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.

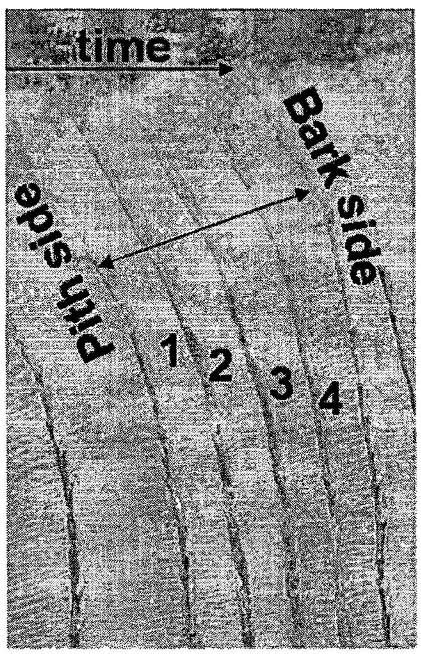

Fig.3.1. A photograph depicting a ring which was divided into four parts.

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

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

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 $\delta^{18}O$ variations

Sub-annual $\delta^{18}O$ 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 $\delta^{18}O$ values of the growth segments whose positions are marked as percent distance from the pith side.

In general, the coarse resolution $\delta^{18}O$ variations observed for samples Jag03 (**Fig.3.2a**), Jag04 (**Fig.3.2b**) and AP1 (**Fig.3.2c**) show a pattern with higher $\delta^{18}O$ values at the beginning and end of the ring and lower values at the intermediate part. The amplitudes of sub-annual $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ profiles (**Fig.3.3**) for the trees from central India show a more consistent pattern with higher $\delta^{18}O$ values at the ring extremities and lower $\delta^{18}O$ values in between. For Jag03 sample, the amplitudes of sub-annual $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$ profile. **Fig. 3.4(a)** and **3.4(b)** show sub-annual $\delta^{18}O$ profiles of the rings analyzed with coarse and high resolution sampling, respectively. The data

