind the approach

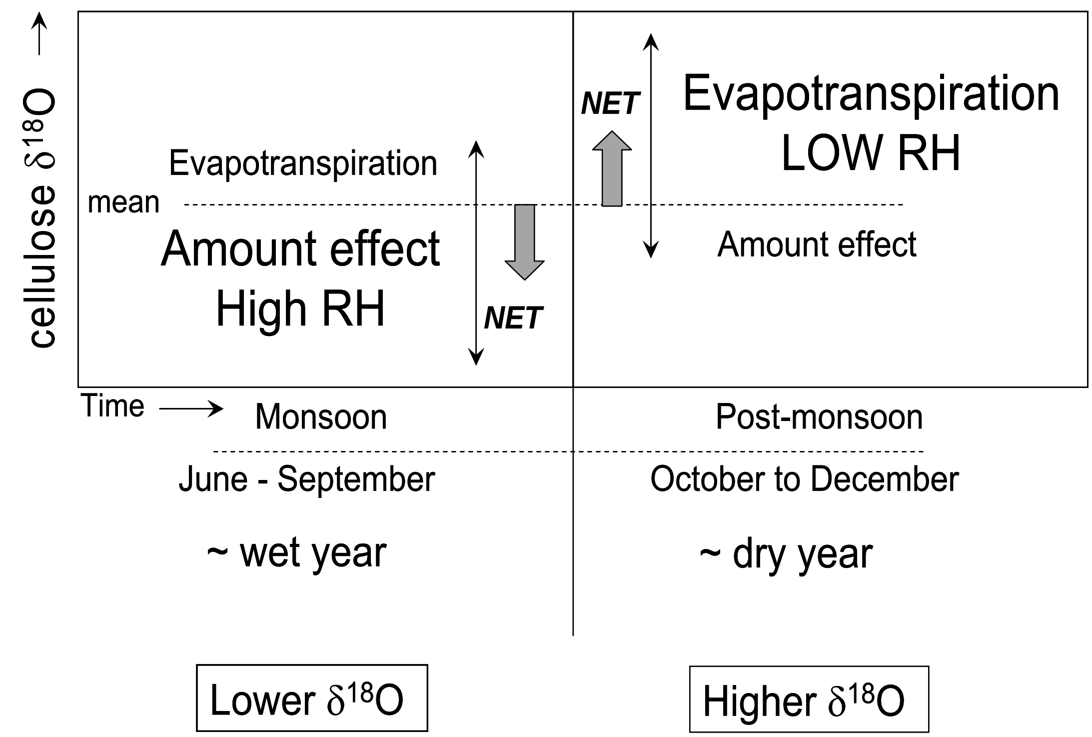

Fig.1.1. Schematic diagram showing effect of the amount effect and relative humidity on $\delta^{18}O$ of cellulose. Modified after Evans and Schrag (2004).

$\delta^{18}O$ of tree cellulose depends, among other factors, upon $\delta^{18}O$ of the tree's source water and the level of evaporative enrichment of the source water in the leaf during transpiration. The former is controlled largely by the $\delta^{18}O$ of precipitation through the amount effect while relative humidity governs the latter. Lower atmospheric humidity causes higher vapor pressure gradient between leaf interstitial space – which is saturated with water- and the leaf surroundings leading to a higher evaporative enrichment of the leaf water in ^{18}O. Interestingly, the relative influence of these 'non-biological' factors changes with season (see **Fig.1.1**). During the peak of rainy season, (e.g. peak monsoon season –June to September) higher relative humidity in the atmosphere poses less vapor pressure gradient across the leaf leading to lesser evaporative enrichment of leaf water. In addition to this, higher rainfall during this season results in rainwater depleted in ^{18}O owing to the amount effect. Photosynthates (and hence, subsequently formed cellulose) formed during the monsoon season, as a consequence, are depleted in ^{18}O.

During the post monsoon season, on the contrary, more evaporative enrichment of the leaf water due to lower relative humidity dominates the changes in source water $\delta^{18}O$ caused by amount effect leading to formation of photosynthates relatively enriched in ^{18}O. Various plant physiological models are available for quantifying the effect of these factors on $\delta^{18}O$ of cellulose. Using these models, one can decide what governs the $\delta^{18}O$ of cellulose formed during various phases of growing season, understanding of which is important in interpreting inter-annual variations in cellulose $\delta^{18}O$.

Using the same analogy, a year with higher rainfall (and higher average relative humidity) is characterized by cellulose with lower $\delta^{18}O$ values as compared to the year with lower rainfall (and lower average relative humidity). This relationship can be used to interpret variation in $\delta^{18}O$ of tree rings in terms of variation in the amount of rainfall the tree receives.

The relationship between rainfall amount and $\delta^{18}O$ of cellulose, however, is primarily complicated by two factors. Firstly, the amount effect at a given place may not be pronounced - poor correlation between the amount of rainfall and its $\delta^{18}O$ - and may vary in magnitude with time. Secondly, in case of regions which receive rainfall with seasonally changing $\delta^{18}O$, relative strength of two rains will ultimately decide the $\delta^{18}O$ of cellulose.

1.8 Statement of the problem

The proposed work aims at building past monsoon rainfall variations by using the oxygen isotopic records of teak (*Tectona grandis*) trees. Such reconstruction involves finding a relationship between comparison of observed variations in tree cellulose $\delta^{18}O$ and the actually measured rainfall of the corresponding period. The relationship is then used to reconstruct rainfall of the period for which no instrumental records are available. To use this relationship effectively, a proper understanding of what governs the isotopic ratio of tree ring is imperative.

Besides reconstructing annually resolved past rainfall, specific questions addressed in the thesis are

1. What governs the evolution of the isotopic composition of tree cellulose during growing season?
2. How do teak trees from different climatic regions of India respond to the ambient climatic setting?
3. Is it possible to reconstruct the SW and NE monsoon simultaneously using $\delta^{18}O$ studies of teak trees from southern India, a region which is under the influence of both the monsoons?

The use of stable isotopes in dendroclimatological investigations started about three decades ago while the potential of tropical trees is yet to be investigated in sufficient detail as only a few tree species in tropics exhibit distinct and clearly datable growth rings. Further, the isotopic composition of rainfall in tropics is seldom related to temperature; it is rather affected by factors such as season, amount of rainfall and the rainout history. This hampers the meaningful interpretation of stable isotopic variations in tropical trees.

Understanding of how teak (*Tectona grandis*) trees respond to changes in amount and isotopic composition of rainfall and humidity is critical for interpreting inter-annual variations in $\delta^{18}O$ of these trees, the only species available in tropical Asia for climate reconstruction. Despite some preliminary work, it is still not clear how these factors affect the $\delta^{18}O$ of teak trees. Our isotopic analysis of teak trees from carefully selected locations can shed light on issues discussed above. Teak has a widespread distribution in tropical areas of South-east Asia – Java, Sumatra, Burma and Thailand – a region important for tracking El Nino- Southern Oscillation phenomenon. The outcome of this study can also be extended to other tropical Asian regions.

In India, after successful demonstration of the usefulness of isotope dendroclimatology in reconstructing past climate by Ramesh et al., (1989), no further work has been done in this direction to obtain long isotopic records from tree-rings. This study is the first to reconstruct rainfall record for central and southern India using $\delta^{18}O$ time series of teak tree-rings. These reconstructed rainfall records can be used to test models aimed at understanding global climate change.

Chapter 2 Regional climate settings, materials and methods

2.1 Introduction

Monsoonal precipitation over India is caused by a periodic northward movement of east-west oriented precipitation belt named as tropical convergence zone (TCZ) from the southern (its winter position) to the northern hemisphere (its summer position) (Gadgil 2003). Some regions receive rains from both the summer/south-west (SW) (Jun to Sep) and winter/north-east (NE) (Oct-Dec) monsoons. The SW monsoon occurs throughout the country, while the NE monsoon prevails mainly over the southern part of the peninsula. The mean annual rainfall for India for the period 1813-2005 is 1166 mm with contributions of winter, summer, monsoon and post-monsoon rain of 3%, 9%, 78% and 11%, respectively (Sontakke et al., 2008).

Indian economy is largely dependent upon agricultural production. Positive relationship between monsoon precipitation and food grain production has been reported by Gadgil (2003). The winter monsoon rainfall over southern India and its effect on rabi (winter) food grain production is also reported (Kumar et al., 2007; Gunnell et al., 2007).

Indian summer monsoonal rainfall and El Niño-Southern oscillation (ENSO) are related (Sikka, 1980; Pant and Parthsarathy; 1981, Rasmusson and Carpenter, 1983; Krishna Kumar et al., 1995). Recent studies show that there could be potential impact of global climate change on the monsoonal precipitation. Goswami et al., (2006) showed for the period 1951-2000 that there was an increase in the frequency and magnitude of extreme rain events and a decrease in the frequency of moderate rain events. Increasing surface temperature trend over Eurasia and its effect on the relationship between ENSO and monsoonal rainfall is shown by Kumar et al., (1999). For the Indian region, IPCC (2007, Chap.11, page 850), in its fourth assessment report, has suggested a warming above the global mean, a likely increase in summer precipitation, very likely increase in frequency of intense precipitation events and a likely increase of extreme rainfall and winds associated with tropical cyclones. This makes it important to understand natural variability in the monsoonal rainfall.

To understand the effects of global climate change on monsoon precipitation, it is necessary to understand how monsoon precipitation varied in the past. Instrumental rainfall data collected by Indian Meteorological Department (IMD) dates back to 1813A.D. when the first rain gauge station was established in Chennai. By 1871 a fairly good network of rain gauge stations was established with a total of 312 meteorological stations. To know the variation of rainfall prior to 1871, it is necessary to use climate proxies. Long term monsoon rainfall reconstruction was done using speleothems (Yadava et al., 2004; and Yadava and Ramesh, 2005). However, such reconstructions are spatially limited and may not always give annual time resolution. Tree rings, in this context, can give valuable information as they are geographically wide spread and give annual to sub-annual resolution.

In India, the potential of trees in climate reconstruction has been demonstrated by Pant (1979), Pant and Borgaonkar (1983), Ramesh et al., (1985, 1989), Bhattacharyya et al., (1992), Hughes (1992), Bhattacharyya et al., (2007), Borgaonkar et al, (2007) and Sigh and Yadava (2007). Teak (*Tectona grandis*) is one of the few tropical species showing distinct and reliable growth rings and holds potential for reconstructing monsoonal precipitation over India. Teak has a widespread distribution in south-east Asia – Java, Sumatra, Burma and Thailand – a region important for tracking the history of El Nino- Southern Oscillation phenomenon. Bhattacharyya et al., (1992), Borgaonkar et al, (2007) and Shah et al., (2007), Somaru Ram et al., (2008) have shown that the variations in ring-widths of teak trees from India can be used in reconstruction of the past climate. However, the relationship between ring-width and climate is complicated by a variety of non-climatic parameters (Fritz, 1976). For example, in case of teak, attack by teak defoliator, *H. puera*, is shown (Sudheendrakuamr et al., 1993) to reduce tree growth (and hence ring width). In this context, isotope based tree ring studies are advantageous and their efficacy in rainfall reconstruction was shown by Ramesh et al., (1989).

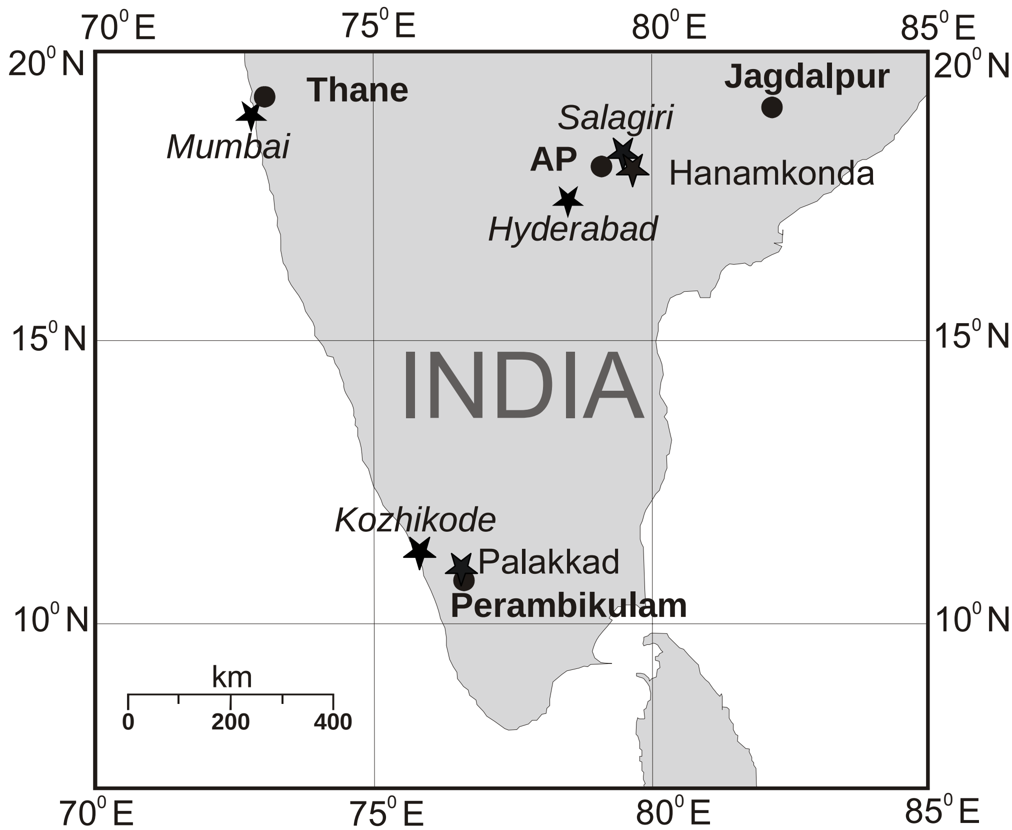

Fig.2.1. Locations of the teak tree samples (circles and bold letters) and IMD/GNIP stations (starts and letters in italics).

2.2 Climatology of sample locations

To understand how teak growing in different climatic settings responds to ambient climate, trees from different parts of the peninsular India were selected. While selecting the locations care was taken with respect to duration, pattern and amount of rainfall these locations receive. **Fig.2.1** shows locations of the trees used in the present study (locations indicated by circles and bold letters). The samples are from locations near Thane, Jagdalpur, Hanamkonda and Perambikulam. **Fig.2.1** also shows IMD weather stations (Mumbai, Jagdalpur, Hanamkonda and Palakkad- also known as Palghat) near the sample locations. **Fig.2.2** shows climatologies of IMD weather stations nearest to the respective locations. The data used in these figures is monthly mean data of climatological parameters based on observations from year 1951 to 1980. Among these locations, Palakkad receives the highest amount of rainfall (2163 mm) and has the highest number of rainy days (~103 days). Mumbai (earlier called Bombay), although receives rainfall comparable to Palakkad, yet has only ~76 rainy days. Hanamkonda receives the lowest amount of rain and has the least number of rainy days.

Summer monsoon is the prominent source of rainfall at Mumbai, Jagdalpur and Hanamkonda. The summer rainfall is associated with formation of monsoon depressions which form in the Bay of Bengal north of 18°N latitude and their west-northwest movement along the monsoon trough (Pant and Rupa Kumar, 1997). It is also known that the north-south movement of the monsoon trough can affect rainfall over this region: north-ward shift of monsoon trough towards the foot-hills of the Himalaya results in decrease and increase in the rainfall over the peninsular India and the foot-hills of the Himalaya, respectively. Rainfall over Palakkad, on the contrary, is also dominated by winter monsoon, mainly due to the passage of cyclonic systems passing over the southern part of India during October to December. The ratios of NE to SW monsoon rainfall at these stations are ~0.04 (Mumbai), ~0.11 (Jagdalpur), ~0.17 (Hanamkonda) and ~0.27 (Palakkad).

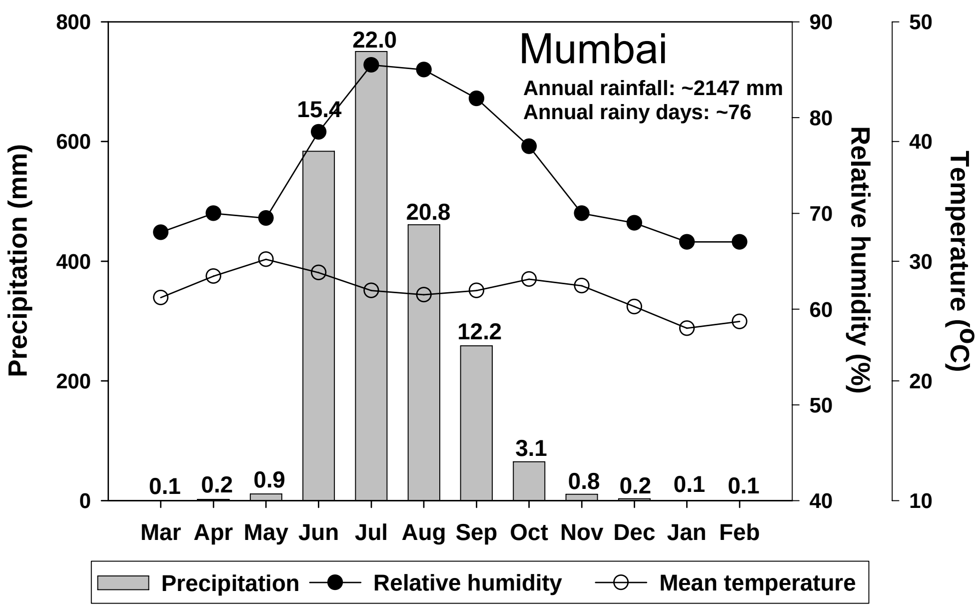

Fig.2.2a. Climatology of Mumbai. Numbers above the histogram bars indicate number of rainy days in the respective month.

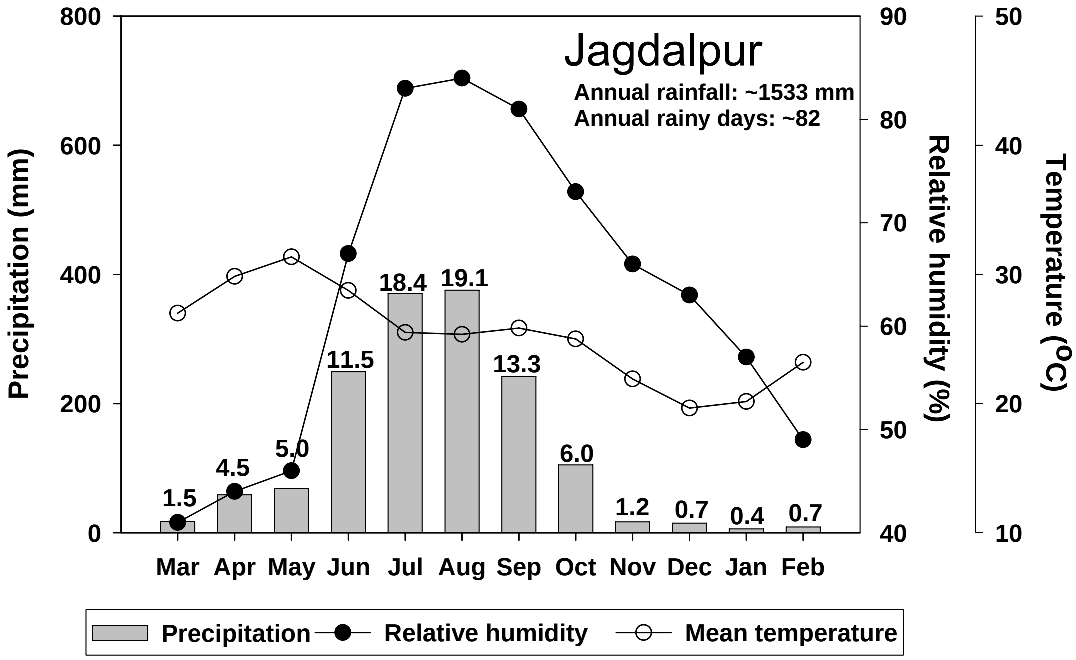

Fig.2.2b. Climatology of Jagdalpur. Numbers above the histogram bars indicate number of rainy days in the respective month.

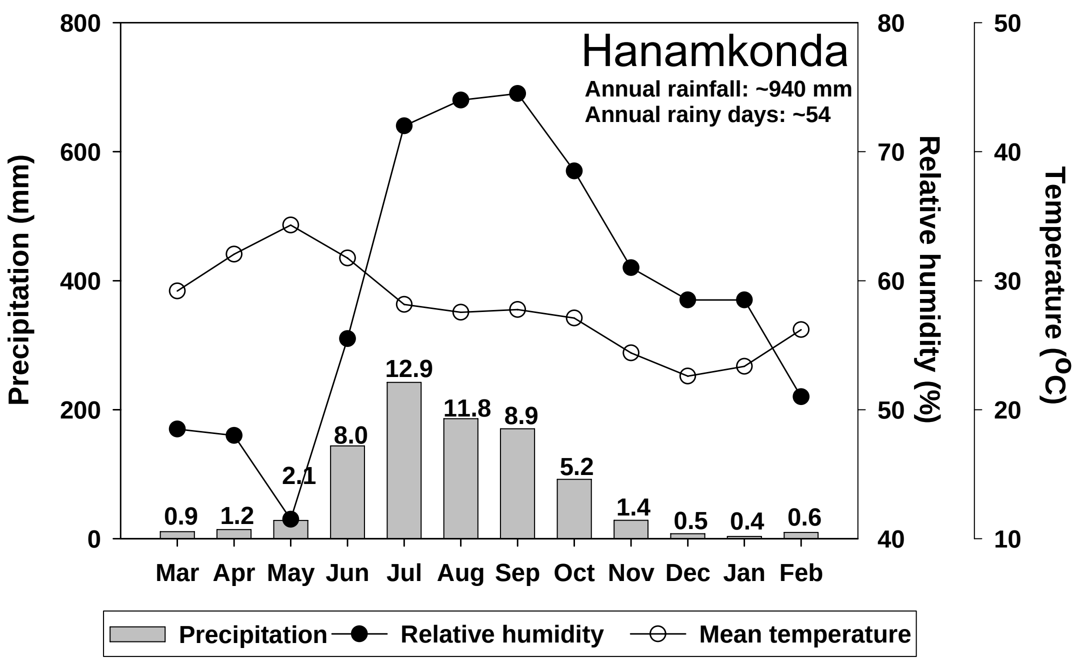

Fig.2.2c. Climatology of Hanamkonda. Numbers above the histogram bars indicate number of rainy days in the respective month.