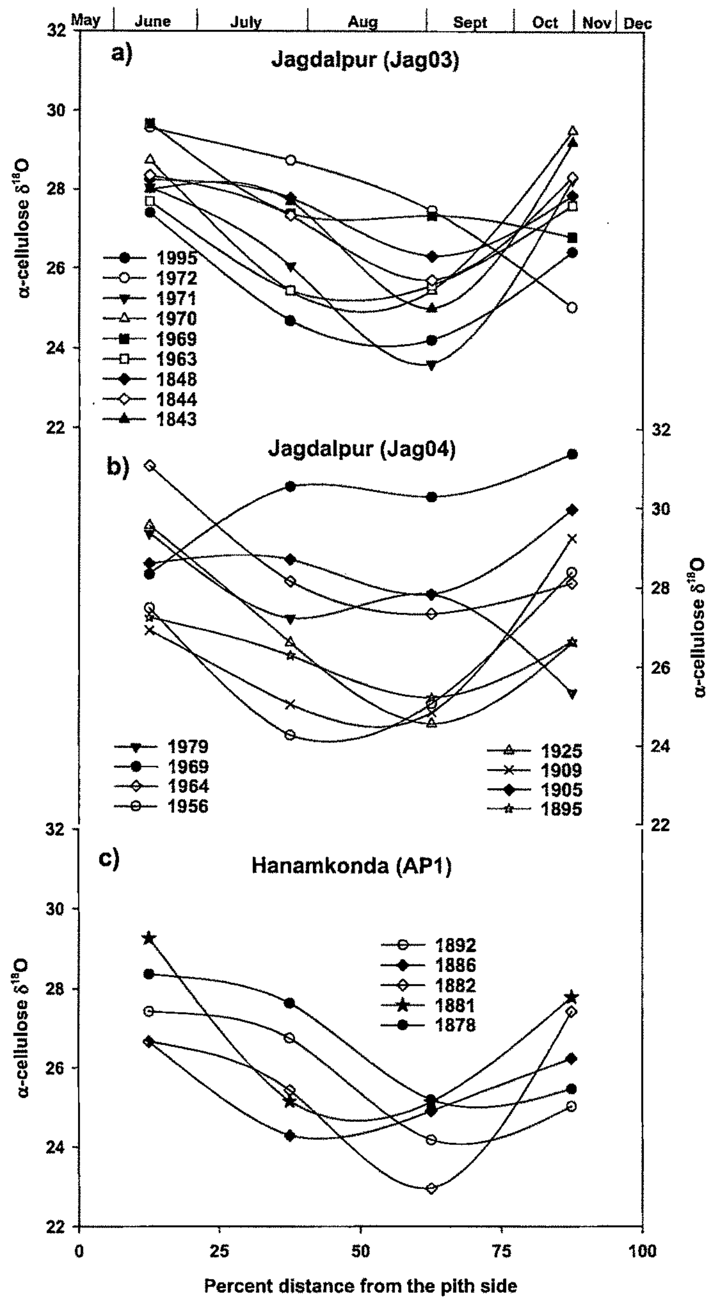

Fig.3.2. Coarse resolution sub-annual cellulose $\delta^{18}O$ profiles observed for teak trees from area near Jagdalpur, Jag03 (a) and Jag04 (b), and Hanamkonda, AP1 (c). Legends represent years corresponding to the rings analyzed. Months shown on the top of the graph are approximately assigned based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

points in these figures represent the cellulose $\delta^{18}O$ of the corresponding segments of rings. The $\delta^{18}O$ 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 $\delta^{18}O$ 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 $\delta^{18}O$, 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.

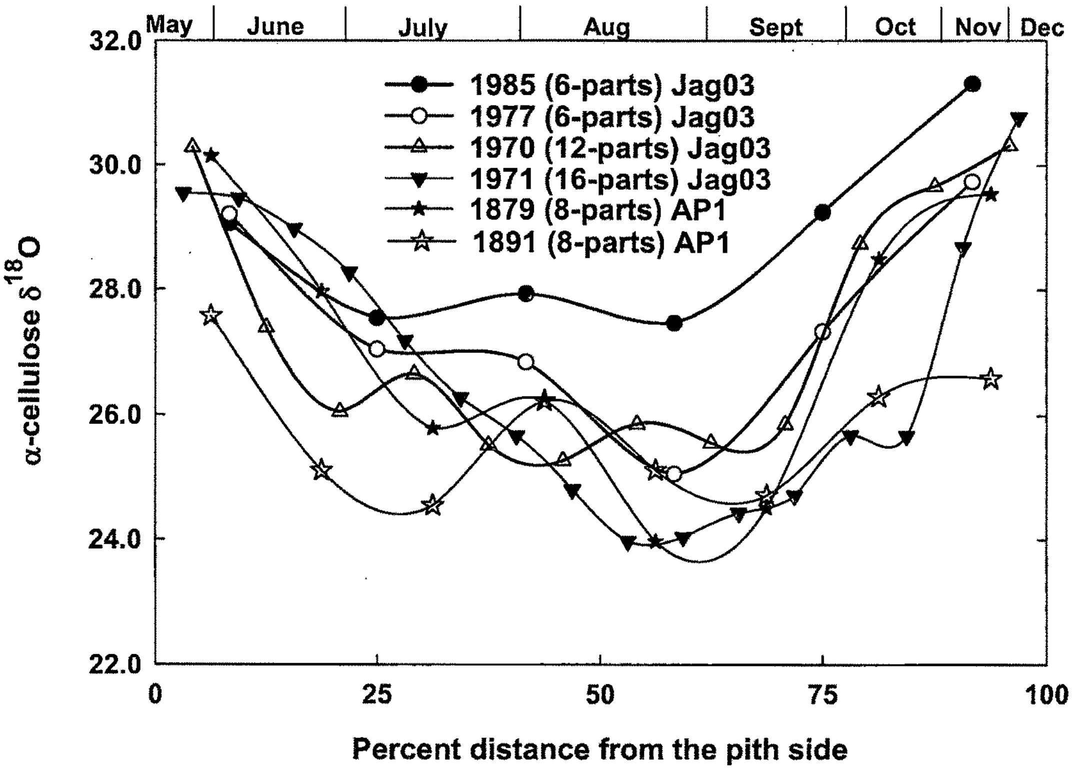

Fig.3.3. Fine resolution sub-annual cellulose $\delta^{18}O$ profiles observed for teak trees from area near Jagdalpur (Jag03) and Hanamkonda (AP1). Legend represents years corresponding to the rings analyzed, the numbers of parts the rings were sub-sampled into and sample name. Months shown on the top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

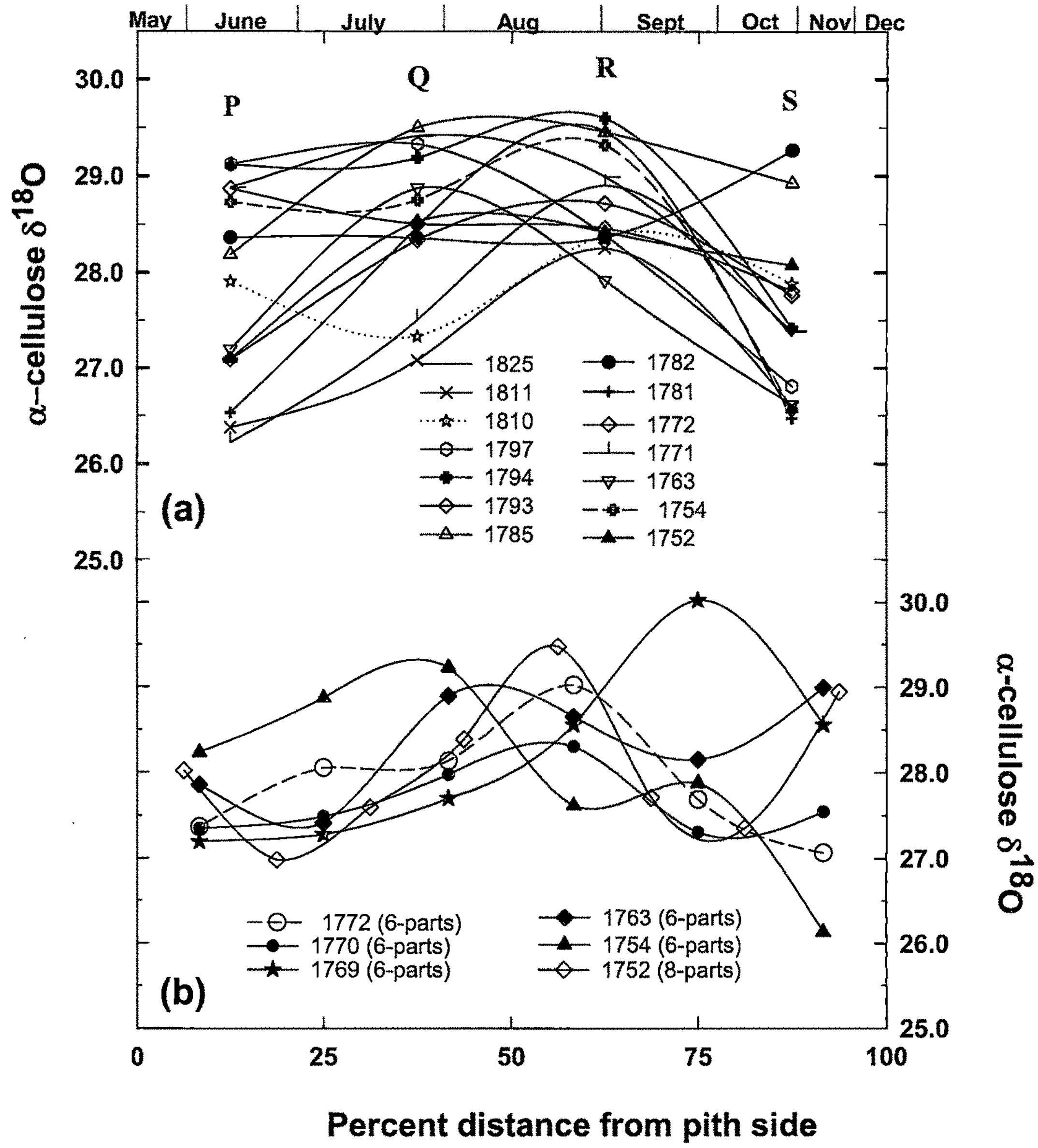

Fig. 3.4. Sub-annual cellulose $\delta^{18}O$ profiles of the rings of the teak from Perambikulam (PKLM): (a) $\delta^{18}O$ variation of the rings which were divided into four equal parts; (b) higher resolution sub-annual $\delta^{18}O$ profiles. Months shown on the top of the graph are approximately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