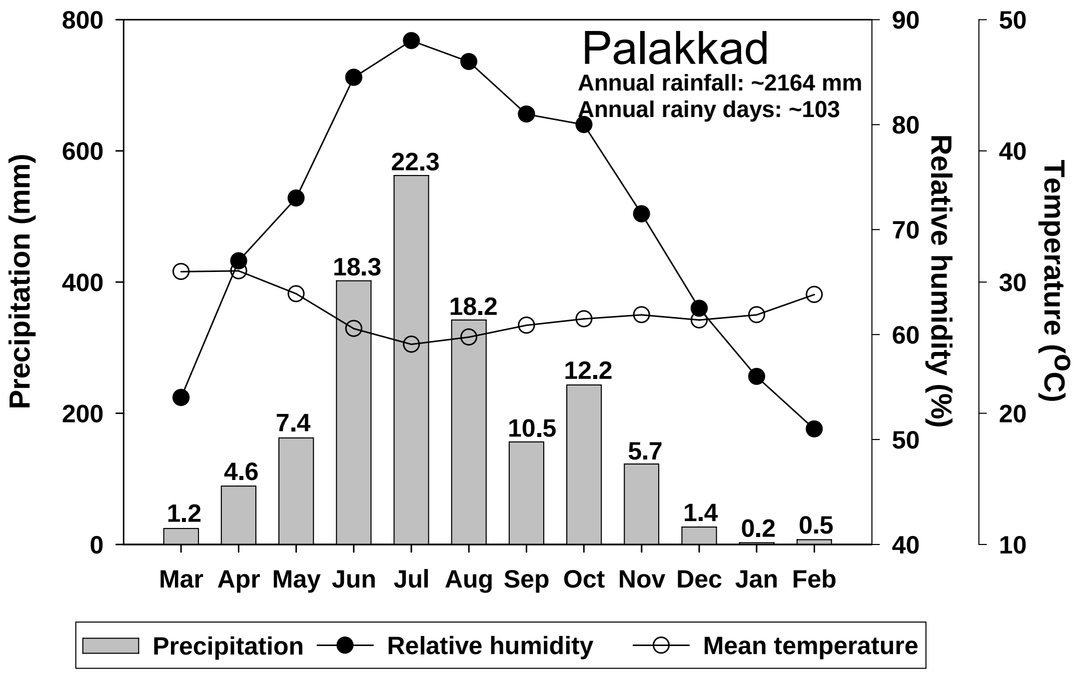

Fig.2.2d. Climatology of Palakkad. Numbers above the histogram bars indicate number of rainy days in the respective month.

2.3 Rainfall $\delta^{18}O$ record

Isotope data of rainwater is available for GNIP (Global Network of Isotopes in Precipitation) stations located nearby the sample locations (**Fig.2.1**, location indicated by 'star' marks and letters in italics). These stations are Mumbai (18.9°N, 72.82°E), Kozhikode (11.25°N, 75.78°E), Hyderabad (17.45°N, 78.47°E) and Salagiri (18.19°N, 79.44°E). Mumbai covers data from year 1961 to 1966 A.D. and from 1972 to 1976 A.D.; Hyderabad, from 1997 to 2000 A.D.; Kozhikode, from 1997 to 2004 A.D.; and Salagiri, for 1977 A.D. only. Mean weighted (by amount of precipitation) monthly oxygen isotopic composition ($\delta^{18}O$) of rainfall and monthly precipitation for the corresponding period for Mumbai, Kozhikode and Salagiri is shown in **Table 2.1**. Along with Salagiri, GNIP has also recorded monthly $\delta^{18}O$ of nearby stations viz. Bhopalpalli (18.27°N and 79.52°E), Chinpak (18.28°N and

79.44°E), Kamalpur (18.29°N and 79.54°E), Nasarampur (18.26°N and 79.47°E) and Tundla Buzurg (18.32°N and 79.47°E). All these stations show (**Fig.2.3**) a similar pattern of monthly $\delta^{18}O$ values indicating similarity in the monthly $\delta^{18}O$ of rainfall

Month	Mumbai		Salagiri		Kozhikode	
	Amount, mm	Weighted Mean $\delta^{18}O$, ‰	Amount, mm	Weighted Mean $\delta^{18}O$, ‰	Amount, mm	Weighted Mean $\delta^{18}O$, ‰
April					73	-4.3
May					335	-3.0
June	544	-1.1			687	-2.1
July	698	-1.7	286	-2.2	608	-1.8
August	395	-1.1	145	-3.6	396	-1.5
September	248	-1.8	140	-10.7	181	-3.4
October	90	-4.8	18	-7.8	311	-4.5
November	15	-5.4	51	-9.1	125	-7.3
December	19	-0.2			58	-6.2

Table 2.1. Monthly $\delta^{18}O$ of rainfall for the locations near to the sample locations.

on that scale. Yearly fluctuations in the amount weighted mean yearly $\delta^{18}O$ of rainfall for Kozhikode are shown in **Fig.2.4**. For Mumbai, such yearly fluctuations in $\delta^{18}O$ can be as high as 2 ‰. Relation between weighted (by amounts of precipitation) monthly rainfall $\delta^{18}O$ and monthly amount of rainfall for station Kozhikode is shown in **Fig.2.5**. $\delta^{18}O$ record at Kozhikode shows a large variation in the mean monthly rainfall $\delta^{18}O$ values which are not necessarily correlated with the amount of rainfall in the respective months. **Fig.2.6** shows the spread in monthly rainfall $\delta^{18}O$ values based on observations from year 1997 to 2004 A.D. In addition to GNIP stations, Yadava and Ramesh (2005) monitored rainfall isotopic composition near Jharsuguda (22°N and 84°E) for the year 1999 and Yadava et al., (2007) near Mangalore for June to October 2000 to 2002 A.D. Yadava and Ramesh (2005) found an inverse relation between amount of rainfall and its $\delta^{18}O$ i.e. amount effect. They observed a depletion rate of -9.2 ± 1.1 ‰ and -2.2 ± 0.8 ‰ for 100 mm rain for each rain event and total monthly rain, respectively for Jharsuguda. The ^{18}O depleted nature of rainfall during NE monsoon and a positive amount effect for Mangalore was reported by Yadava et al., (2007).

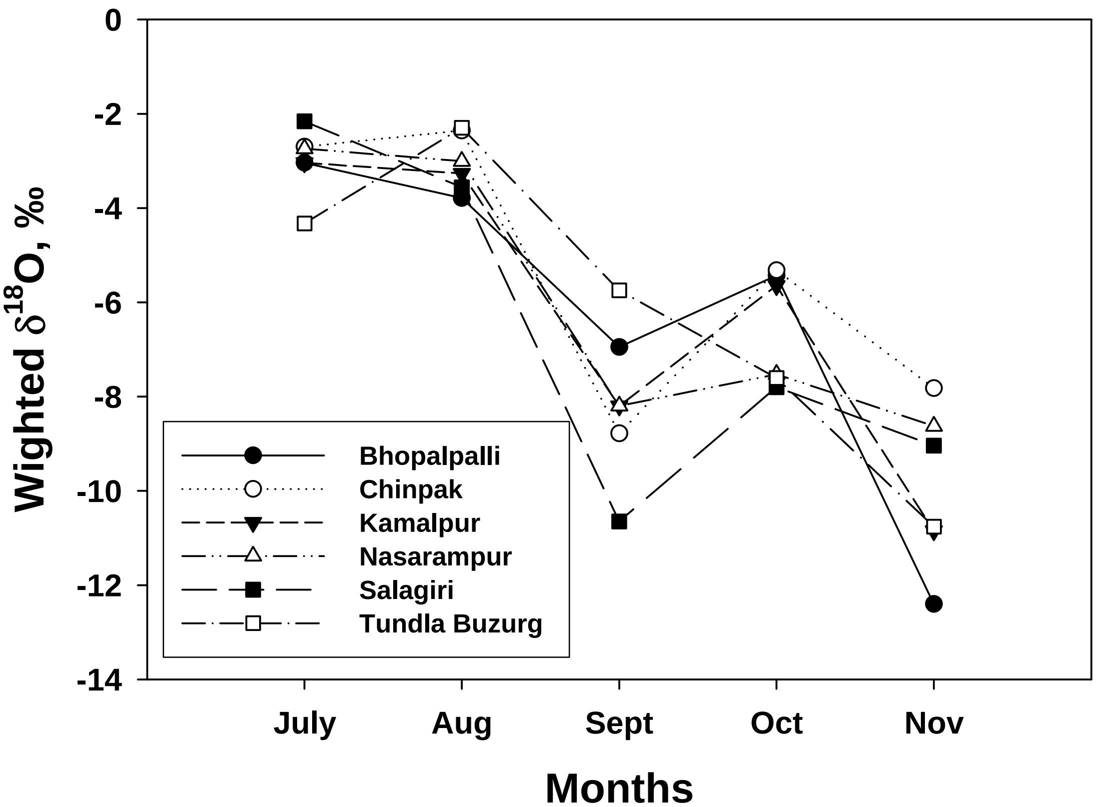

Fig.2.3. Monthly rainfall $\delta^{18}O$ values for various stations in central India for year 1977.

Based on GNIP precipitation and its $\delta^{18}O$ record and work done by Yadava and Ramesh (2005), Yadava et al., (2007) the following points can be deduced:

1. NE monsoon rainfall is depleted in ^{18}O than the SW monsoon rainfall
2. Amount effect is observed in individual rain events and monthly rainfall of particular season i.e. the SW or NE monsoon season
3. During the SW monsoon season, rain at central India (Salagiri) is more depleted in ^{18}O than at southern India (Kozhikode)

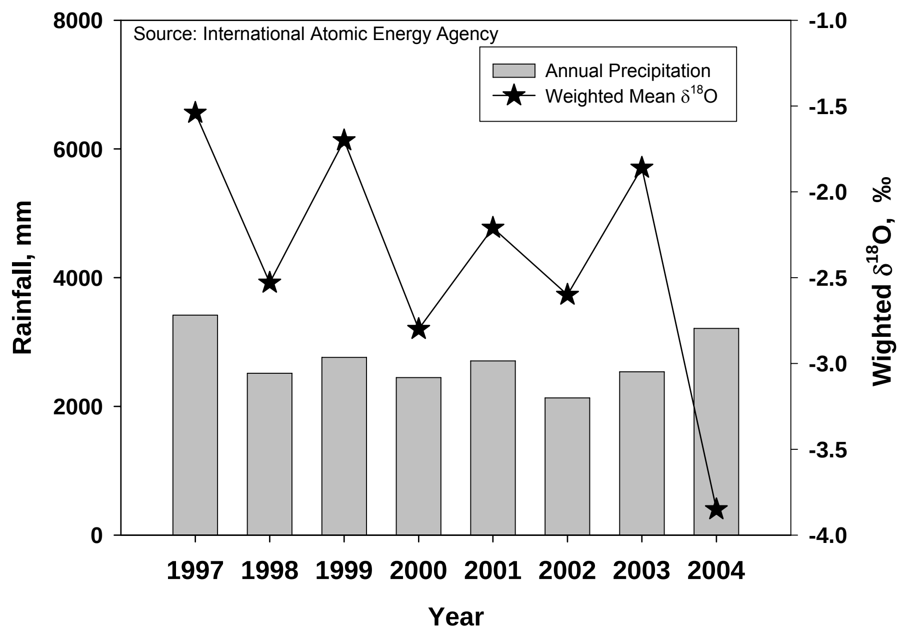

Fig.2.4. Yearly rainfall (bars) and weighted annual rainfall $\delta^{18}O$ (stars) observed at Kozhikode.

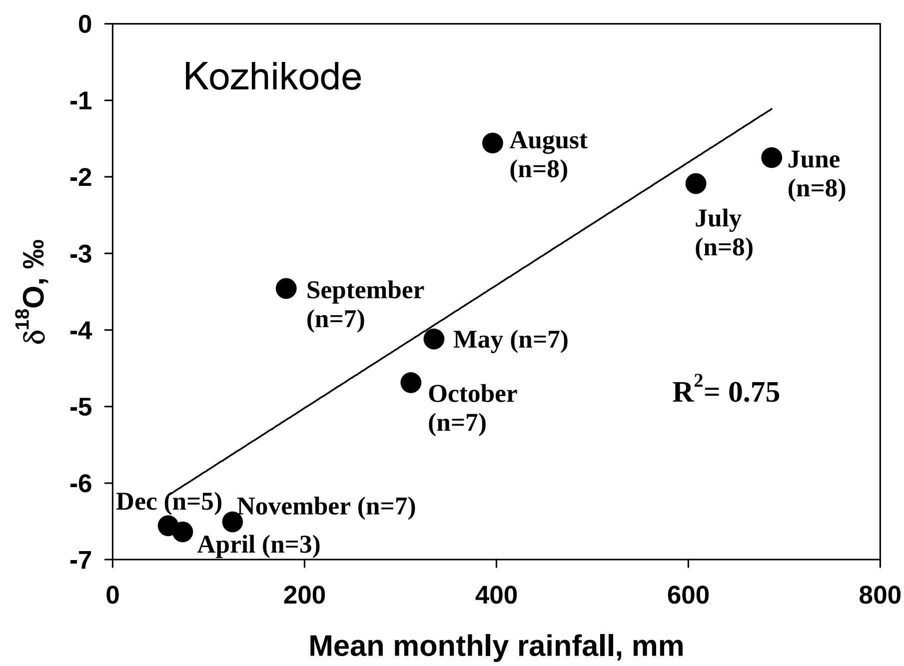

Fig.2.5. Relation between monthly rainfall and amount weighted monthly $\delta^{18}O$ observed at Kozhikode.

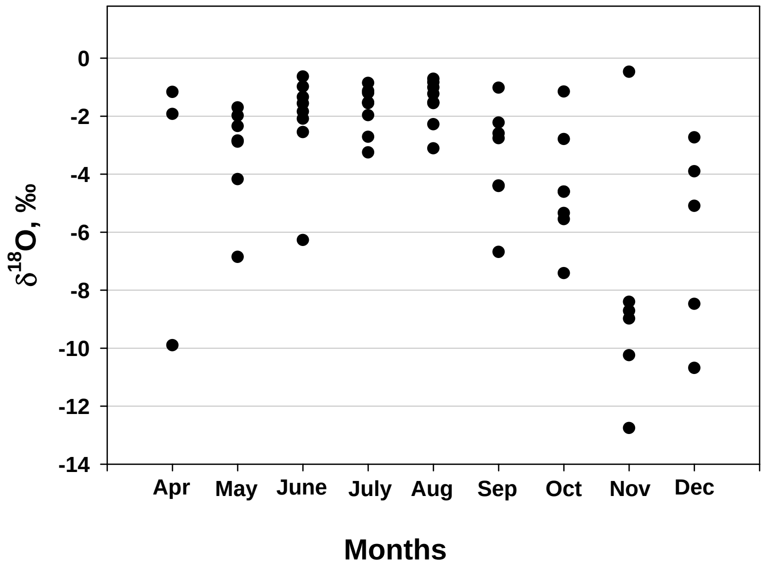

Fig.2.6. Mean monthly rainfall $\delta^{18}O$ values observed at Kozhikode based on observations from year 1997 to 2004 A.D.

2.4 Sample collection

All the samples used in the present study are tree discs collected either by the Indian Institute of Tropical Meteorology (IITM), Pune, India or the Birbal Sahani Institute of Palaeobotany (BSIP), Lucknow, India. IITM and BSIP are routinely involved in tree-ring width based dendrochronological and dendroclimatological investigations. The locations and time spans covered by the samples used in the present study are given in **Table 2**.

Sample Name	Nearest town	Latitude	Longitude	Years covered
THN	Thane	19°12' N	73°02' E	1920-1962
Jag03	Jagdalpur	19°03' N	82°03' E	1824-2003
Jag04	Jagdalpur	19°05' N	82°20' E	1866-2004
AP1	Hanamkonda	18°03' N	79°02' E	1875-1960
AP2	Hanamkonda	18°03' N	79°02' E	1729-1952
PKLM	Perambikulam	10°20'-10°26'N	76°35'-76°50'E	1743-1988

Table 2.2. Names and locations of the samples collected in the present study and time spans covered by them.

The samples from the western (Thane) and central (Jagdalpur and Hanamkonda) India were obtained from the IITM collection. The details regarding collection and dating of the sample from Thane is given by Pant and Borgaonkar (1983). They collected several tree discs from the Murbad forest, Maharashtra, India (19°14′ N, 73°24′ E). Standard procedures were employed for dating these discs and the discs showed a good cross-match with no double or missing rings. Dr. H. P. Borgaonkar collected (years 2000 and 2004 A.D.) several tree cores and discs from central India and found a good cross matching between the cores from the same tree and from different trees at the same site for some sites (Borgaonkar et al., 2007). These discs and cores are currently being studied for the development of tree ring index chronologies. In the present study, two tree discs (Jag03 and Jag04) were selected out of this collection and used for climate reconstruction. These discs were taken from wind-felled tree from Chattisgarh and the distance between them is about 25 km. Based on their year of fall, years A.D. 2003 and 2004 were assigned to the outermost rings of Jag03 and Jag04, respectively.

Two more cross dated tree discs (AP1 and AP2) were selected from the IITM collection. These trees belong to area near Hanamkonda, Andhra Pradesh and are located about 100 km south of trees selected from Chattisgarh. Tentative cross dating yielded years A.D.1960 and 1952 to the outermost rings of AP1 and AP2.

The sample from southern India was collected and dated by Dr. Amalava Bhattacharyya of BSIP. The sample was collected from area near Perambikulam (10°20′–10°26′N; 76°35′–76°50′E) during March 2000 A.D.. It is a disc cut out of a wind-felled tree. The dating of the sample was done through cross dating with the master tree ring plot for the area. The sample dates from 1743 to 1986 A.D. and the dates were checked using the computer program COFECHA (Holmes, 1983). The details regarding sample collection and the master tree ring plot is described by Bhattacharyya et al., (2007). For the purpose of the present work, it is assumed that the dates are correct to ± 1 year.

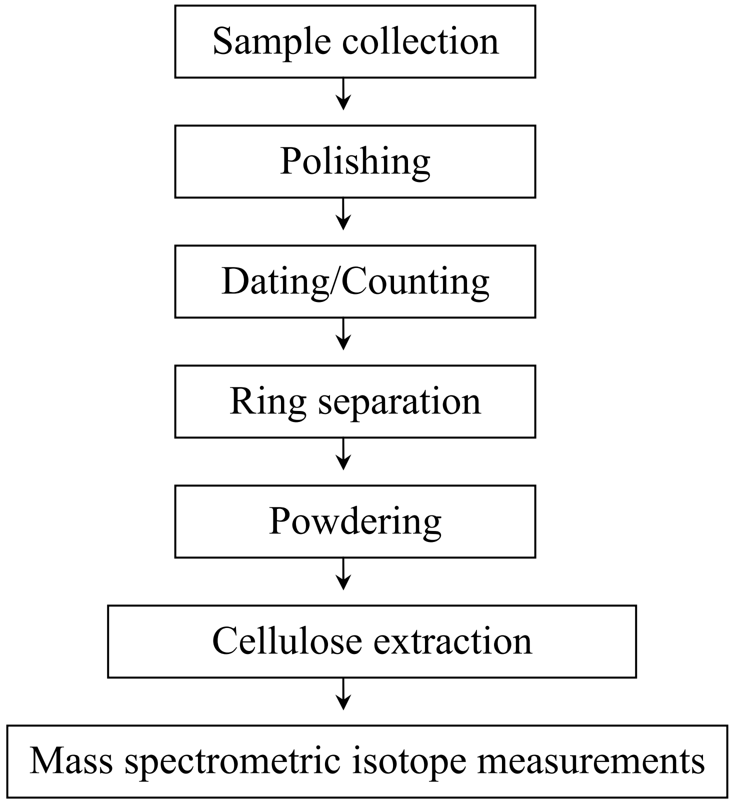

Fig.2.7. Flow chart showing the experimental procedure followed in the present study.

2.5 Ring separation and powdering

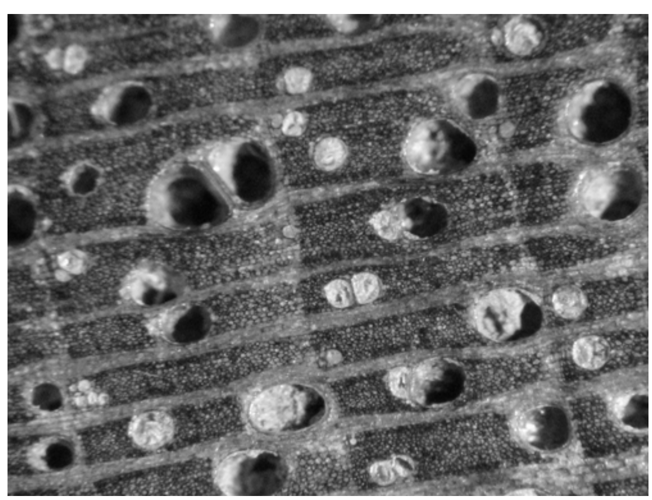

Fig.2.8. Ring porous vesicle structure observed in the teak samples.

The experimental procedure adopted in the present study is shown in **Fig.2.7**. Radial strips along the selected directions were cut from the discs mentioned above. The radial strips were manually polished thoroughly using different grades of sandpaper. Upon polishing all the samples showed clear ring-porous structure (**Fig.2.8**). The vesicle size and frequency decreased from the pith-side to the bark-side. Rings were counted under microscope and calendar years were assigned to them by counting the rings, knowing the year of felling/fall.

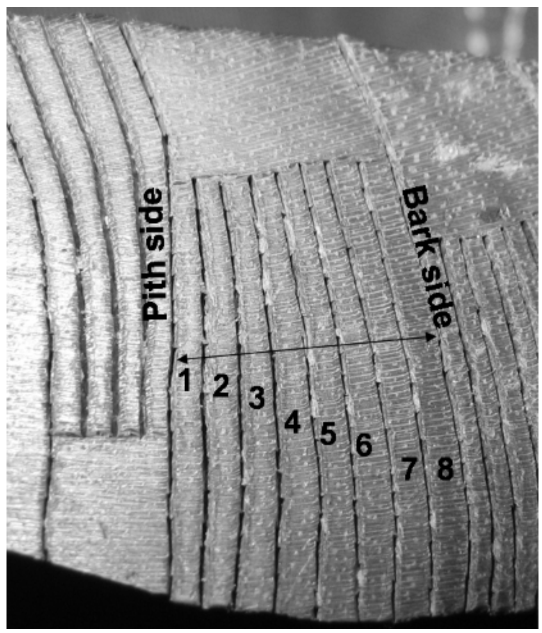

Fig.2.9. Photograph of a ring subdivided into 8 parts for studying sub-annual $\delta^{18}O$ variations.

Subsequent to the dating of samples, individual rings were separated using scalpel, chisel and hammer. The resolution with which the rings were separated depended upon width of the rings; rings with widths less than 0.6mm were combined together. Use of recently developed cellulose extraction methods, which are described later, enabled to extract cellulose from small amounts of wood material and hence facilitated a higher resolution sampling. While separating the rings, maximum care was taken to avoid contamination from the adjacent rings. Intra-ring sampling was done to understand how the isotopic composition of photosynthates varied along the radial direction within a ring. For this, about 10 rings from each sample (except the sample from Thane) were selected randomly and further separated into four equal parts. Some of these rings which were comparatively wider were sampled with higher as well as lower resolutions. In the higher resolution sampling, the rings were subdivided into 6 or 8 or 12 or 16 parts. The widest ring from central Indian sample (Jag03) was sampled with the highest resolution: the ring was subdivided into 16 parts. **Fig.2.9** depicts a representative photograph of a ring which was subdivided into 8 parts. The separated rings/parts of the rings were powdered in a Wiley mill. The mill was cleaned thoroughly after powdering of each ring sample. The powdered material was transferred to a plastic vial with screw cap and stored for further treatment.

2.6 Extraction of α-cellulose

α-cellulose was extracted from the powdered wood material using a method suggested by Gaudinski et al., (2005) with some modifications. Gaudinski et al., (2005)'s method, called 'MBrendel' method, is a modification of the method given by Brendel et al., (2000). The steps followed in the present study are as follows

STEP 1

- Take about 50 mg of wood powder in a dry round bottom glass tube with stoppers
- Add 2ml of 80% acetic acid
- Add 0.2ml of 69% nitric acid
- Seal the tube with stoppers using Teflon tape
- Boil at 120°C for 30 minutes

STEP 2

- Allow the tubes to cool (~5-10 min)
- Transfer the solution to glass centrifuge tubes having screw caps with Teflon inliers
- Add 2.5 ml 99% ethanol

STEP 3

- Vortex
- Centrifuge for 5 minutes at 3500 rpm or higher
- Decant supernatant

STEP 4

- ADD 2 x 2.5 ml 99% ethanol in tow steps; the first 2.5 ml is added and mixed, the second addition is to make wash sown the sides of the glass tube to force samples back to solution
- Repeat step 3

STEP 5

- Add 2 x 2.5ml of distilled deionised water (DDI)
- Repeat step 3

STEP 6

- Add 2 x 2.5 ml 17% (w/v) NaOH using glass pipettes
- Stir the sample pellets with thin glass rod
- Ultrasonicate the mixture for ~5 min
- Let the mixture sit for one hour
- Repeat step 3

STEP 7

- Add 2 x 2.5 ml DDI water
- Repeat step 3

STEP 8

- Add 2.2 ml DDI water + 0.6 ml acetic acid
- Vortex
- Add 2.2 ml DDI water to wash the sides of the glass tubes and mix gently
- Repeat step 3

STEP 9

- Repeat step 3 three times

STEP 10

- Add 2 x 2.5 ml 99% ethanol
- Repeat step 3

STEP 11

- Add 2 x 2.5 m acetone
- Repeat step 3

STEP 12

- Allow the sample to dry overnight in an oven at 50°C
- Transfer the sample to 1.5 ml polypropylene centrifuge tube and keep the tube in desiccator

In the present study, some modification were introduced in the STEP 6 of Gaudinski et al., (2005)'s method. These modifications are ultrasonicating the mixture (sample and NaOH) for ~ 5min and keeping the solution for one hour instead of ~10 min as suggested in the original method. In a day, cellulose was extracted from two batches of samples each containing 16 samples, a number determined by the capacity of the centrifuge.

Gaudinski et al., (2005) pointed out that the Brendel's method adds carbon and nitrogen to the cellulose and left a residue that contains remnant lipids and waxes. In case of oxygen, the authors reported that cellulose extracted using Brendel's method is enriched in ^{18}O relative to the other methods and proposed a method, MBrendel, involving an additional step that treats the cellulose further with 17% NaOH, followed by water rinsing and acidification.

2.7 FTIR spectroscopy of extracted α-cellulose

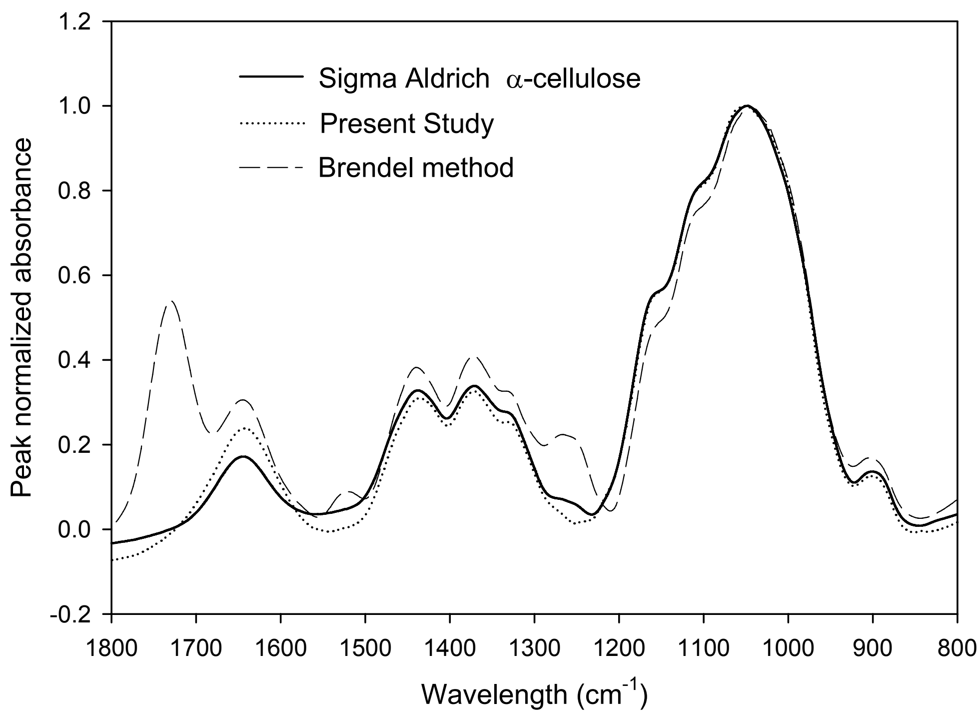

Fig.2.10. Representative FTIR spectra of α-cellulose extracted using present method, Brendel et al., (2000)'s method and commercial available α-cellulose of Sigma Aldrich.

Purity of the α–cellulose extracted in the present study was checked by Fourier transform infrared spectroscopy (FTIR) using Varian 3100 FT-IR spectrometer at Ahmedabad Textile Research Institute (ATIRA), Ahmedabad, India. All the measurements were done using KBr pellets. **Fig.2.10** shows representative spectra of α-cellulose extracted using the present method, Brendel et al., (2000)'s method and commercial available α-cellulose of Sigma Aldrich. Anchukaitis et al., (2008) reported that α-cellulose extracted using Brendel et al., (2000)'s and Gaudinski et al., (2005) methods resulted in acetylation of cellulose with its peak in FTIR spectra at 1720 cm^{-1}. It can be seen from the **Fig.2. 10** that FTIR spectra of the α-cellulose extracted in the present study does not show acetylation peak. Thus, there is no significant contribution of oxygen atoms to α-cellulose from acetic acid through cellulose acetylation.

2.8 Mass spectrometric isotope measurements and analytical precision

The isotopic measurements were done using Thermo Quest's Finnigan Delta plus continuous flow Isotope Ratio Mass Spectrometer (IRMS) available at the National Facility, University of Agricultural Sciences, Bangalore, India. The peripherals attached with the mass spectrometer were High Temperature Conversion Elemental Analyzer (TC/EA) and ConFlo III. TC/EA was operated at 1350°C to ensure complete pyrolysis of the samples. To avoid isotopic interference of CO and N_2 the pyrolyzed gases were then passed through Gas Chromatograph (GC) column (0.6m x 1/4″ x 4mm, Stainless Steel). The molecular sieve used in GC was 5Å, 80-100 mesh size. ConFloIII is a device coupling TC/EA and IRMS. It works with an open-split arrangement whereby a gas flow of ~80-100 ml/min coming from TC/EA is reduced to ~0.3ml/min, a rate at which gas in introduced into the IRMS. ConFloIII contains two open split cells: one 'sample section' and the other 'reference section'. 'Sample section' and 'reference section', splits the gas coming from TC/EA and reference gas cylinder, respectively.

For isotopic measurement, about 0.85 mg of cellulose was packed in silver foil and the sample capsules were put in oven kept at 60°C for at least 10 hours before measurements. Typically, 50 samples were analyzed in a single run. These contained 44 cellulose samples and 6 standards with standards at 1^{st}, 10^{th}, 20^{th}, 30^{th}, 40^{th} and 50^{th} positions. The standards used were in-house calibrated starch ($\delta^{18}O$ = 26.8‰) and Australian National University (ANU) sucrose ($\delta^{18}O$ = 36.4‰). All the measurements were done with ConFloIII on 'He dilution ON' mode. During measurement of a sample, three reference gas pulses were injected in IRMS first followed by a sample gas injection and again reference gas injection. Time required for the measurement of one sample was 10 min. The reference gas injections gave internal precision less than 0.1 ‰. The external precision of the measurements were consistently less than 0.3 ‰. **Table 2.3** gives precisions of the ANU sucrose $\delta^{18}O$ values measured during individual runs and the date of respective runs. Plot of $\delta^{18}O$ measurements of all the ANU sucrose standards used during cellulose sample measurements is shown in **Fig.2.11** Oxygen isotopic composition all the samples reported in the present study are relative to VSMOW.

Date	External Precision	Date	External Precision	Date	External Precision
July 7	± 0.3	July 14	± 0.3	July 22	± 0.4
July 8	± 0.3	July 14	± 0.2	July 23	± 0.3
July 8	± 0.2	July 15	± 0.3	July 24	± 0.4
July 9	± 0.1	July 15	± 0.2	July 25	± 0.3
July 10	± 0.3	July 16	± 0.3	July 26	± 0.3
July 10	± 0.3	July 16	± 0.2	July 26	± 0.2
July 11	± 0.3	July 17	± 0.1	July 28	± 0.2
July 12	± 0.2	July 17	± 0.2	July 29	± 0.2
July 13	± 0.2	July 21	± 0.3	July 30	± 0.2

Table 2.3. Standard deviations (1 sigma) of $\delta^{18}O$ measurements of ANU sucrose samples measured during various runs in July 2008. Mean of the measurements is 36.4 ‰.

Typically the reactor was changed every 250 samples. The system was degassed overnight with TC/EA at 1350°C and GC at 300°C after changing the reactor. After checking for leak in the connections, background levels were measured. The typical background on CUP1 for peaks 28, 29 and 30 were 7mV, 4mV, and 29mV, respectively with He dilution in ConFloIII ON (48mV, 32mV, and 29mV when He dilution in ConFloIII was OFF). The backgrounds for masses 18, 28, 32 and 44 on CUP 2 were 7000mV, 500mV, 900mV and 105mV, respectively. After this, internal precision of the mass spectrometer was checked by 'ZERO ENRICHMENT or Standard ON/OFF' method in which a reference CO gas was injected repeatedly and its $\delta^{18}O$ was measured. This is followed by $\delta^{18}O$ measurements of external standards (in-house calibrated starch and ANU sucrose) for checking external precision.

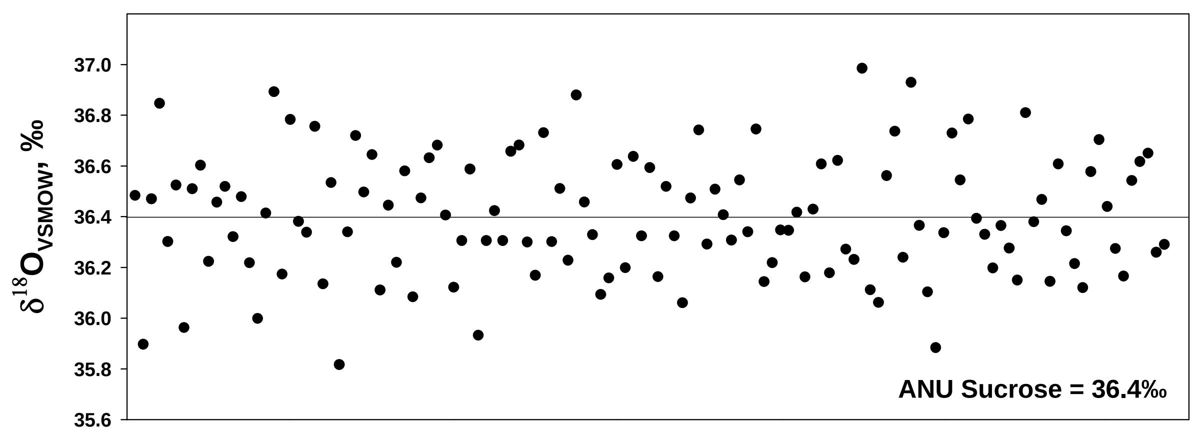

Fig.2.11. Scatter plot showing $\delta^{18}O$ values of all the ANU sucrose standards measured along with cellulose samples in the present work over a period of ~ 20 days.

Chapter 3 Sub-annual $\delta^{18}O$ record in teak

3.1 Introduction

Teak (*Tectona grandis*) is one the few tropical tree species having well developed annual rings. Annual nature of growth rings in teak trees was established by Coster (1927), Berlage (1931) and Chowdhary (1939). As pointed out in the earlier chapters its wide geographical distribution, especially in south and south-east Asia – India, Java, Sumatra, Burma, and Thailand – a region important for tracking El Nino-Southern Oscillation phenomenon, makes it an important candidate for reconstruction of past monsoon variability. Several studies (Berlage, 1931; D'Arrigo et al. 1994, Pumijumnong et al., 1995; Borgaonkar et al., 2007; Buckley et al., 2007, Shah et al., 2007) have reported reconstruction of past climate, especially rainfall, using variations in ring-widths of teak.

Reconstruction of past rainfall using ring-width variations involves finding a response function for tree growth, which in turn involves finding regression coefficients between ring widths and monthly rainfall of the corresponding year. From the above mentioned studies, the response of teak growth to the ambient climatic parameters (mainly rainfall) appears to be site-specific. Ramesh et al., (1989) analyzed hydrogen isotope ratios of teak tree near Mumbai, India and stressed importance of length of growing season in determining teak growth. Jacoby and D'Arrigo (1990) based on ring-width analysis of teak trees from Java showed that the growth is insensitive to the amount of wet season rainfall while Pumijumnong et al., (1995) showed growth to be correlated with the first half of the wet season. Buckley et al., (2007) reported that the variability of teak growth in western Thailand is correlated with rainfall during the beginning and end of the monsoon season. Borgaonkar et al., (2007) based on analysis of teak trees from central and southern India showed a significant correlation between ring-width and pre-monsoon and post-monsoon climate and suggested role of a moisture index rather than direct rainfall as a major factor controlling ring-width variations. Recently, after studying ring width variations of teak trees from central India, Somaru Ram et al., (2008) also reported importance of soil moisture and rainfall during the monsoon season in deciding teak growth. Reconstructing past rainfall using variations in ring-widths thus requires a good understanding of the relationship between tree growth and rains during various phases of the growing season. Unfortunately, ring-width/isotope based whole ring approach can elucidate such relationship in a limited way. A proper understanding of sub-annual isotope variations in trees is the key for interpreting inter-annual variations in their isotopic composition, the basis for reconstructing past climate.

Recent studies (Loader et al., 1995, Poussart et al., 2004, Evans and Schrag, 2004, Poussart and Schrag 2005, Dodd et al., 2008, Verheyden et al., 2004, Miller et al., 2006) show the potential of sub-annual isotope studies in understanding past climate. The applications of such studies range from reconstruction of past rainfall, relative humidity, temperature, source water composition, tree growth rates to establishing chronometry in trees lacking visible growth rings and to tracking tropical cyclones. The advent of faster cellulose extraction techniques (e.g. Brendel et al., 2000, Evans and Schrag 2004, Gaudinski et al., 2005, Anchukaitis et al., 2008) and plant physiological models (Flanagan et al., 1991; Saurer et al., 1997; Farquhar et al., 1998; Barbour and Farquhar, 2000; Roden et al., 2000, Barbour et al., 2004) for interpreting isotope values of trees has greatly facilitated sub-annual isotope analysis.

In this chapter, a case is presented where three trees from central India and one from southern India were analyzed with different spatial resolutions for understanding factors governing the sub-annual $\delta^{18}O$ variations. Local meteorological data and a plant physiological model were used to decipher factors governing the sub-annual and whole ring cellulose $\delta^{18}O$ values. The chosen geographical locations of these samples enable the understanding of how trees growing in different climatological settings respond to the ambient climate. Analysis of xylem water/cellulose had shown (Ehleringer and Dawson 1992, Lin et al., 1996, Schwinning et al., 2002, Evans and Schrag 2004) that plants record seasonally varying isotopic composition of precipitation. The present work tests whether this is true for teak trees living in the bimonsoon regime of southern India. Implications to the reconstruction of rainfall based on inter-annual variations in the cellulose $\delta^{18}O$ of teak trees are discussed. A brief discussion is also made regarding possible time resolution achievable by sub-seasonal $\delta^{18}O$ studies.

3.2 Rings selected for sub-annual cellulose $\delta^{18}O$ studies

Out of three central Indian samples selected for sub-annual $\delta^{18}O$ studies, two samples viz. Jag03 and Jag04, come from near Jagdalpur (Lat: 19°05'N and Long: 82°02'E) and one viz. AP1, from area near Hanamkonda (Lat: 18°01'N and Long: 79°34'E). The teak sample from southern India viz. PKLM comes from area near Perambikulam (10°20'-10°26'N, 76°35'-76°50'E), Kerala. The locations of these samples were shown in **Fig. 2.1**, **Chapter 2**. The details regarding sample collection, dating and local climate was described in the previous chapter.

For studying sub-annual $\delta^{18}O$ variation, rings of various sizes from Jag03, Jag04, AP1 and PKLM were manually separated along a radial direction into different equal parts using scalpel and chisel. Maximum care was taken to avoid contamination from the adjacent segments/rings. The sample-wise details of the years (A.D.) corresponding to rings are given below.

Sample Name: Jag03

1843(8.2,**4,**20), 1844(6.2,**4,**21), 1848(7.2,**4,**25), 1963(7.0,**4,**140), 1969(10.0,**4,**146), 1970(8.4,**4,**147), 1970(8.4,**12,**147), 1971(13.0,**4,**148), 1971(13.0,**16,**148), 1972(8.6,**4,**149), 1977(6.6,**6,**154), 1985(4.6,**6,**162), and 1995(7.0,**4,**172)

Sample Name: Jag04

1895(7.4,**4,**31), 1905(6.4,**4,**41), 1909(6.6,**4,**45), 1925(9.8,**4,**61), 1956(9.8,**4,**92), 1964(7.8,**4,**100), 1969(7.4,**4,**105), and 1979(7.2,**4,**115)

Sample Name: AP1

1878(5.0,**4,**6), 1879(12.4,**8,**7), 1881(6.0,**4,**9), 1882(4.0,**4,**10), 1886(5.8,**4,**14), 1891(6.8,**4,**19), and 1892(3.8,**4,**20)

Sample Name: PKLM

1752(7.0,**4,**10), 1752(7.0,**8,**10), 1754(5.0,**4,**12), 1754(5.0,**6,**12), 1763(4.2,**4,**21), 1763(4.6,**6,**26), 1769(4.6,**6,**27), 1770(4.8,**6,**28), 1771(6.0,**4,**29), 1772(5.6,**4,**30), 1772(5.6,**6,**30), 1781(5.0,**4,**39), 1782(5.0,**4,**40), 1785(4.2,**4,**43), 1793(4.2,**4,**51), 1794(4.6,**4,**52), 1797(4.4,**4,**55), 1810(3.8,**4,**68), 1811(4.0,**4,**69) and 1825(3.6,**4,**83).

The numbers in parentheses are the ring widths in mm, number of sub-samples into which the corresponding ring is divided (bold faced) and cambial age (ring number from the pith) (underlined), respectively. Some rings were sampled twice from two adjacent spots, but with different spatial resolutions. Photograph in **Fig. 2.9** in **Chapter 2** illustrates, with the help of a ring which was subdivided into 8 parts, the manner in which sub-annual sampling was carried out. **Fig. 3.1** depicts a ring which was divided into 4 parts.