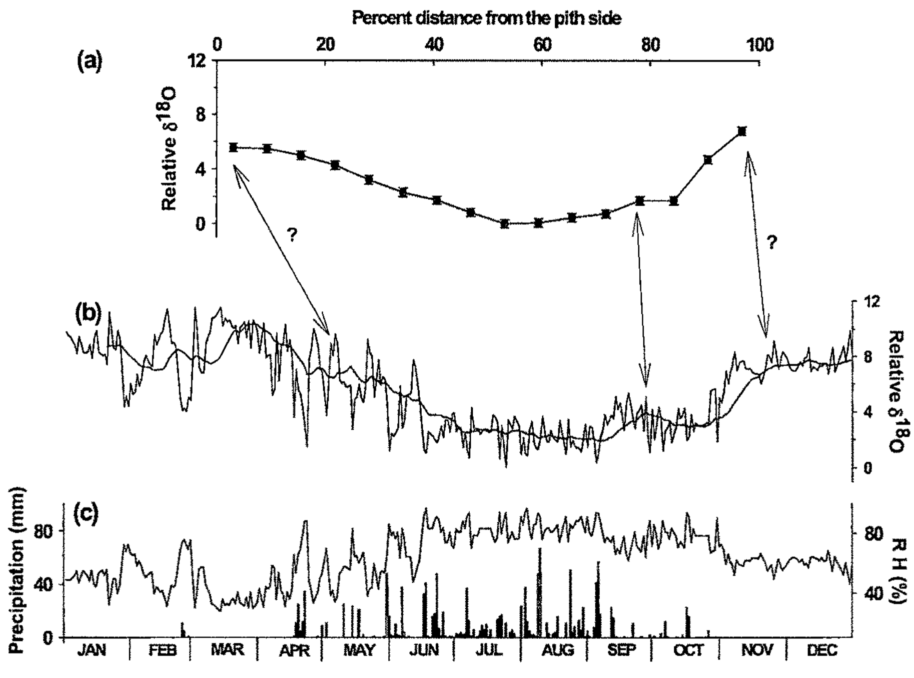

Fig.3.5. (a) Sub-annual cellulose $\delta^{18}O$ variation observed in one of the ring (year 1971 A.D.) of teak from Jagdalpur, Jag03. (b) the modeled $\delta^{18}O$ variations calculated based on daily weather data. (c) daily precipitation (black bars) and relative humidity for the same year (black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

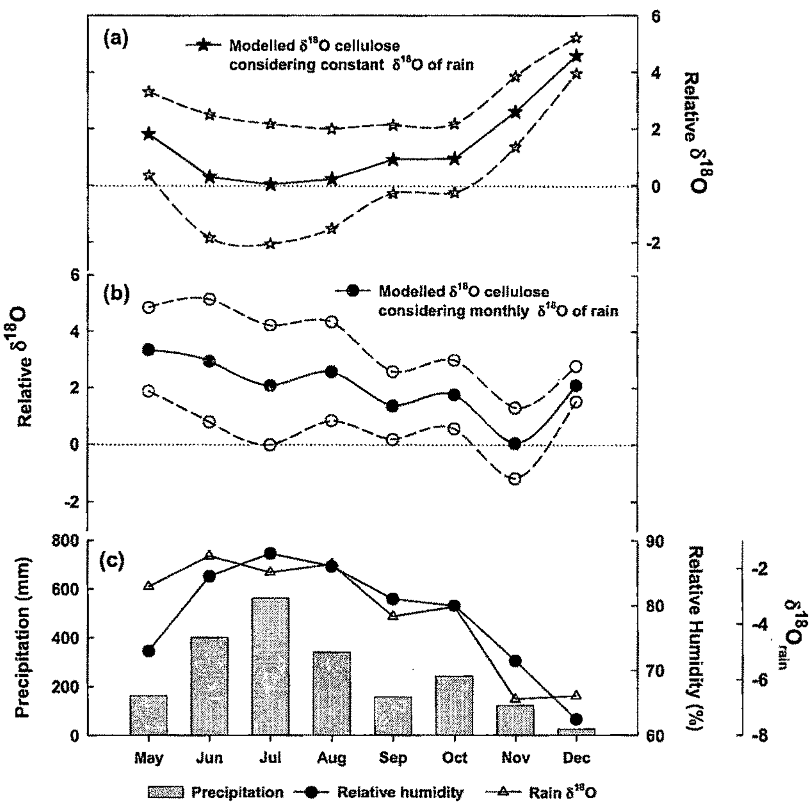

Fig. 3.6. Modeled climatological cellulose $\delta^{18}O$ profile considering constant $\delta^{18}O$ of rainwater (a); and varying $\delta^{18}O$ of rainwater (b). The dashed lines show one-sigma uncertainty. (c) shows precipitation (grey bars), relative humidity (filled circles) and rain water $\delta^{18}O$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