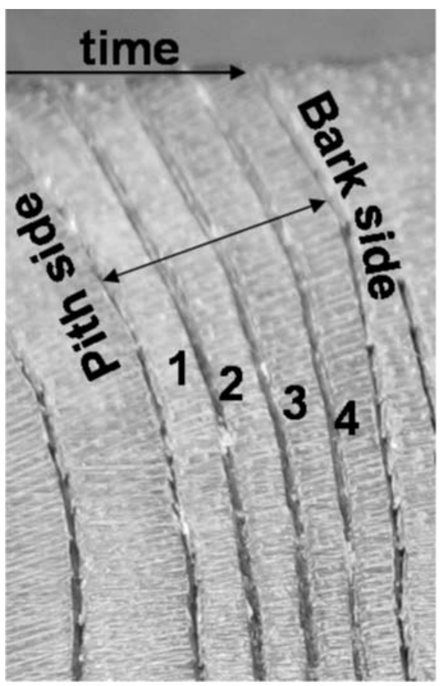

Fig.3.1. A photograph depicting a ring which was divided into four parts.

3.3 Assigning time to sub-annual segments

Dendrometric growth (Sudheendrakumar et al, 1993 and Buckley et al., 2001) and cambial activity studies (Priya and Bhat, 1999) of teak clearly demonstrate a positive relationship between rainfall and diameter growth. For teak trees from southern India, Sudheendrakumar et al., (1993) observed a bell shaped growth curve with high growth rates during June to September. Cambial activities of teak trees studied by Priya and Bhat (1999) established the influence of rainfall on cambial activity. Their work demonstrated bud break occurs in March/April and there is almost a month's gap between bud break and initiation of the radial growth. They also pointed out coincidence of the peak period of cambial activity and a period of the highest amount of rainfall (June-July). The authors also mentioned that the wider rings are associated with prolonged periods of cambial activity and contain higher percentage of latewood.

Even though a cambial 'pinning' or 'scratching' would demonstrate it conclusively, it can be safely concluded by above mentioned studies that the beginning, intermediate and end part of sub-annual $\delta^{18}O$ profiles correspond to growths during the early (May), main (June to September) and end (October to December) of the growing season, respectively. Sub-annual segments shown by number 1, 2-3 and 4, in **Fig.3.1** thus contain photosynthates synthesized during the pre-, main- and post-monsoon seasons respectively.

3.4 Model used for explaining sub-annual cellulose $\delta^{18}O$ variations

$\delta^{18}O$ of tree cellulose depends upon $\delta^{18}O$ of the source water, the level of evaporative enrichment of the source water in the leaf during transpiration, biochemical fractionation associated with the synthesis of sucrose in the leaf and the extent of exchange between sucrose and xylem water during cellulose synthesis. Roden et al., (2000)'s mechanistic model for interpreting hydrogen and oxygen isotope ratios of tree cellulose gives the final oxygen isotope composition of tree cellulose ($\delta^{18}O_{cx}$) as

$$\delta^{18}O_{cx} = fo \cdot (\delta^{18}O_{wx} + \varepsilon o) + (1 - fo) \cdot (\delta^{18}O_{wl} + \varepsilon o), \quad (1)$$

where f_O is the fraction of carbon-bound oxygen that undergoes exchange with medium water, $\delta^{18}O_{wx}$ and $\delta^{18}O_{wl}$ refer respectively, to the oxygen isotopic composition of the xylem and leaf water at the site of sucrose synthesis. $\delta^{18}O_{wl}$ in Eq. (1) is calculated following Dongmann et al., (1974) and Flanagan et al., (1991). The isotopic composition of leaf water ($\delta^{18}O_{wl)}$ used in Eq. (1) is observed to be more enriched than that of the bulk leaf water due to Péclet effect – an effect describing transpirational advection of ^{18}O depleted (xylem) water to the evaporating site opposed by backward diffusion of ^{18}O enriched water from the leaf (Farquhar and Lloyd 1993). Barbour et al., (2004) have proposed a model considering the Péclet effect, the use of which demands knowledge of Péclet number for teak. Instead of using this model with its assumed value, the present work considers Roden et al., (2000)'s model for estimating cellulose $\delta^{18}O$. As the conclusion of this work is based on relative $\delta^{18}O$ variability, this should not cause any serious discrepancy.

Roden et al., (2000)'s model was used to construct the $\delta^{18}O$ profile of tree cellulose produced during the teak growing season (Mar-Dec), assuming that there is no intra-seasonal transfer of photosynthates. The model is freely available online at http://ecophys.biology.utah.edu/public/Tree_Ring/. To construct modeled sub-annual $\delta^{18}O$ profile for Jag03 and PKLM meteorological data from Indian Meteorological Department (IMD)'s weather station at Jagdalpur and Palakkad, respectively were used. The monthly meteorological parameters used in the model were taken from climatological tables (IMD, 1999) which are based on observations from 1951-1980 A.D. Daily weather data used for constructing sub-annual $\delta^{18}O$ profile for a ring (year 1971 A.D.) from Jag03 was taken from IMD's Indian Daily Weather Records (IDWR) reports. $\delta^{18}O$ values of rainfall for PKLM sample were from GNIP station Kozhikode. Atmospheric water vapor $\delta^{18}O$ was considered 11‰ depleted relative to $\delta^{18}O$ of rainfall (Srivastava et al., 2008). Leaf temperature was estimated as given by Linacre (1964). Stomatal conductance values were estimated using a relationship between vapor pressure deficit and stomatal conductance ($r = 0.8$, $P < 0.0005$)

(Kallarackal and Somen, 2008). Boundary layer conductance was taken as 1 mol m^{-2} s^{-1}, a value in accordance with Grace et al., (1980).

3.5 Sub-annual cellulose δ^{18}O variations

Sub-annual δ^{18}O variations observed for samples from central India, (Jag03, Jag04 and AP1) in coarse (rings sub-divided into four parts) and fine (rings sub-divided into 6 or 8 or 12 or 16 parts) resolution sampling are shown in **Fig.3.2** and **Fig.3.3**, respectively. The data points represented in these figures show δ^{18}O values of the growth segments whose positions are marked as percent distance from the pith side.

In general, the coarse resolution δ^{18}O variations observed for samples Jag03 (**Fig.3.2a**), Jag04 (**Fig.3.2b**) and AP1 (**Fig.3.2c**) show a pattern with higher δ^{18}O values at the beginning and end of the ring and lower values at the intermediate part. The amplitudes of sub-annual δ^{18}O variations range from 1.9-4.6 ‰ (mean = 3.4 ± 1.0 ‰) for Jag03, from 2.0-5.0 ‰ (mean = 3.6 ± 1.1 ‰) for Jag04, 2.4-4.5 ‰ (3.5 ± 0.8 ‰) for AP1. In the case of rings analyzed with different resolutions, the profile of lower resolution represents the moving average of the higher resolution profile. The spread in δ^{18}O values of segments of different rings is more at the intermediate part and is less at the extremities of the ring.

Fine resolution sub-annual δ^{18}O profiles (**Fig.3.3**) for the trees from central India show a more consistent pattern with higher δ^{18}O values at the ring extremities and lower δ^{18}O values in between. For Jag03 sample, the amplitudes of sub-annual δ^{18}O variations range from 3.8 ‰ to 6.8 ‰; for AP1 sample, 3.0 to 6.2 ‰. Like coarse resolution sampling, fine resolutions sampling also shows higher spread of δ^{18}O values of different rings at intermediate positions than at extremities.

In contrast to the teak samples from central India, PKLM shows an opposite trend in sub-annual δ^{18}O profile. **Fig. 3.4(a)** and **3.4(b)** show sub-annual δ^{18}O profiles of the rings analyzed with coarse and high resolution sampling, respectively. The data

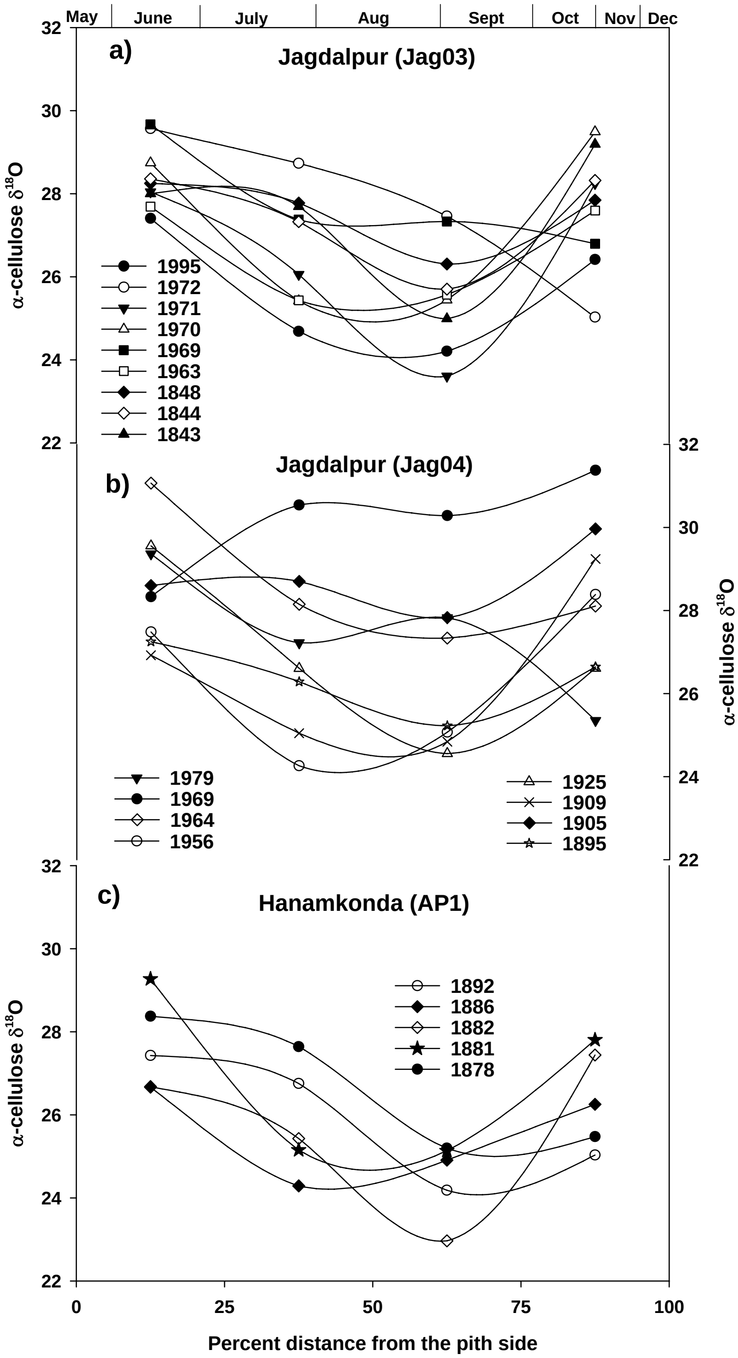

Fig.3.2. Coarse resolution sub-annual cellulose $\delta^{18}O$ profiles observed for teak trees from area near Jagdalpur, Jag03 (a) and Jag04 (b), and Hanamkonda, AP1 (c). Legends represent years corresponding to the rings analyzed. Months shown on the top of the graph are approximately assigned based on teak growth studies by Sudheendrakumar et al., (1993).

points in these figures represent the cellulose δ^{18}O of the corresponding segments of rings. The δ^{18}O profiles of coarse resolution sub-annual analysis of PKLM (**Fig. 3.4a**) show amplitudes varying in the range 1-3‰ (mean = 1.9 ± 0.7 ‰). In general, the δ^{18}O values are low at the beginning and at the end of growing season and higher at the intermediate season. The spread in the values is more at the extremities than at intermediate segments. The high resolution sub-annual profile of PKLM (**Fig. 3.4b**) shows higher frequency fluctuations in δ^{18}O, probably filtered out in the coarse resolution analysis (**Fig. 3.4a**); despite this, the amplitude (range: 1-3‰; mean = 2.1±0.8 ‰) and trend of the high resolution sub-annual variation are not significantly different from those of the coarse resolution analysis.

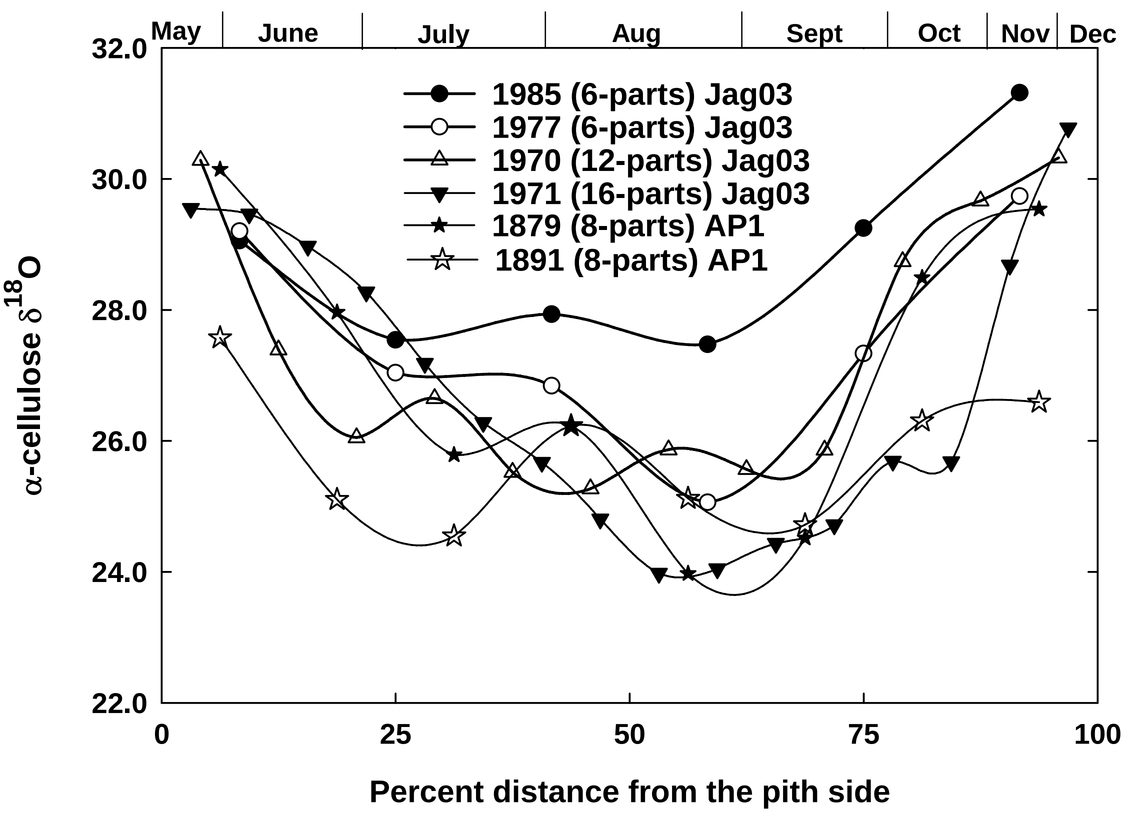

Fig.3.3. Fine resolution sub-annual cellulose δ^{18}O profiles observed for teak trees from area near Jagdalpur (Jag03) and Hanamkonda (AP1). Legend represents years corresponding to the rings analyzed, the numbers of parts the rings were sub-sampled into and sample name. Months shown on the top of the graph are approximately assigned based on teak growth studies by Sudheendrakumar et al., (1993).

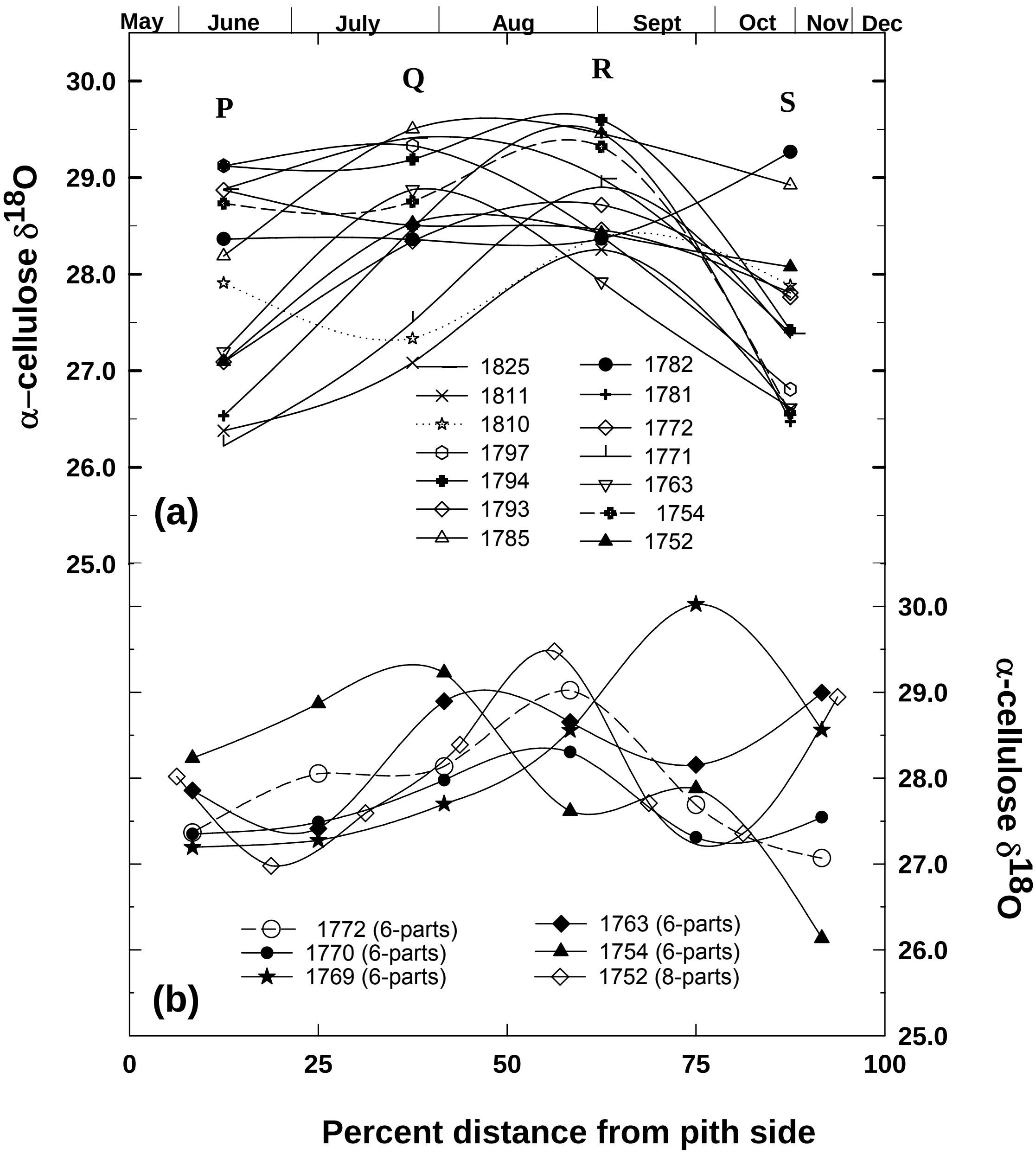

Fig. 3.4. Sub-annual cellulose $\delta^{18}O$ profiles of the rings of the teak from Perambikulam (PKLM): (a) $\delta^{18}O$ variation of the rings which were divided into four equal parts; (b) higher resolution sub-annual $\delta^{18}O$ profiles. Months shown on the top of the graph are approximately assigned based on teak growth studies by Sudheendrakumar et al., (1993).

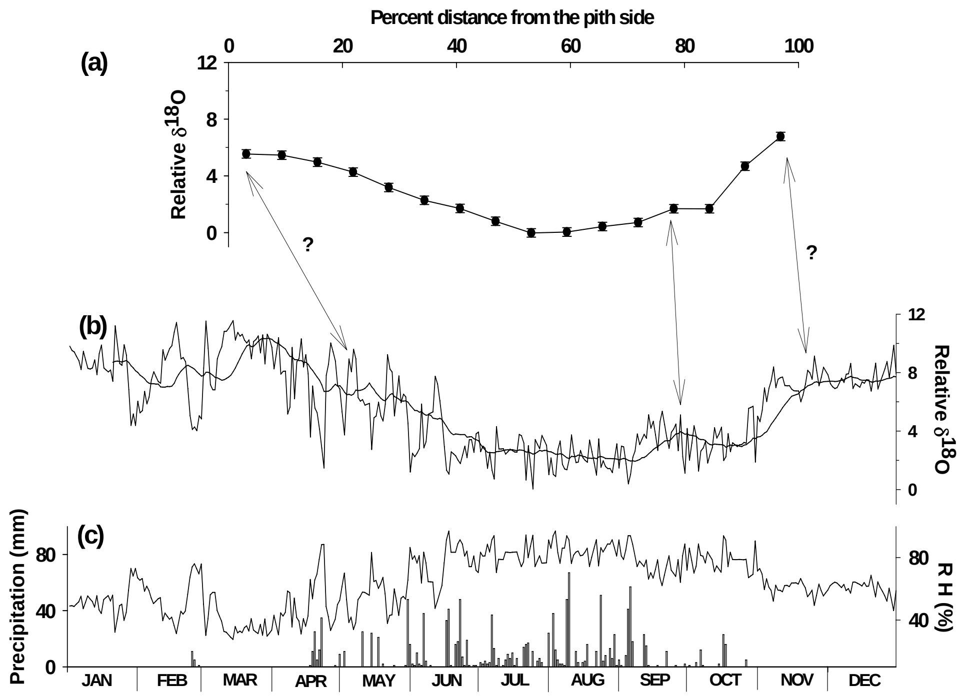

Fig.3.5. (a) Sub-annual cellulose $\delta^{18}O$ variation observed in one of the ring (year 1971 A.D.) of teak from Jagdalpur, Jag03. (b) the modeled $\delta^{18}O$ variations calculated based on daily weather data. (c) daily precipitation (black bars) and relative humidity for the same year (black line). The smoothed line in (b) is 20-day running means of model-calculated daily $\delta^{18}O$ values.

Ring belonging to year 1971 A.D. in the sample Jag03 was the widest (width = 13mm) and was subdivided into 16 parts. **Fig.3.5** shows a comparison of the actual sub-annual $\delta^{18}O$ profile observed for this ring (**Fig.3.5a**) with the profile constructed using Roden et al., (2000)'s model (**Fig.3.5b**). $\delta^{18}O$ values of cellulose synthesized daily during 1971 A.D. was modeled using daily meteorological data observed at Jagdalpur. The constructed daily profile and its 20 day running mean are depicted in **Fig.3.5b**. Observed daily variations in relative humidity (thin line) and rainfall (bars) at Jagdalpur during 1971 A.D are also shown in Fig.**3.5c**.

3.6 Rainfall, relative humidity and $\delta^{18}O$ of cellulose

Coarse resolution sub-annual $\delta^{18}O$ analysis in general and fine resolution analysis in particular, observed in three teak trees from central India show a consistent trend which can be divided mainly into 3 parts respectively: the early growing season with higher $\delta^{18}O$ values; the intermediate growing season with lower $\delta^{18}O$ values; and the late growing season with higher $\delta^{18}O$ values. Based on the pattern of teak growth (Sudheendrakumar et al, 1993 and Priya and Bhat, 1999) these parts likely correspond to pre- (April, May, early June), main- (late June to September) and post-monsoon (October to December) seasons, respectively. $\delta^{18}O$ values of various segments of the rings from samples from central India suggest that about 50% of the rings, i.e. the first and last segments out of four segments (**Fig.3.2** and **Fig.3.3**), are associated with presence photosynthates produced during relatively lower relative humidity. Out of this, the first segment from the pith side may contain photosynthates carried from the previous year as has been suggested by Jacoby and D'Arrigo (1990) for teak trees in Java.

Assignment of precise time to the points in **Fig.3.5a** is not possible as the time of initiation and cessation of radial growth and variation of the growth rate through time is not precisely known. Nevertheless, based on general observations regarding teak growth- pre-monsoon showers leads to bud break/leaf flushing (Priya and Bhat, 1999; Yoshifuji et al., 2006) and about a month's interval between bud break and initiation of radial growth (Priya and Bhat, 1999) – a time of mid May can be assigned to the first $\delta^{18}O$ point from the pith side. The last segment could possibly represent the end of November as leaf fall starts about a month after the last rain (Yoshifuji et al., 2006) and growth rate decreases rapidly afterwards. The actual sub-annual $\delta^{18}O$ profile (**Fig.3.5a**) and the modeled profile with 20 days running mean (**Fig.3.5b**) for the corresponding duration (mid-May to the end of November) show similarity in pattern and amplitude pointing to the importance of relative humidity in controlling sub-annual $\delta^{18}O$ profile. It is interesting to note that rainfall in July 1971 was 142 mm less than the average for July, but had a relative humidity similar to the average for July. This suggests relative humidity is more important than rainfall in determining sub-annual $\delta^{18}O$ values.

Finding correlation between sub-annual $\delta^{18}O$ values and monthly meteorological parameters is difficult as time can not be assigned accurately to various sub-annual segments. However, some insight can be achieved if we assign months to various segments based on observed radial growth increment of teak (Sudheendrakumar et al, 1993). In this context, for 6 rings from Jag04 which were divided into 4 equal parts if months of May-June, July-August, August-September and October-November are assigned to 1st, 2nd, 3rd and 4th sub-annual segments from pith side, respectively, sub-annual $\delta^{18}O$ values are correlated with rainfall and relative humidity with the correlation coefficients of 0.21 ($N=24$, $P<0.25$) and 0.58 ($N=24$, $P<0.005$).

	RH_Jun	RH_July	RH_Aug	RH_Sept	RD_Jun	RD_July	RD_Aug	RD_Sept
R_Jun	0.1				0.28			
R_July		0.12				0.31		
R_Aug			0.2				0.32	
R_Sept				0.16				0.51
RH_Jun					0.24			
RH_July						0.34		
RH_Aug							0.36	
RH_Sept								0.44

Table 3.1. Correlation coefficients among monthly rainfall, monthly relative humidity and monthly number of rainy days. Letters R_, RH_ and RD_ preceding month's name indicate rainfall, relative humidity and rainy days, respectively.

Sub-annual $\delta^{18}O$ profile relate to time averaged environmental conditions, especially relative humidity, during respective times. Rainfall and relative humidity during the peak rainy season (June to September) at Jagdalpur are poorly correlated (**Table 3.1**). The numbers in **Table 3.1** are correlation coefficients among monthly rainfall, monthly relative humidity and monthly number of rainy days of corresponding month based on meteorological data at Jagdalpur from year 1955 to 2000 A.D. Higher correlation between monthly relative humidity and monthly number of rainy days suggest relative humidity of a month depends more upon how uniformly the rainfall is distributed throughout the month rather than total amount of rainfall in that month. Correlation between monthly rainfall and relative humidity for April, May, October, November and December are respectively 0.53, 0.49, 0.45, 0.40 and 0.12. This indicates the limitations of using sub-annual $\delta^{18}O$ fluctuations in reconstruction of the amount of rainfall.

It can be inferred from the present study that the growth taking place in the post-monsoon seasons as a result of the post-monsoon rain spells would lead to production of photosynthates relatively enriched in ^{18}O i.e. the dry season rainfall/growth would lead to increased whole-ring $\delta^{18}O$ values. Yoshifuji et al., (2006) pointed out that the total length of growing season of teak can increase with early (~pre-monsoon) and late (~post-monsoon) rains. The authors have also shown that such rains result in augmenting soil moisture (hence, the growth duration) which lasts longer than the increase in relative humidity caused by such rains. As a consequence, a tree grows when more evaporative enrichment in the leaves leads to the formation of photosynthates enriched in ^{18}O.

The spread of sub-annual $\delta^{18}O$ in various rings are higher in the intermediate segments i.e. during periods of higher relative humidity (June to September), than at the extremities. This could happen because of occurrence of a dry spell among the good pre-monsoon showers and the peak monsoon rainfall and heavy post-monsoon showers. Such dry periods are known to produce false rings in teak (Priya and Bhat 1998). The spread in the monthly $\delta^{18}O$ values of rainfall during July to September observed at GNIP station Hyderabad (17.45°N, 78.47°E) for a period from 1997 to 2000 A.D. is -3.9 ± 2.1 ‰. The variable $\delta^{18}O$ values of rainfall may also contribute to the spread of sub-annual $\delta^{18}O$ values observed at the intermediate segments. Another possible reason for such fluctuations could be presence of a 'break-monsoon', an abrupt weakening of rainfall and presence of drier weather during the peak rainy season. Monsoon breaks vary in duration from 3 to 17 days (average 5.8 days) (Ramamurthy, 1969) and are associated with reduced surface relative humidity (Krishnamurthy and Biswas, 2006). As the growth rates are higher in general during the months of July and August, it is likely that such breaks would result in enrichment of cellulose $\delta^{18}O$ of concurrent season. Similarity of $\delta^{18}O$ values at the end of the growing season (**Fig.3.3**) perhaps indicate that teak stops growing at similar relative humidity conditions and produces photosynthates with similar $\delta^{18}O$ values. Clearly, more work is required in this direction.

3.7 Rainfall with seasonally changing $\delta^{18}O$ and sub-annual cellulose $\delta^{18}O$ variations

The observed opposite trend of sub-annual $\delta^{18}O$ profile of PKLM with respect to the samples from central India can be explained if the former ingests water of the NE-monsoon (winter monsoon) which is relatively depleted in ^{18}O with respect to SW-monsoon (summer monsoon). The $\delta^{18}O$ depleted nature of the NE monsoon is discussed in the previous chapter (See **Table2.1, Fig.2.5 and Fig.2.6, Chapter 2**). Yadava et al., (2007) analyzed rains (2000 to 2002 A.D.) at Mangalore which receives both the monsoon and showed that the NE monsoon precipitation is relatively more depleted in ^{18}O. The depleted nature of the winter monsoon observed in the southern India is in contrast with observations elsewhere in South-East Asia, where summer rains are depleted in ^{18}O relative to winter rains (Araguás- Araguás et al., 1998). Roden et al., (2000)'s model can be used to explain the sub-annual $\delta^{18}O$ profiles of PKLM. The model calculated sub-annual $\delta^{18}O$ values for the main growing season are shown in **Fig. 3.6**.

If we assume teak in this region (Perambikulam) samples only the SW monsoon, then according to **Fig. 3.6(a)**, $\delta^{18}O$ of cellulose at the end of growing season should be higher than that at the mid/main growing season. This is because the average relative humidity during the NE monsoon (Oct-Dec) is lower than that of the SW monsoon (Jun-Sep). However, most observed $\delta^{18}O$ values (**Fig. 3.4a**) associated with the late growing season are lower, relative to the main growing season. Therefore, changes in relative humidity, temperature and associated plant physiological parameters alone cannot account for the observed lower $\delta^{18}O$ values at the end of growing season. It is clear from **Fig**.**3.4b** that while the $\delta^{18}O$ values are certainly reduced at around 75% distance from the pith side, in a few years, a small increase is observed subsequently. This could be the effect of the lower ambient humidity during the end of the growing season, as also seen in the model profile in **Fig**.**3.6b**. The depleted cellulose $\delta^{18}O$ values associated with the end of the rings (**Fig. 3.4a and 3.4b**) can be explained only if the tree records the NE monsoon rain as well.

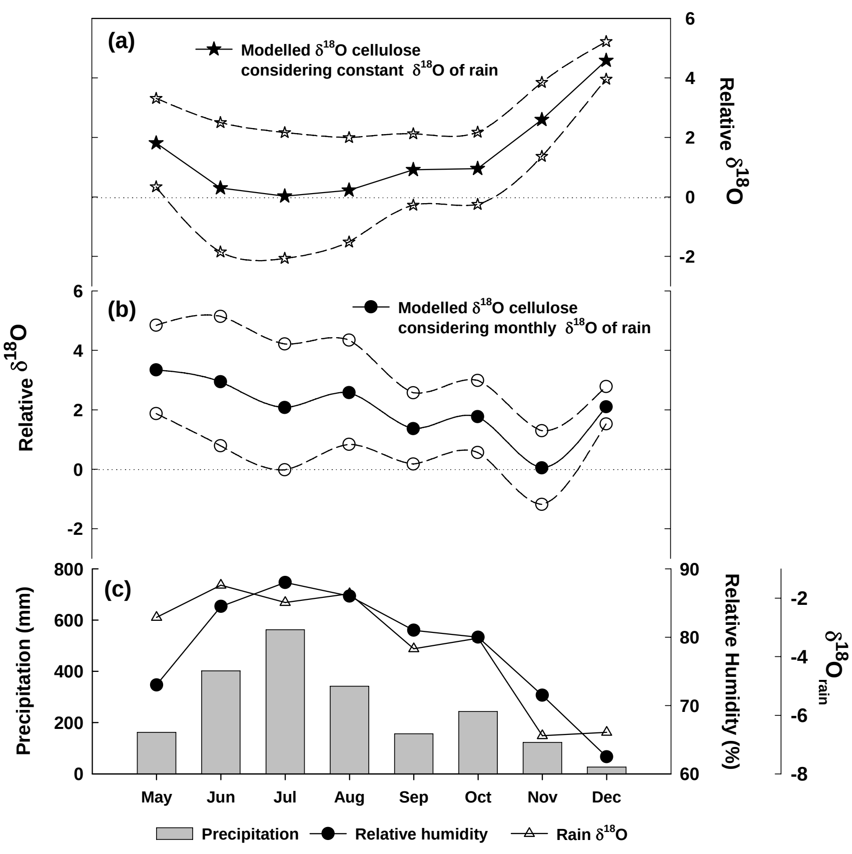

Fig. 3.6. Modeled climatological cellulose $\delta^{18}O$ profile considering constant $\delta^{18}O$ of rainwater (a); and varying $\delta^{18}O$ of rainwater (b). The dashed lines show one-sigma uncertainty. (c) shows precipitation (grey bars), relative humidity (filled circles) and rain water $\delta^{18}O$ from GNIP data (triangles and right offset axis).

The lower $\delta^{18}O$ values associated with the early growing season (**Fig. 3.4a,** values at the pith side) are also not consistent with the $\delta^{18}O$ profile presented in **Fig. 3.6a**. As growth during early season is associated with higher evapo-transpiration in the leaf due to lower relative humidity, the wood corresponding to this season (**Fig. 3.4a**) is expected to have relatively higher $\delta^{18}O$. The evaporation of rainwater in soil at the beginning of the wet season is expected to enrich the source (soil) water used by the plant in ^{18}O and thereby enhancing the overall ^{18}O enrichment. Therefore, the observed lower $\delta^{18}O$ (relative to model values) values of early wood are likely because of ^{18}O depleted pre-monsoon convective rain; they could also represent photosynthates carried from the end of the previous year to some extent. The possibility of transfer of carbohydrates from one year to the next year, especially in teak, is discussed in literature. Bhattacharyya et al., (2007) analyzed the same tree for vessel area associated with the early wood and showed a positive correlation ($r = 0.484$, $P<0.05$) between the mean vessel area of the early wood and the NE rain of the previous year. For teak trees, the possibility of use of previous year's photosynthates was also suggested by Jacoby and D'Arrigo (1999). The depleted nature of the early wood observed in the present study suggests likely transfer of photosynthates formed during the end of previous year. Considering the higher variability of $\delta^{18}O$ for samples at the beginning of the growing season, this contribution appears to vary significantly.

The observation that tropical trees can preserve isotopic signature of rainfall of different monsoon systems has a few important implications. Araguás- Araguás et al., (1998) have shown that a large part of the South-East Asia exhibit significant difference between weighted mean $\delta^{18}O$ values of summer (rainy period) and winter (mostly dry period) precipitation. These include locations where winter season contributes a considerable fraction of annual rain. In such locales, including Perambikulam, teak is likely to sample both the monsoons and hence care should be taken while interpreting their inter-annual isotopic variations. In the context of the Indian sub-continent, El-Nino years are known to be associated with below-normal

SW monsoon precipitation (Pant and Rupa Kumar, 1997) and above-normal NE monsoon rainfall (Suppiah, 1997; Kumar et al., 2007). As the $\delta^{18}O$ values associated with the end of the growing season are likely to be influenced by the NE rain, in years of normal/above-normal NE monsoon, the latewood of teak trees is likely to inherit a strong signal of the same. Thus it should be possible to use $\delta^{18}O$ of latewood cellulose to effectively track the El-Nino years, and thereby track temporal changes in monsoon-El-Nino relationships, for periods that precede the instrumental weather records.

3.8 Time resolution achievable by sub-annual sampling

The possible time resolution that can be achieved by doing sub-annual isotope analysis depends upon the sampling resolution and the extent of mixing of photosynthates sequentially produced before being finally laid in the ring. The processes and time lag between formation of photosynthates in a leaf and its incorporation into stem is not clearly understood. In addition, transfer of photosynthates from one growing season to the next can create serious problems in assigning time to different parts of the rings. Kangawa et al., (2005) based on carbon isotope analysis ($\delta^{13}C$) for *Cryptomeria japonica* tree suggested a time resolution of 8.7-28 and 33-42 days for the earlywood and latewood, respectively. Another way of addressing this issue is by comparison of the observed and modeled sub-annual $\delta^{18}O$ profile. Visual similarity of the observed sub-annual $\delta^{18}O$ profile (**Fig.3.5a**) and modeled profile with 20 days of running mean (**Fig.3.5b**) crudely suggests the possibility of achieving about 20 days of resolution during the peak growing season (June-Sept). Whether sampling with resolution higher than the present case would lead to achieve resolution higher than 20 days needs to be further explored.

3.9 Conclusions

Coarse and fine resolution sub-seasonal $\delta^{18}O$ analysis of rings selected from teak trees from central and southern India in general shows a seasonal cycle in $\delta^{18}O$ values. The amplitude of such variations can vary from 1‰ to 7‰. This underscores the need to obtain truly representative samples of rings when a relationship is to be established between climate and tree ring $\delta^{18}O$ values on inter-annual scale.

The seasonality in sub-annual $\delta^{18}O$ values observed in the present study substantiates an approach, 'tropical isotope dendrochronology', established by Evans and Shrag (2004), wherein wood corresponding to one seasonal cycle of $\delta^{18}O$ is considered as a 'ring' and regular dating/counting methods are used to assign calendar years to tropical trees lacking visible growth rings. As our study shows teak growing in Indian region respond to changes in the relative humidity during growing season, tropical trees other than teak are also expected to show seasonal variations in $\delta^{18}O$ values. This can be exploited to establish chronometry and understanding past climate using the approach outlined by Evans and Schrag (2004).

A seasonal cycle in sub-annual $\delta^{18}O$ enables to divide a ring into parts containing photosynthates formed during the pre-, main- and post-monsoon seasons implying the possibility of reconstructing time averaged climatic parameters during respective seasons. Possibility of achieving about 20 day of time resolution by fine resolution sub-annual isotope studies was also realized in the present study.

Results from sub-annual $\delta^{18}O$ variations of samples from central India point out that relative humidity, rather than rainfall, governs the $\delta^{18}O$ profile and about 50% of wood is formed from the photosynthates formed during relatively lower humidity conditions. It can be implied from the results that the growth taking place in post-monsoon seasons as a result of rain spells during the late growing season may result in higher whole-ring cellulose $\delta^{18}O$ value.

Sub-annual $\delta^{18}O$ analysis of 17 arbitrarily selected teak rings from southern India also show a systematic $\delta^{18}O$ variation with a pattern opposite to the one reported for teak trees from central India. These and the model-calculated values from local meteorological data appear to suggest that $\delta^{18}O$ values associated with the main and end of the growing season are respectively relatable to the $\delta^{18}O$ of SW and NE monsoon rains. Thus although the relative strengths of both the monsoons could be reconstructed by high-resolution sub-annual isotope analysis of teak from this bimonsoon climatic regime, care should be taken while interpreting inter-annual $\delta^{18}O$ variations: the varying amounts of isotopically different rains are also likely to affect the whole ring cellulose $\delta^{18}O$.

Chapter 4 Inter-annual $\delta^{18}O$ record in teak

This chapter deals with the inter-annual variations in ring-widths and cellulose $\delta^{18}O$, and their climatic significance. First, the results of ring-width and cellulose $\delta^{18}O$ variations are presented. The latter discussion includes (i) finding the common signal in ring-width and $\delta^{18}O$ among trees from the same site (ii) finding the relationship between cellulose $\delta^{18}O$ and the instrumental rainfall record and (iii) reconstructing the past rainfall history using the isotope record. As the chronologies of AP1 and AP2 are being checked with the other teak chronologies of the same region, results regarding their common signal and their relationship with rainfall are not discussed. The purpose of analyzing THN, which covers only a limited time span, is to get an idea about how ring-widths and $\delta^{18}O$ of trees growing in western India are correlated with rainfall on an inter-annual scale. The samples from the same region viz. Jag03 and Jag04 – distance between them was about 25 km – were analyzed for common signal in ring-widths and cellulose $\delta^{18}O$. Correlation between rainfall and $\delta^{18}O$ was calculated for samples THN, Jag03 and PKLM.

4.1 Results

Statistics of the ring-width and cellulose $\delta^{18}O$ variations of all the samples are given in **Table.4.1**. Statistics shown in **Table.4.1** contains mean (± standard deviation), mean sensitivity and lag-1 autocorrelation. A hand held lens fitted with a scale was used for ring-width measurements. **Fig.4.1** depicts time series of ring-width variations of all the samples. **Fig. 4.2** to **4.4** illustrate ring-width and ring-width index record of all the samples but THN. Ring-width indices were calculated from ring-widths by fitting a growth curve to them and dividing each ring-width value by a corresponding value of the growth curve. Various types of growth curves were fitted to get ring-width indices: for samples Jag03, Jag04 and AP2, an 8th-order polynomial curve was fitted; for samples AP1 and PKLM 7th-order polynomial and negative exponential curve were used, respectively. As the time span covered by THN is limited and no growth curve seemed appropriate for it, the actual ring-width values rather than ring-width indices were considered for various purposes. **Fig.4.5,**

4.6, 4.7, 4.8 and 4.9 respectively show yearly variations in cellulose $\delta^{18}O$ of THN, Jag03 and Jag04, AP1, AP2 and PKLM.

	Statistics	THN	Jag03	Jag04	AP1	AP2	PKLM
WIDTH	**Mean (std. dev., 1-sigma)**						
	Ring-width (mm)	3.08 (1.10)	2.75 (2.24)	3.08 (1.92)	2.43 (2.39)	1.38 (0.83)	1.91 (1.39)
	Ring-width index		1.02 (0.71)	0.95 (0.51)	1.01 (0.59)	1.00 (0.45)	1.00 (0.50)
	Mean sensitivity						
	Ring-width	0.30	0.51	0.42	0.44	0.40	0.38
	Ring-width index		0.51	0.42	0.43	0.41	0.39
	Lag-1 autocorrelation (R^2)						
	Ring-width	0.14^{*}	0.47^{***}	0.22^{***}	0.63^{***}	0.36^{***}	0.61^{***}
	Ring-width index		0.20^{***}	0.04^{*}	0.23^{***}	0.07^{***}	0.20^{***}
Cellulose $\delta^{18}O$	**Mean (± std. dev., 1-sigma)**	29.0 (1.8)	27.3 (1.1)	27.6 (1.3)	26.9 (1.3)	27.8 (1.2)	28.5 (1.0)
	Mean sensitivity	0.05	0.05	0.05	0.06	0.04	0.03
	Lag-1 autocorrelation (R^2)	0.29^{***}	0.00	0.03^{**}	0.00	0.10^{***}	0.08^{***}

Table.4.1. Statistics of ring-width, ring-width index and cellulose $\delta^{18}O$ variations of trees selected in the present study.

* $P< 0.01$,

** $P< 0.05$,

*** $P< 0.0005$.

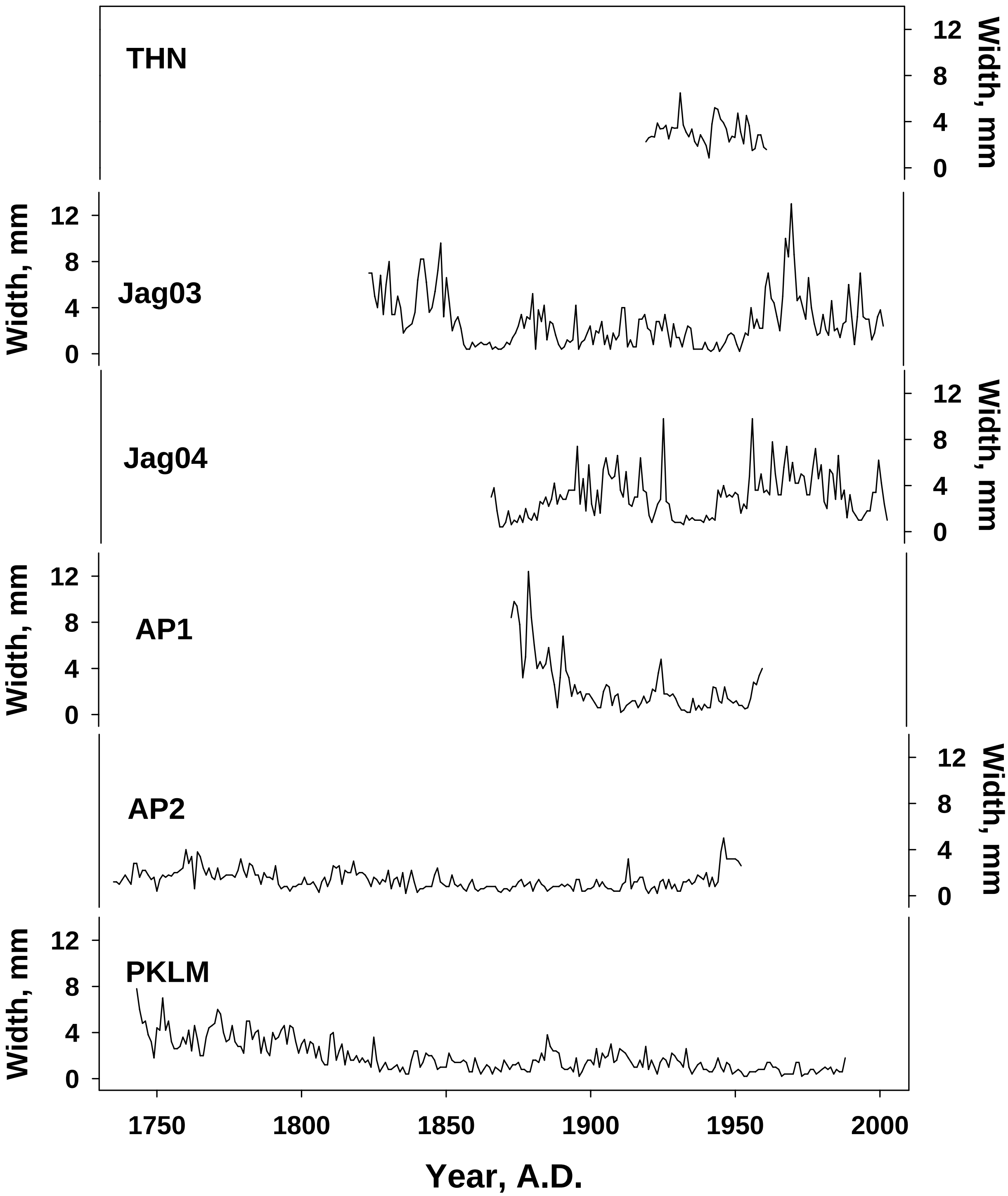

Fig.4.1. Time series of ring-width variations of all the samples.

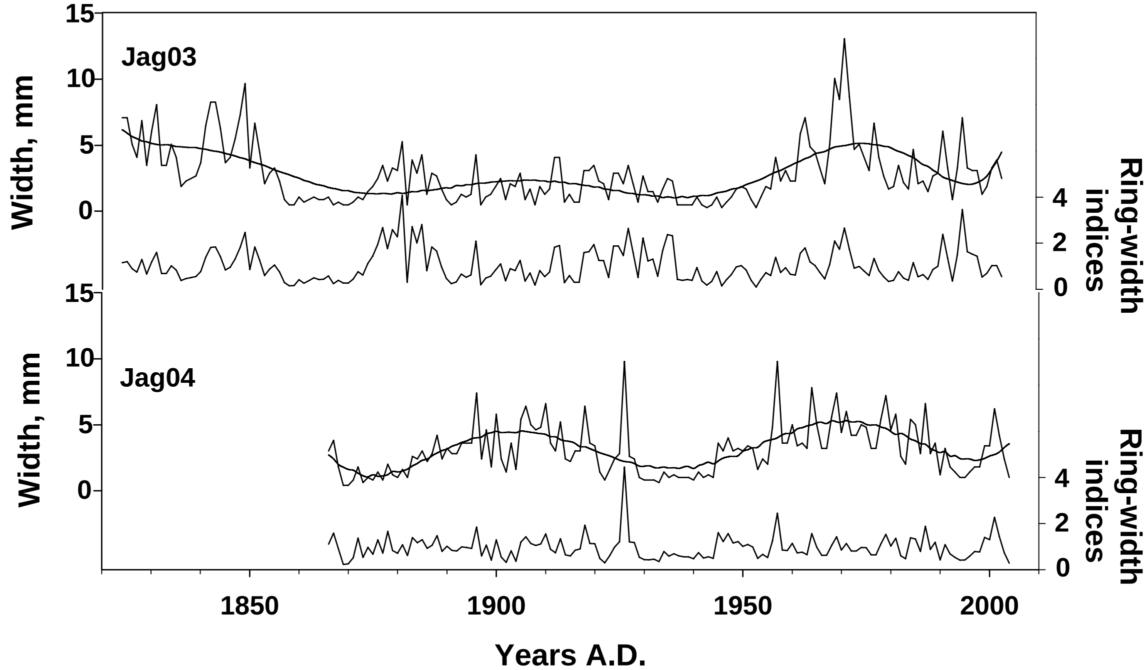

Fig.4.2. Time series of ring-widths and ring-width indices of Jag03 and Jag04.

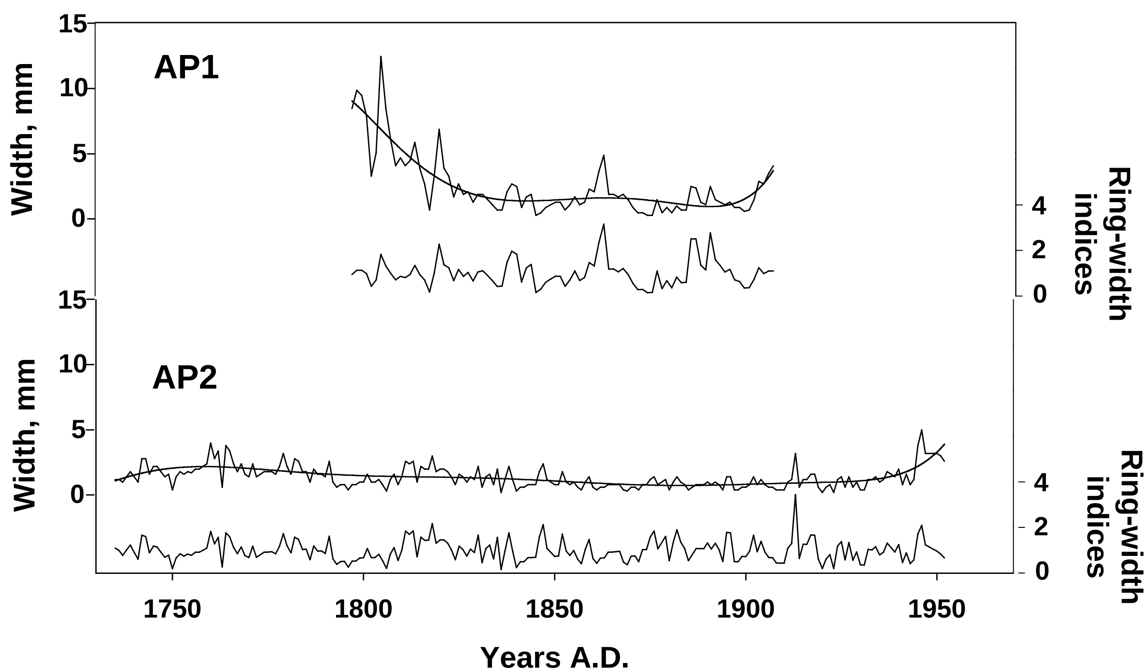

Fig.4.3. Time series of ring-widths and ring-width indices of AP1 and AP2.

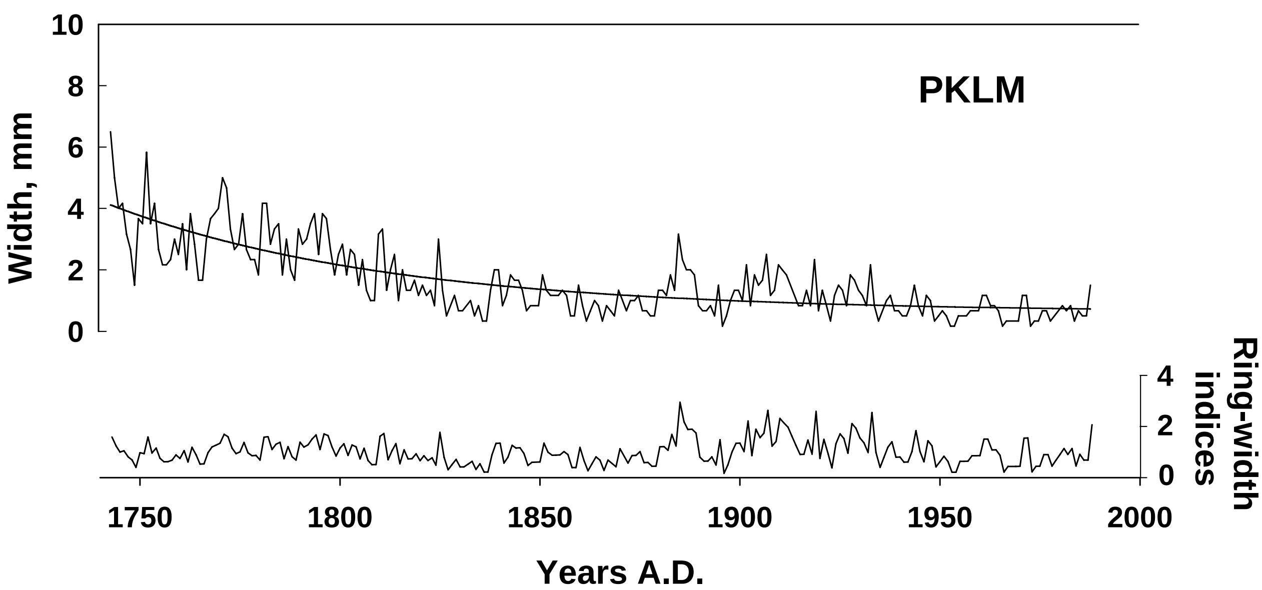

Fig.4.4. Time series of ring-widths and ring-width indices of the sample from Kerala, PKLM.

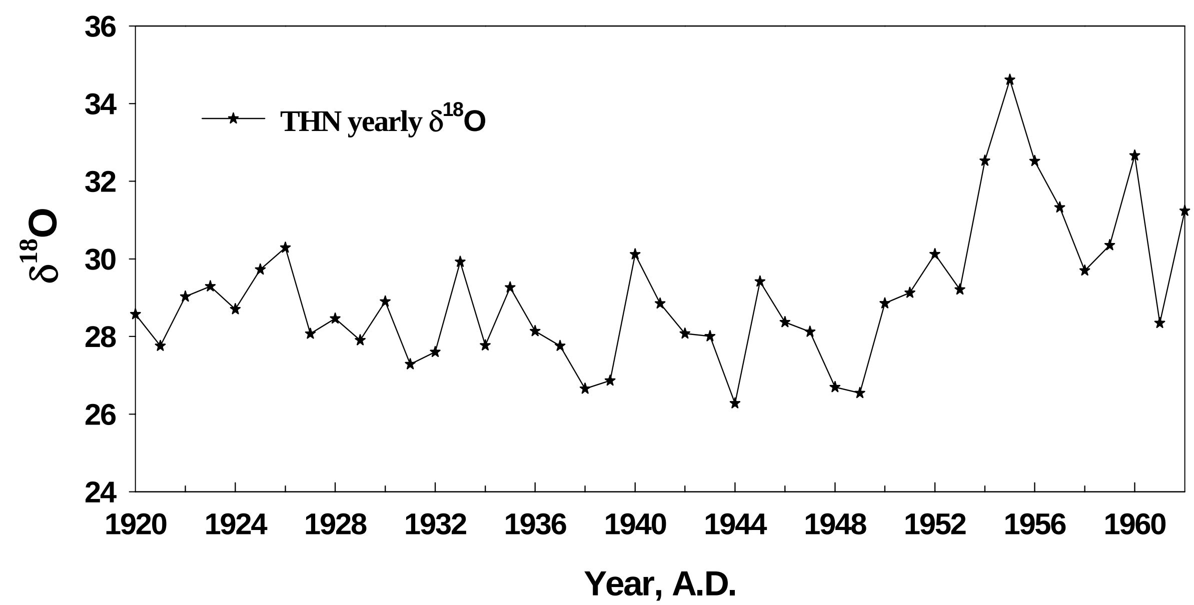

Fig.4.5. Time series of cellulose $\delta^{18}O$ variations of the sample from Thane, THN.

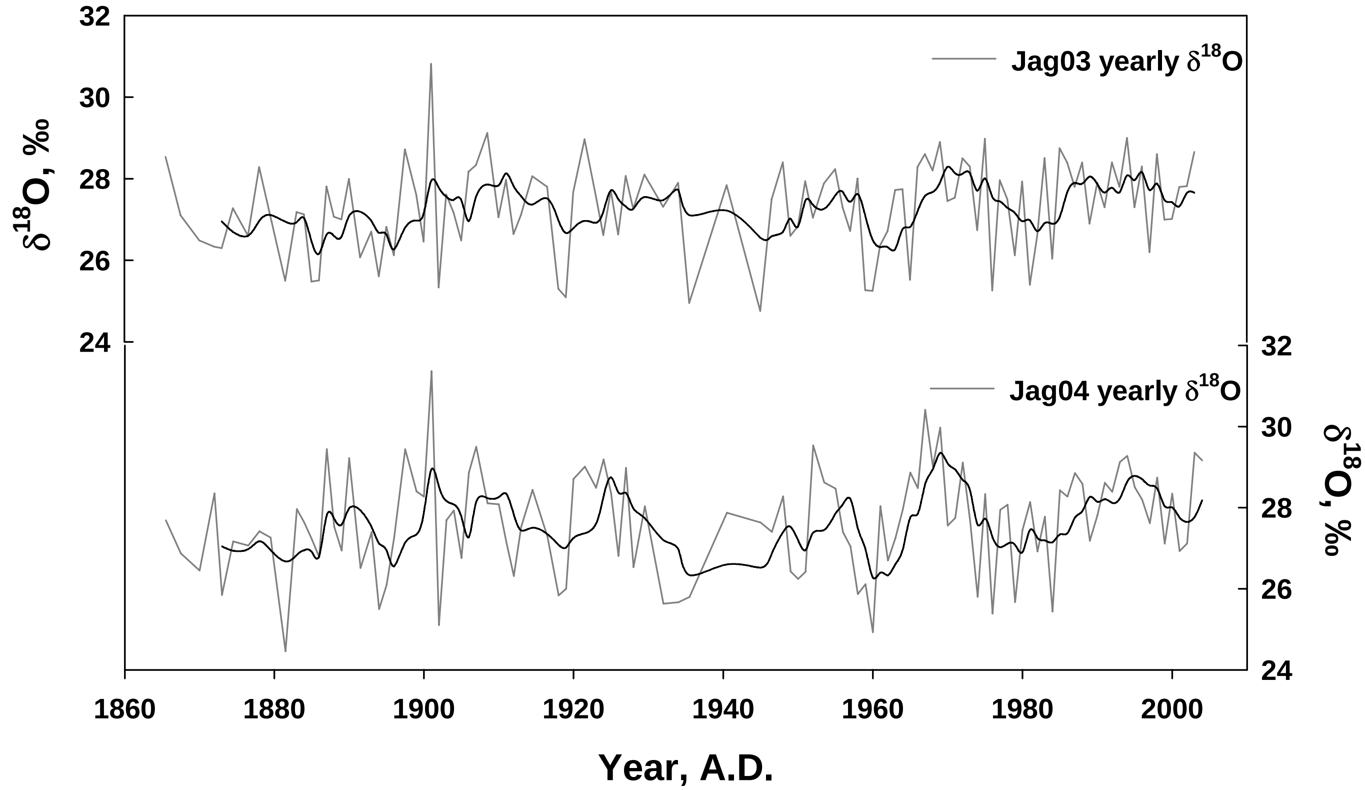

Fig.4.6. Time series of cellulose δ^{18}O variations of the samples from Jagdalpur, Jag03 and Jag04.

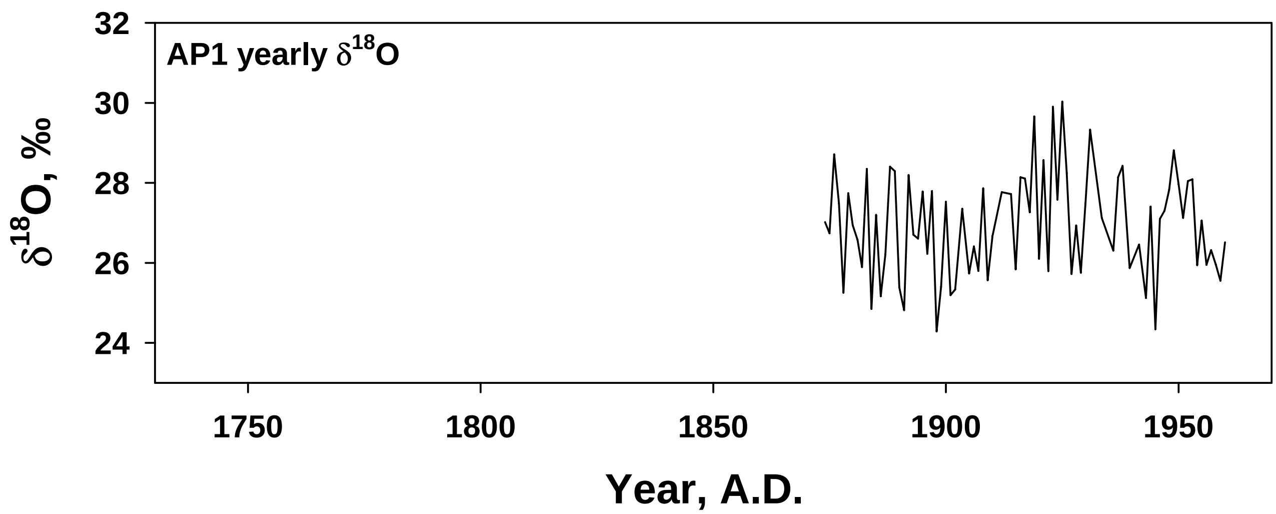

Fig.4.7. Time series of cellulose δ^{18}O variations of sample AP1, from Andhra Pradesh.

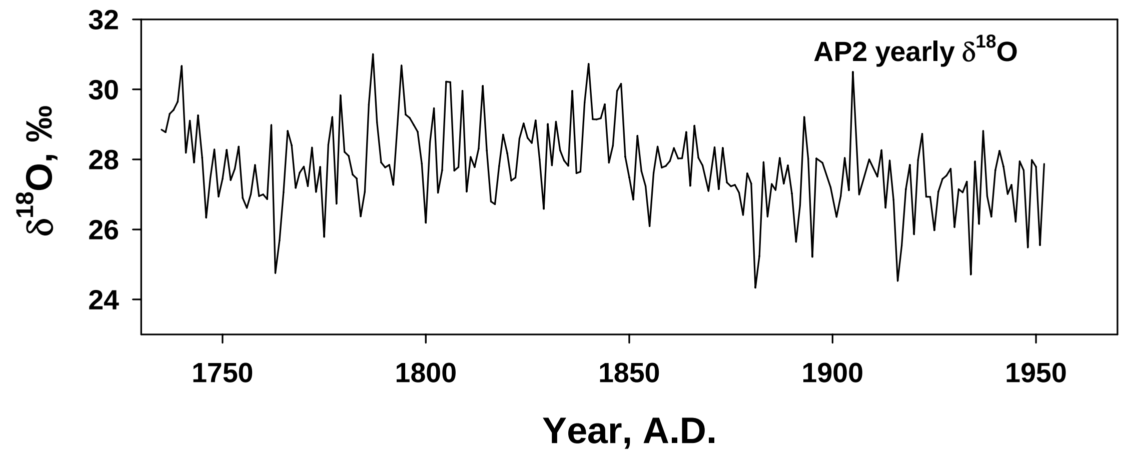

Fig.4.8. Time series of cellulose δ^{18}O variations of sample AP2, from Andhra Pradesh.

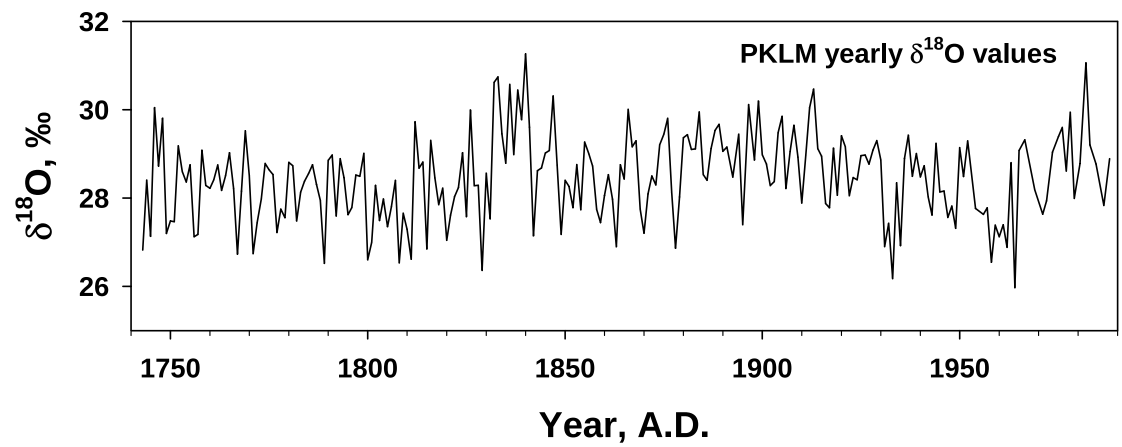

Fig.4.9. Time series of cellulose δ^{18}O variations of the sample from Kerala, PKLM.

4.2 Discussion

The present discussion starts with a general description of ring-width and cellulose δ^{18}O variations observed in the samples. A subsequent section deals with finding similarity in ring-width as well as cellulose δ^{18}O series of Jag03 and Jag04, among the samples located in the same region and likely to contain common climate signal in them. This is followed by a discussion regarding inter-correlation between the ring-width/ring-index and cellulose $\delta^{18}O$ record. Further, ring-width and cellulose $\delta^{18}O$ records are compared with available instrumental record of rainfall of the corresponding sites to decipher their inter-relationship. At the end, past rainfall is reconstructed using the relationship thus established.

The ring-width and cellulose $\delta^{18}O$ of rings for all the samples were measured along a single radial direction. In all the samples, THN, Jag03 and Jag04 show higher mean ring-width values (**Fig 4.1**). AP2 has the lowest mean and standard deviations of ring-width. AP1 and PKLM exhibit larger ring-width values in the early stages of growth; the latter shows more consistent decrease in ring-width values with age than the former (**Fig.4.1, 4.3** and **4.4**). Both Jag03 and Jag04 exhibit a low frequency variation in ring-width values with a wave period of about 70 years. They show somewhat higher ring-width values around 1900 A.D. and 1970 A.D. and lower ring-width values around 1940 A.D. (**Fig.4.2**).

For trees from higher altitude/latitude regions, a simple exponential curve is often sufficient to represent their growth trend. For deciduous species in a dense forest, factors such as stand disturbance and changing forest environment result in complicated growth trends which cannot be removed by a simple exponential curve (Fritz, 1976). Except for PKLM, other trees require higher order polynomials to approximate the growth trend; a simple exponential curve represents the growth trend for PKLM (**Fig.4.4**). For samples Jag03, Jag04 and AP2, an 8^{th}-order polynomial curve was fitted; for sample AP1 7^{th}-order polynomial curve was used (**Fig.4.2, 4.3**). The ring-width indices thus obtained have a mean ~1. The standard deviation of ring-indices observed in the present study is higher than that reported by Somaru Ram et al., (2008) for teak trees from central India.

The mean cellulose $\delta^{18}O$ for trees varies with location: trees from central India (Jag03, 27.3 ‰; Jag04, 27.6 ‰; AP1, 26.9 ‰; and AP2, 27.8 ‰) show lower $\delta^{18}O$ values than the trees from southern (PKLM, 28.5 ‰) and western India (THN, 29.0

‰). This is consistent with $\delta^{18}O$ of rainfall observed over the region. GNIP data set gives the mean weighted-$\delta^{18}O$ value of -1 ‰, -2 ‰ and -4 ‰ for the stations in western, southern and central India, respectively. The samples show similar standard deviations in $\delta^{18}O$.

Mean sensitivity is the mean difference between each measured yearly value (ring-width, ring-width index, cellulose $\delta^{18}O$) of one ring and the next; the values range from 0 where the values are the same to 2 where a zero value exists next to a non-zero value in the time series. For climate reconstruction higher mean sensitivity is useful. Mean sensitivities of ring-width and ring-width index are similar for the present samples and both are higher than that reported by Somaru Ram et al., (2008) for teak trees from central India. All samples show similar mean sensitivity in $\delta^{18}O$.

Lag-1 autocorrelation represents a relationship between each value in a time series and the value immediately preceding it. This relation exists due to persistence, trend, cycles or other non-random components produced by climate and factors that control tree growth (Fritz, 1976). The effect of preceding year's ring to the next can potentially interfere with causal relationship between the ring-width/cellulose $\delta^{18}O$ and climate. Photosynthates carried over from one year to the next in teak (Jacoby and D'Arrigo, 1990) might be the reason for lag-1 autocorrelation in ring-width as well as their $\delta^{18}O$ values. Soil moisture carried over from one year to the next is also likely to introduce lag-1 autocorrelation (Borgaonkar et al., 2007) in ring-width series. Lag-1 autocorrelation observed in the present study (**Table 4.1**) varies for ring-width (ring-index) from 0.14 (0.04) to 0.63 (0.23). For a given tree, less auto-correlation is observed in ring-width indices than in ring-widths. The procedure used to remove growth trend reduces the lag-1 autocorrelation to some extent. The samples (AP1 and PKLM) showing gradual decrease in ring-width with age show higher amount of lag-1 autocorrelation. Somaru Ram et al., (2008) have reported lag-1 autocorrelation varying from 0.45 to 0.58 for central Indian teak chronologies built without autoregressive modeling. In case of $\delta^{18}O$ variation, except for sample THN, there is a very weak ($R^2 = 0.08$, $P<0.0005$) to no lag-1 autocorrelation.

4.2.1 Coherence of tree ring (ring-width, ring-width index and cellulose $\delta^{18}O$) record

Ring-width and $\delta^{18}O$ variations in trees are affected by climatic as well as non-climatic factors. The latter includes site specific conditions such as soil type, crown position of a tree, competition among trees, insect/pest attack, and phenotypic variations among trees. To fully exploit trees from a given region for reconstruction of past climate, it is desirable to have minimal effect of non-climatic factors. In this context, it is important to discern common signal in trees from the same region as it is less likely to be affected by site specific non-climatic factors. In the most cases, deciphered common signal indicates the common forcing factor over the region, which is likely to be climate.

	Statistics	
Width related	**Correlation (R) between Jag03 and Jag04**	
	Ring-width	
	Yearly	0.36^{***}
	5-yr moving average	0.45^{***}
	Ring-width index	
	Yearly	0.14^{**}
	5-yr moving average	0.08
	Common signal (between Jag03 and Jag04)	
	Ring-width	
	Yearly	36 %
	5-yr moving average	44 %
	Ring-width index	
	Yearly	13 %
	5-yr moving average	6 %
$\delta^{18}O$ related	**Correlation (R) between Jag03 and Jag04**	
	Yearly	0.66^{***}
	5-yr moving average	0.77^{***}
	Common signal (between Jag03 and Jag04)	
	Yearly	66 %
	5-yr moving average	73 %

Table.4.2. Common signal in ring-widths, ring-width indices and cellulose $\delta^{18}O$ between Jag03 and Jag04.

** $P< 0.05$, *** $P< 0.0005$.

The common signal is calculated by finding mean correlation coefficients of all possible pair wise combinations of ring-width/ring-index/cellulose $\delta^{18}O$ time series of trees from a region. The other way of calculating common signal is by the procedure outlined by Fritz (1976). This involves finding variance components attributed by different cores from the trees, different trees, different age groups, etc. This technique is useful in deciphering relative importance of sources of variations in ring-indices.

Borgaonkar et al., (2007), Shah et al., (2007) and Somaru Ram et al., (2008) have reported common signal in ring-index chronologies from network of teak trees from central India. The common signal in their work is the mean correlation coefficient between ring-index chronologies constructed by measuring ring-width variations along different radial directions within the discs of the same tree and discs of different trees of the region covering common interval of time. Shah et al., (2007) have given mean correlation among all trees 0.228, between trees 0.206, and within trees 0.661. Borgaonkar et al., (2007) mentioned mean correlation of 0.30, 0.35 (central India) and 0.39 (southern India) for teak chronologies. The common variance reported by Somaru Ram et al., (2008) is 0.31.

Ramesh et al., (1985, 1989) have calculated common variance of isotope record in various trees. In Kashmir valley Ramesh et al., (1985) have reported a common variance, interpreted as a common signal, among the different radii of *Abies pindrow* of ~95% for δD and $\delta^{18}O$ and ~89% for $\delta^{13}C$. For Abies trees which grew ~10 m apart, the authors (ibid.) found a common signal of ~92% for δD and ~83% for $\delta^{13}C$. The same work reports a common signal of ~79% for δD and ~84% for $\delta^{13}C$ among two *Abies pindrow*, one *Cedrus deodara* and one *Pinus wallichiana* trees growing within a distance of ~50m. For teak trees from western India, Ramesh et al., (1989) found a correlation coefficient of ~0.73 for δD record from different radial directions within one tree and a common signal of 60% between two trees separated by a distance of ~10 km. Poussart et al., (2004) have found a correlation up to 0.69 ($P<0.0001$) in $\delta^{18}O$ record of two teak trees from Indonesia.

To understand the common signal in ring-width and $\delta^{18}O$ between teak trees from the same region, two trees from central India *viz.* Jag03 and Jag04 were considered. The distance between the two trees was about 25 km. Observed correlation and common signal (calculated by method outlined by Fritz, 1976) of ring-widths, ring-indices and $\delta^{18}O$ record is depicted in **Table. 4.2**. It can be seen from the table that the correlation between Jag03 and Jag04 is higher in ring-widths than ring-width indices. Further, correlation for 5-yr moving averages of ring-widths is higher than yearly variations. The correlation of ring-width between Jag03 and Jag04 for moving averages of 10-yr and 20-yr are 0.53 ($P<0.0005$) and 0.70 ($P<0.0005$), respectively. This clearly indicates that the low frequency variations dominate the observed correlation. Like the correlation observed for ring-widths and ring-width indices, common signal in ring-widths and ring-width indices is higher for 5-yr moving averages than for yearly variations, again pointing to the contribution of low frequency variations to the common signal.

The common signal in ring-indices observed in the present study is lower than that reported for teak tree chronologies from central and southern India, discussed earlier in this section (Borgaonkar et al., 2007; Shah et al., 2007; Somaru Ram et al., 2008). This could possibly be a result of inadequate replication: the width measurements were done along a single radial direction and from only two trees. The teak chronologies mentioned earlier (ibid.) were constructed by averaging ring-width indices from numerous radial directions (~30) from number of trees (~15) and in the process likely to cancel/reduce the noise in ring-indices of individual radial directions and trees.

The observed yearly (5-yearly moving averages) correlations and common signals in $\delta^{18}O$ record of Jag03 and Jag04 are 0.66 (0.77) and 66% (73%), respectively. The correlations observed are significant at $P<0.0005$. These values are higher than those observed for the ring-width and ring-width index record. Further, the correlation and common signal obtained are more than that reported for various ring-indices based teak chronologies from central and southern India. The common signal reported by Ramesh et al., (1989) for δD record between two teak trees (60%) is also higher than the reported values based on ring-indices. Thus, it appears that the isotope record in teak is able to capture more common variance than the ring-width/ring-index record.

4.2.2 Correlation of ring-width with rainfall and cellulose $\delta^{18}O$ record

Growth of trees is primarily controlled by the most growth limiting factor; rainfall, in case of teak trees from India. Priya and Bhatt (1999) have demonstrated that the cambial activity of teak is influenced by rainfall. Hence, ring-width variations are expected to show a good correlation with rainfall amount. However, widths of all the samples analyzed in the present study do not show any significant relationship with the amount of rainfall. The lack of correlation could be attributed to different reasons.

Although rainfall is the most growth limiting factor for teak, the degree of its limiting effect may not be equal throughout the growing season. Correlation of teak ring-width indices with ambient monthly rainfall reported for various teak chronologies is site specific. Jacoby and D'Arrigo (1990), based on ring-width analysis of teak trees from Java, showed that the growth was insensitive to the amount of wet season rainfall, while Pumijumnong et al., (1995) showed the growth to be correlated with rainfall during the first half of the wet season. Buckley et al., (2007) reported variability of teak growth in western Thailand to be correlated with rainfall during the beginning and end of the monsoon season. Borgaonkar et al., (2007) and Somaru Ram et al., (2008), based on analysis of teak trees from central and southern India, demonstrated a significant correlation between ring-width and pre-monsoon and post-monsoon climate and suggested role of a moisture index rather than total rainfall as a major factor controlling ring-width variations. This demonstrates that, depending on the locality, rainfall during some months is more important than the other. In this context, it is important to know whether trees are 'over-irrigated' i.e. rainfall is not a growth limiting factor during the periods of higher intensity rainfall. In the first case soils would be filled up to field capacity and excess water would move to the deeper soil layers while the latter implies more surface run off. This would partly explain low correlation between total rainfall and ring-width variations.

Length of the growing season is an important factor deciding ring widths. Cambial activity studies by Priya and Bhat (1999) have shown that the cambial activity begins after the first rains and early pre-monsoon showers can pre-date the beginning of the growing season. Teak canopy studies by Yoshifuji et al., (2006) have demonstrated that protracted rainfall activity – result of the early and late rains at the beginning and the late growing season, respectively – can increase the length of growing season. This supports that timing of rain during pre- and post-monsoon season also affects ring-widths. Further, Priya and Bhat (1999) have also demonstrated that the length of the growing season also depends on the age the tree: juvenile/younger trees have a shorter dormancy period than mature older trees.

In addition to the climatic factors, tree growth, and hence ring-width, is also controlled by parameters such as soil quality, age of tree, competition between trees, gravity stress, crown position of tree. Attack by teak defoliator (*H. puera*) is also reported to reduce the growth of teak (Sudheendrakumar et al., 1993). Inadequate sampling could also be one of the important reasons as mentioned in the previous section.

Like the relationship between ring-width/ring-width index and rainfall, all the samples do not show any significant relationship between ring-width/ring-width index and cellulose $\delta^{18}O$ of teak. Factors that decide width of a ring have already been discussed earlier in this section. Factors influencing $\delta^{18}O$ of plants in general and teak from central India in particular have been described respectively in

Chapter 1 and **Chapter 2**. Relative humidity and $\delta^{18}O$ of rainfall are important in deciding $\delta^{18}O$ of teak from central and southern India. Correlation between the width of a ring and its $\delta^{18}O$ primarily depends on how both are individually correlated with the amount of rainfall. As the former is not correlated with the amount of rainfall, it is not surprising that there is no correlation between ring-width/ring-width index and cellulose $\delta^{18}O$ of teak rings.

4.2.3 Correlation between cellulose $\delta^{18}O$ and rainfall record

Yearly variation in $\delta^{18}O$ values of the teak samples (**Fig.4.5** to **4.9**) are mainly result of the variations in mean climatic as well as non-climatic conditions during the growing season of the concurrent years. One of the important factors governing $\delta^{18}O$ of trees is $\delta^{18}O$ of rainfall. As $\delta^{18}O$ of rainfall and its amount are inversely correlated in general with each other in tropical areas, the amount of rainfall also plays a role in deciding $\delta^{18}O$ of trees. The details regarding factors affecting $\delta^{18}O$ of trees are discussed in **Chapter 1**. One way to understand how rainfall amount controls teak $\delta^{18}O$ variations is to find the correlation between yearly teak $\delta^{18}O$ values and local rainfall in the corresponding years. A suitable regression then can be used to reconstruct past rainfall of the region.

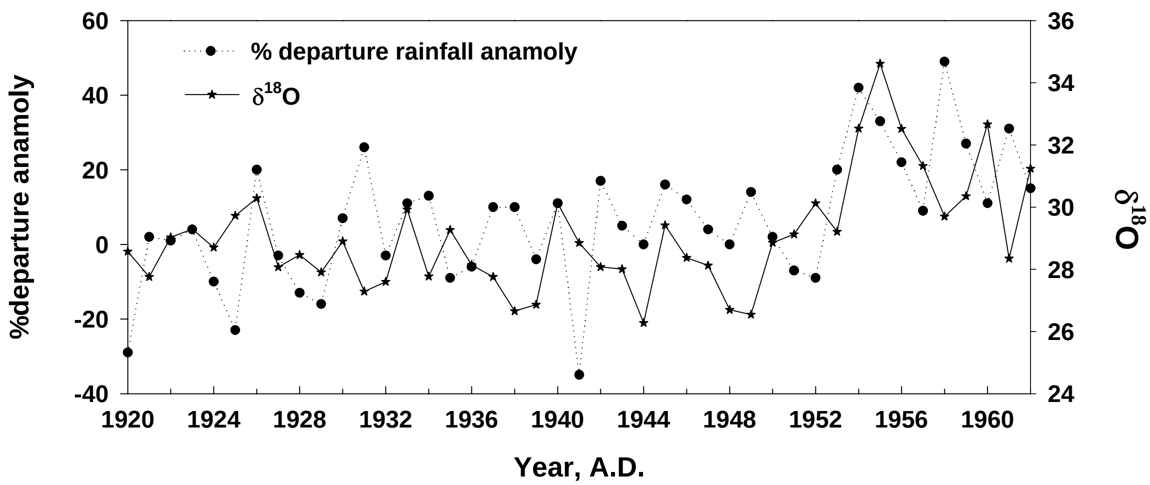

Fig.4.10. Comparison of percentage rainfall anomaly (dotted line) and cellulose $\delta^{18}O$ record (solid line) of sample THN.

In addition to finding the correlation between $\delta^{18}O$ and rainfall, the aim of the present exercise is also to understand how the $\delta^{18}O$ record of teak trees growing in different climatic settings of India responds to local rainfall on inter-annual scale. For this purpose, teak samples were collected from various parts of India. The details regarding sample locations and local climate are given in **Chapter 2**. The observed $\delta^{18}O$ record is compared with local rainfall record and a correlation is found.

Comparison of $\delta^{18}O$ record and rainfall record for THN is shown in **Fig.4.10**; the rainfall record is from Mumbai. The comparison revealed a positive correlation with correlation coefficient (r) of 0.37, significant at 0.01 level. Interestingly, GNIP data for Mumbai shows no significant correlation between monthly $\delta^{18}O$ of rainfall and its amount. The observed positive correlation suggests that trees from regions with no amount effect in rainfall could be used for reconstruction of past rainfall. Ramesh et al., (1989) studied the same sample for δD variations and found it to be positively correlated with the amount of rainfall and maximum temperature during November to February. In the case of $\delta^{18}O$ variation, addition of a temperature term in the regression equation doesn't improve the correlation significantly.

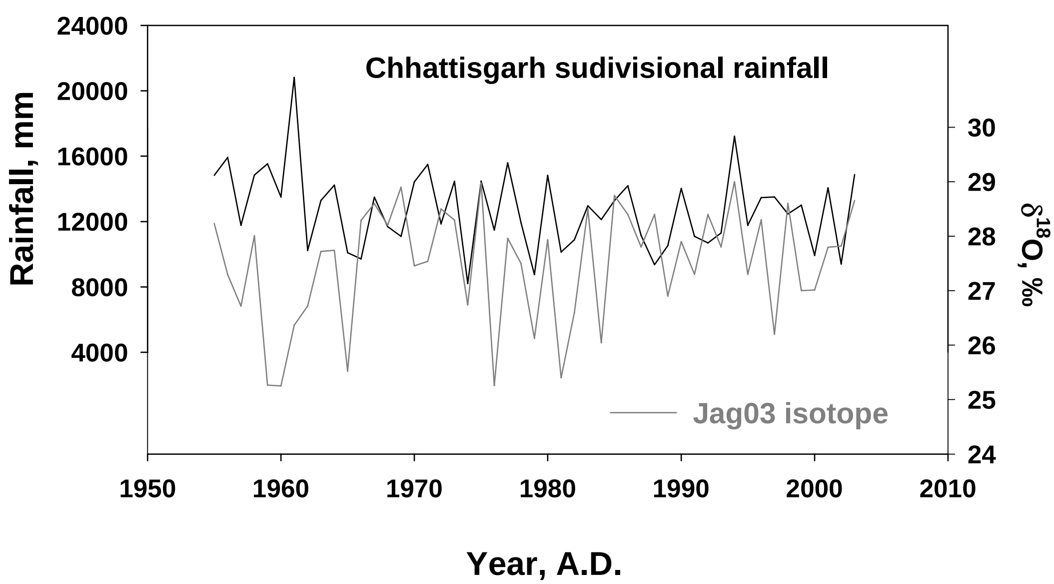

Fig.4.11. Comparison of cellulose $\delta^{18}O$ record of Jag03 (gray lines) and Chattisgarh sub-divisional rainfall (solid line). See text for explanation of sub-divisional rainfall.

Fig.4.11 depicts comparison of the $\delta^{18}O$ record of Jag03 and Chattisgarh sub-divisional rainfall. The rainfall record for Chattisgarh sub-division was obtained from data provided on Indian Institute of Tropical Meteorology (IITM) web page (http://www.tropmet.res.in/static_page.php?page_id=53). In each meteorological sub-division there are different rain-gauge stations. The sub-divisional rainfall series is an area weighted rainfall series for the sub-division and has been prepared by assigning the district area as the weight for each rain-gauge station in that sub-division. Comparison of sub-divisional rainfall and $\delta^{18}O$ variation shows a general positive correlation. The correlation is 0.44 ($P<0.005$) for a duration from 1962 to 2003 and 0.52 ($P<0.005$) for 1973 to 2003.

Comparison of yearly rainfall of Palakkad rain-gauge station and teak $\delta^{18}O$ record of the sample from southern India, PKLM, is shown in **Fig. 4.12**. Contrary to the teak trees from western (THN) and central India (Jag03), PKLM shows a negative correlation with the amount of rainfall. The observed correlation is -0.47, significant at 0.005 level. Similarly, on a longer time scale, rainfall of Kerala sub-division and PKLM $\delta^{18}O$ record shows a negative relationship (**Fig.4.13**) with a correlation of -0.32 ($P<0.0005$). The way sub-divisional rainfall is calculated is described in the earlier paragraph.

The observed positive correlation between rainfall and teak $\delta^{18}O$ record for teak trees from western and central India is contrary to what would be expected. Higher rainfall is expected to lower rainfall $\delta^{18}O$ values through the amount effect. Trees, as a consequence, are expected to show lower $\delta^{18}O$ values as they ingest rainwater depleted in ^{18}O through roots. Further, even though there is no/weak relationship between the amount of rainfall and its $\delta^{18}O$, higher rainfall is generally associated with higher relative humidity. This would lead to less evaporative enrichment of the leaf water during the growing season. Since $\delta^{18}O$ of trees is related with $\delta^{18}O$ of the leaf water, higher relative humidity conditions would also result in lower tree $\delta^{18}O$.

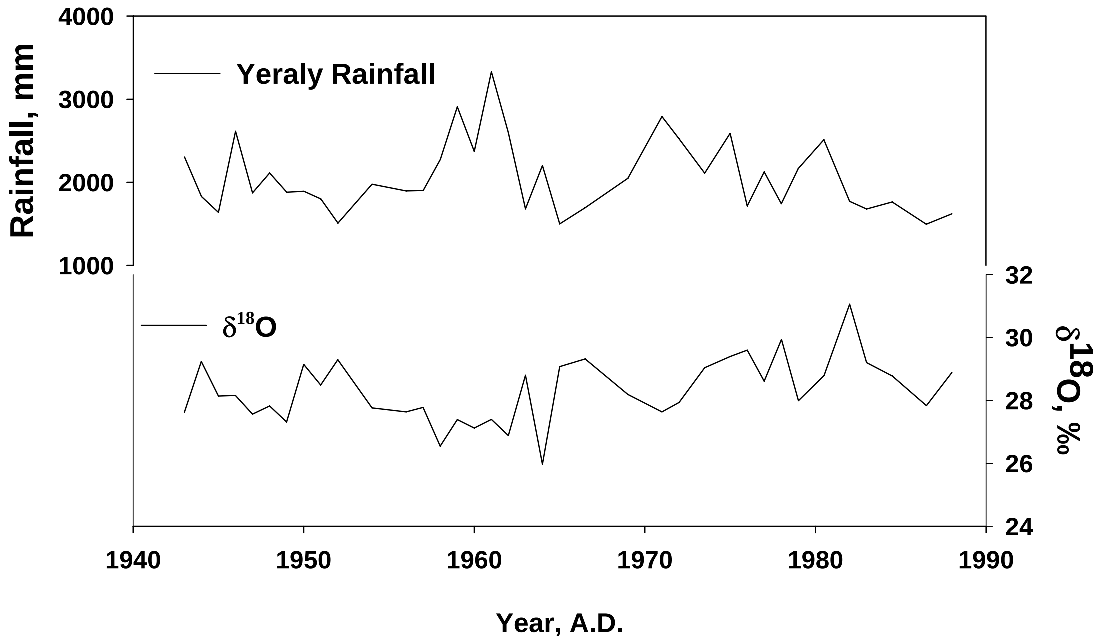

Fig.4.12. Yearly rainfall of Palakkad (upper panel) and cellulose $\delta^{18}O$ record of sample from southern India, PKLM (lower panel).

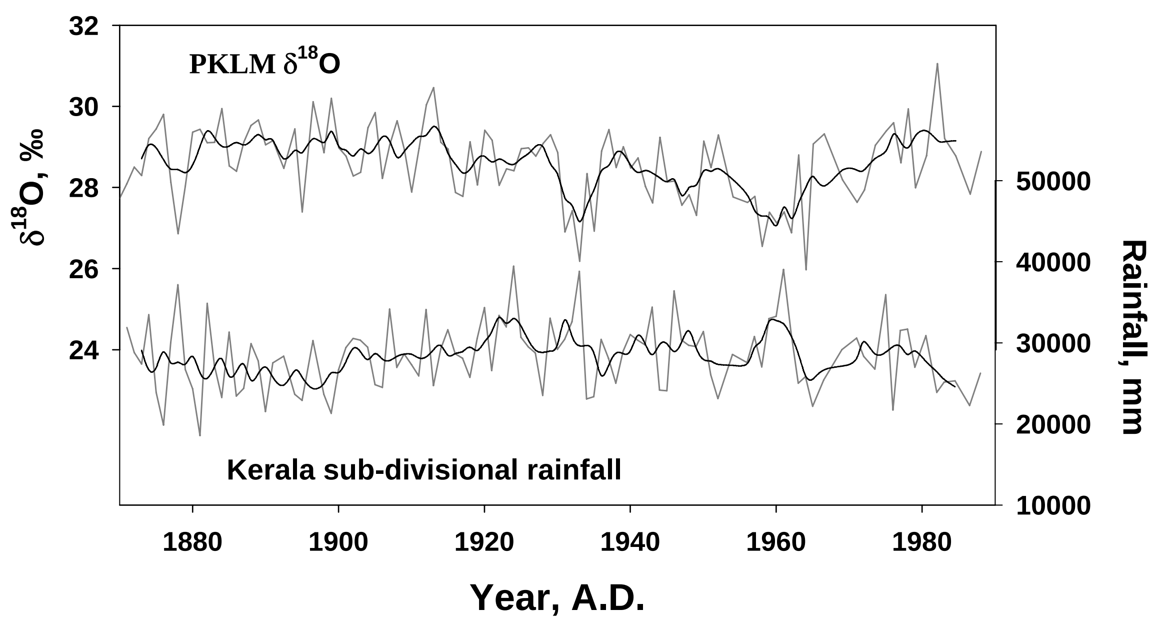

Fig.4.13. Comparison between PKLM cellulose $\delta^{18}O$ record and Kerala sub-divisional rainfall. See text for explanation regarding sub-divisional rainfall.

The observed positive relationship could be explained only if higher rainfall results in increasing the length of the growing season. Teak is a deciduous species and its length of the growing season depends critically on soil moisture availability (Yoshifuji et al., 2006). Relative humidity during the growing season controls the extent of the leaf water enrichment in ^{18}O; higher (lower) humidity results in lower (higher) $\delta^{18}O$ values of the leaf water and trees (see **Chapter 3** for details). During the years of lower rainfall, soil moisture gets quickly exhausted and teak growth is restricted to a period of relatively higher humidity (>70%). As a consequence, teak gets lower $\delta^{18}O$ value. When the total rainfall is more, as a result of higher rainfall during the peak growing season (July-September) and/or rain during the end of the growing season (October-December), tree continues to grow until a period of lower relative humidity (~65%) leading to higher teak $\delta^{18}O$. This study corroborates the explanation given by Ramesh et al., (1989) for positive correlation between δD and rainfall for THN.

The discussion entails to the possibility of using trees growing in the regions with no relationship between $\delta^{18}O$ of rainfall and its amount, i.e. amount effect, for reconstruction of the past rainfall. Soil water isotopic composition is usually much less variable than that of the rain water implying mixing of various precipitation events (Tang and Feng, 2001). Therefore, even if there is a weak amount effect in rainfall, trees in the region with seasonality in relative humidity are likely to show positive correlation between cellulose $\delta^{18}O$ and local rainfall. The result suggests the length of the growing season could be important in deciding $\delta^{18}O$ of trees.

The plausible reasons for the negative correlation observed between cellulose $\delta^{18}O$ of PKLM and the amount of rainfall (**Fig.4.12, 4.13**) could be the presence of relatively strong amount effect in rainfall of the region, higher rainfall during the north-east (NE) monsoon, one depleted in ^{18}O, and relatively lesser effect of lower relative humidity conditions in deciding tree $\delta^{18}O$. So far no adequate characterization of the amount effect in rains of different regions of India has been done. GNIP data of the rainwater $\delta^{18}O$ for the region is too short to compare the strength of amount effect in rainfall at central and southern India. However, some insight can be gleaned regarding the observed negative relationship between $\delta^{18}O$ of PKLM and rainfall amount from climate of central and southern India. The average relative humidity during the growing season (May-Dec) is 78% at PKLM (Palakkad rain-gauge station) in contrast to 70% at Jag03 (Jagdalpur rain-gauge station). Similarly, relative humidity during the late growing season (Oct-Dec) is 72% at PKLM and 67% at Jag03. This implies that mean evaporative enrichment of the leaf water (and hence $\delta^{18}O$ of trees) would be less for PKLM than for Jag03. In addition to this, PKLM receives significant amount of the NE monsoon rainfall during the late growing season as compared to THN and Jag03. The NE monsoon, being depleted in ^{18}O, is expected to produce photosynthates with lower $\delta^{18}O$ during the late growing season. A detailed discussion regarding sub-annual variation in cellulose $\delta^{18}O$ of teak from central and southern India is given in **Chapter 3**. In summary, it appears at this stage that teak from southern India contain relatively less proportion of photosynthates synthesized from the leaf water enriched by lower ambient relative humidity than teak from central India.

4.2.4 Reconstruction of past climate using cellulose $\delta^{18}O$ record

One of the aims of the present study is to reconstruct past rainfall using $\delta^{18}O$ record to teak cellulose. Such a reconstruction involves finding a relationship between the observed variation in tree cellulose $\delta^{18}O$ and the instrumental rainfall record of the corresponding period from the same site. The relationship is then used to reconstruct rainfall for the period for which no instrumental records exist. Out of all the samples analyzed in the present study, sample from southern India, PKLM, shows the highest correlation between cellulose $\delta^{18}O$ and rainfall. Hence, past rainfall was constructed only for PKLM i.e. for Perambikulam region of Kerala (**Fig.4.14**). The reconstruction, however, is also valid for the most of southern India as it is in good agreement with the instrumental rainfall series reconstructed for south peninsular

India (**Fig.4.14**) by Sontakke et al., (2008). For southern India the oldest rainfall record is available for Chennai from 1813, the number of stations increased to 9 by 1846 and by 1871 the number of station increased to 41 (Sontakke et al., 2008). So far the longest instrumental rainfall series for southern India goes back to 1813 A.D. The earliest record for Palakkad rain station, the one near the sample PKLM, is available from 1871 A.D.. The reconstructed rainfall in the present study goes back to 1743 A.D. and extends the existing record back in time by 70 and 128 years for southern India and Palakkad, respectively. The reconstructed rainfall period partly covers the Little Ice Age (~1350-1900 A.D.).

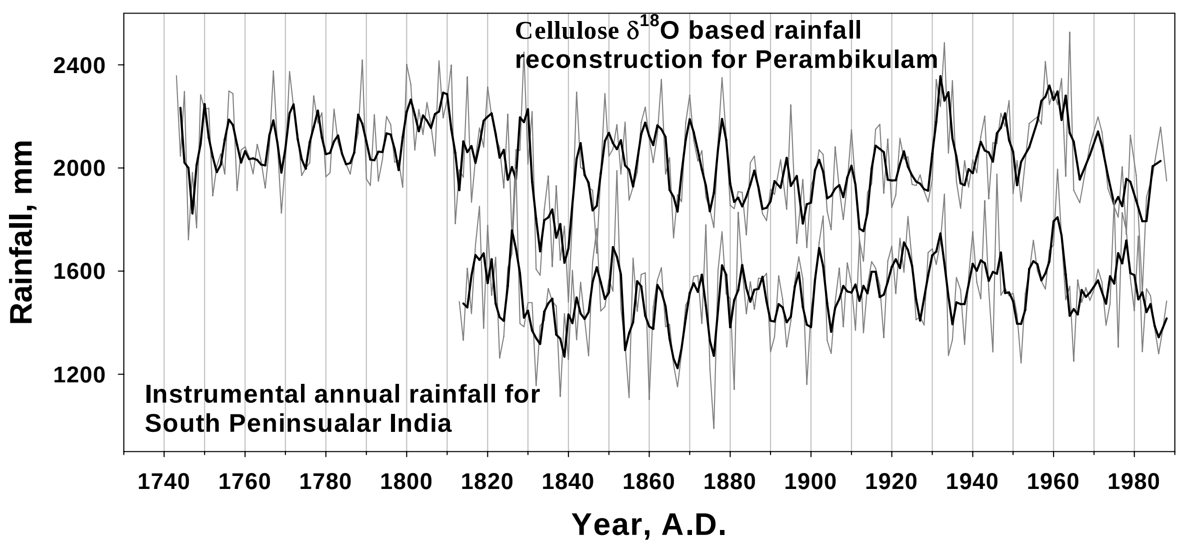

Fig.4.14. Reconstructed past rainfall for Perambikulam region using cellulose δ^{18}O record of PKLM (upper graph). Instrumental rainfall record for the south peninsular India from Sontakke et al., (2008) (lower graph). Gray and black lines are yearly and 3-yearly variations, respectively.

The conspicuous feature of the reconstructed rainfall record is higher rainfall during 1743-1830 A.D. as compared to the later period. Interestingly, the average ring-width index of teak chronology developed from Narangathara, Kerala (Borgaonkar et al., 2007) also exhibit higher ring-width indices during this period. Years with relatively low rainfall in reconstructed series are: 1746, 1748, 1769, 1812, 1832-1841, 1855, 1866, 1876, 1884, 1899, 1905, 1913, 1929, 1937, 1950, 1952, 1965, 1976 and 1982. Good rain spells prevailed during 1800-1811, 1832-1846, 1858-1863, 1935-1937, 1942-1949 and 1954-1964. Most of these years match with observed instrumental rainfall record (**Fig.4.14**).

Chapter 5 Summary and recommendations

5.1 Summary of results

Teak (*Tectona grandis* L.F.) is an important tropical tree species that has good potential in the reconstruction of past rainfall. Dendroclimatologists have built several teak chronologies using variations in the annual growth rings of teak that date back to several centuries. Compared to ring-width variations in teak, the isotopic variations in teak have not been fully exploited for past climate reconstruction even though their potential was realized as early as 1989 (Ramesh et al., 1989). In this context, the present study aims at understanding the relationship between oxygen isotopic composition ($\delta^{18}O$) of teak and climate on sub-annual and inter-annual time scales. Towards this, teak trees growing in different climatic settings of India were analyzed for cellulose $\delta^{18}O$ variations.

Sub-annual $\delta^{18}O$ analysis of several annual growth rings of three teak trees from central India revealed a seasonal cycle with higher values in the early and late growing seasons and lower values in the mid growing season, with amplitudes of 1.9 to 5.0 ‰ and up to 6.8 ‰ in coarse and fine resolution samplings, respectively. Relative humidity rather than the amount of rainfall appears to control the sub-annual $\delta^{18}O$ variations. Further, a comparison of the $\delta^{18}O$ profile of a ring (year 1971 A.D.), analyzed with the highest resolution, and a model profile based on concurrent local meteorological data reveals the possibility of achieving a resolution of ~20 days in monsoon reconstruction by sub-annual $\delta^{18}O$ measurements.

Coarse and fine resolution sub-annual $\delta^{18}O$ analyses of three teak trees from central India show a trend with ^{18}O enriched in extremities of the rings and depleted in the intermediate parts. The amplitude of such variations is from 2‰ to 7‰. This shows the need to obtain truly representative samples of the ring when a relationship is established between climate and tree cellulose $\delta^{18}O$ values on an inter-annual scale. The results indicate the possibility of using currently available plant physiological models for interpreting sub-annual $\delta^{18}O$ variations. A seasonal cycle in $\delta^{18}O$ enables to divide the rings into parts containing photosynthates formed during the pre-, main-and post-monsoon seasons hence identify the growth that occurred during these seasons. The width/$\delta^{18}O$ signature of these portions can be used to reconstruct past climate of respective sub-seasons. Relative humidity, rather than rainfall amount, governs the sub-annual $\delta^{18}O$ variations in the present study area. It is observed that about 50% of ring cellulose is synthesized from the photosynthates formed during relatively lower humidity conditions suggesting a period of lower relative humidity i.e. the pre- and post-monsoon seasons are equally important in deciding whole ring cellulose $\delta^{18}O$.

High and coarse resolution sub-annual analyses of $\delta^{18}O$ of teak cellulose from southern India, receiving both rains, the south-west (SW) (summer) and the north-east (NE) (winter, more depleted in ^{18}O) monsoons, show a seasonal cycle, with some degree of incoherence. The amplitudes vary between 1 to 3 ‰, with lower $\delta^{18}O$ values at the early and late growing seasons and higher values at the middle. The observed pattern is opposite to that reported for teak trees from central India, where the annual rainfall is unimodal, with much less NE monsoon rains. Comparison of the observed and modeled profiles reveals that the observed pattern of sub-annual $\delta^{18}O$ variation can be explained only if the tree sampled rainfall from both the monsoons. Thus it appears possible to detect excess NE monsoon years in the past by analyzing the $\delta^{18}O$ of cellulose from latewood of teak trees.

Sub-annual $\delta^{18}O$ analysis of 17 arbitrarily selected teak rings from southern India shows a pattern opposite to the one reported for teak trees from central India. These and the model-calculated values from local meteorological data appear to suggest that $\delta^{18}O$ values associated with the middle and end of the growing season are respectively relatable to the $\delta^{18}O$ of SW and NE monsoon rains. Thus the relative strengths of both the monsoons could be reconstructed by high-resolution sub-annual isotope analysis of teak from this bimonsoon climatic regime. Further, care should be taken while interpreting inter-annual $\delta^{18}O$ variations of trees from bimonsoonal regimes: the varying amounts of isotopically different rains are likely to affect the bulk ring cellulose $\delta^{18}O$.

The sub-annual isotope pattern in teak observed in the present study corroborates the approach ‘tropical isotope dendrochronology’ taken by Evans and Shrag (2004) wherein wood corresponding to one seasonal cycle of $\delta^{18}O$ is considered as a ‘ring’ and regular dating/counting methods are used to assign calendar years to tropical trees lacking visible growth rings.

The $\delta^{18}O$ record between teak trees from the same region appears to be more coherent than the ring-width record. The observed yearly (5-yearly moving averages) correlations and common signals in $\delta^{18}O$ record of Jag03 and Jag04 are 0.66 (0.77) and 66% (73%), respectively. The correlations observed are significant at $P<0.0005$. These values are higher than those observed for ring-width and ring-width index records – yearly (5-yearly) common signal for the ring-width and ring-width index are respectively 36% (44%) and 13% (6%). Further, the correlation and common signal obtained for $\delta^{18}O$ record are higher than that reported in literature for various ring-indices based teak chronologies from central and southern India. This, in conjunction with the common signal reported by Ramesh et al., (1989) for δD record between two teak trees (60%) appear to suggest that the isotope record in teak is able to capture more common variance than the ring-width/ring-width index record.

Teak from western India (THN) and central India (Jag03) show a weak positive correlation ($r \sim 0.4$) between cellulose $\delta^{18}O$ and rainfall record whereas teak from southern India (PKLM) exhibits a negative relationship ($r \sim -0.5$). The former could be explained by invoking lengthening of the growing season as a consequence of higher rainfall. During years of higher rainfall teak grows until a period of lower relative humidity leading to more evaporative enrichment of the leaf water and hence higher $\delta^{18}O$ values of cellulose. The plausible reasons for the negative correlation in the case of the latter could be the presence of relatively strong amount effect in rainfall in the region, higher rainfall during the north-east (NE) monsoon, one depleted in ^{18}O, and relatively lesser effect of lower relative humidity conditions in deciding tree $\delta^{18}O$.

Based on the relationship observed between PKLM $\delta^{18}O$ record and rainfall record, past rainfall record for Palakkad, Kerala was reconstructed back to 1743 A.D. It was further realized that the reconstructed record is also valid for most of southern India. The cellulose $\delta^{18}O$ based rainfall record extends the existing record back in time by 70 and 128 years for southern India and Palakkad, respectively. The reconstructed rainfall period partly covers the Little Ice Age (~1350-1900 A.D.). Most of the high and low rainfall events in the reconstructed and instrumental record match. One of the conspicuous features of the extended record is higher precipitation during 1743-1830 as compared to the later period.

5.2 Recommendations

Recommendations regarding possible future work that could be undertaken in continuation of the present study are:

- To fully exploit the isotope dendroclimatological potential of teak and other suitable trees from tropical areas an extensive characterization of the amount effect in rainfall is necessary. Existing temporal and spatial coverage of isotopes in rainfall is too inadequate to realize their effect on isotopic composition of plants.

- To use various plant physiological models for interpreting sub-annual as well as inter-annual $\delta^{18}O$ variations in teak, better understanding of stomatal behavior of teak is necessary. In the present study, the stomatal conductance was calculated based only on relative humidity. Soil moisture content and light availability are also known to affect the stomatal conductance. In addition to this, the Peclet effect, an advective mixing of the enriched leaf water and un-enriched source water, was reported to affect plant $\delta^{18}O$ values. Clearly, more field investigations are needed in this direction.

- In the present study, time assigned to the different sub-annual parts of the rings was based on the general growth pattern of teak. Assigning more precise time to the sub-annual parts would give higher credibility to the correspondence established between the sub-annual $\delta^{18}O$ variations and ambient climate. For this, cambial pinning should be carried out on trees and rings from such trees should be studied for sub-annual isotopic analysis.

- The present study shows that sub-annual $\delta^{18}O$ variations are affected by climatic conditions during the growing season. One of the important aspects of Indian monsoon is ‘active’ and ‘break’ spells of rainfall within the summer monsoon season (June-Sept). Such monsoon ‘breaks’ influence the mean summer monsoon rainfall received. In this context, it would be worth probing whether the ‘breaks’ in monsoon leave any distinct signature on intra-annual $\delta^{18}O$ variability.

- The depleted $\delta^{18}O$ values of the early wood observed in a teak tree from Kerala suggests likely transfer of photosynthates formed during the end of previous year. To verify this, an experiment could be conducted by irrigating teak trees with water having distinct $\delta^{18}O$ in the late growing season (Oct-Nov). $\delta^{18}O$ analysis of the subsequent year’s ring will help to resolve the issue of transfer of photosynthates from one year to the next year.

- It has been observed that there is a substantial spatial variation in rainfall over Indian region with different regions showing differing long-term trends in rainfall (Guhatakurta and Rajeevan, 2008). Hence reconstructed temporal trend in rainfall based on tree ring studies is likely to be regional and may not follow trend in all-Indian monsoon rainfall. To get a more representative trend for the all-India summer monsoon rainfall (ISMR), trees from the core monsoon zone (Sikka and Gadgil 1980) should be used.

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