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 8^{th}-order polynomial curve was fitted; for samples AP1 and PKLM 7^{th}-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.

* $P< 0.01$,

** $P< 0.05$,

*** $P< 0.0005$.

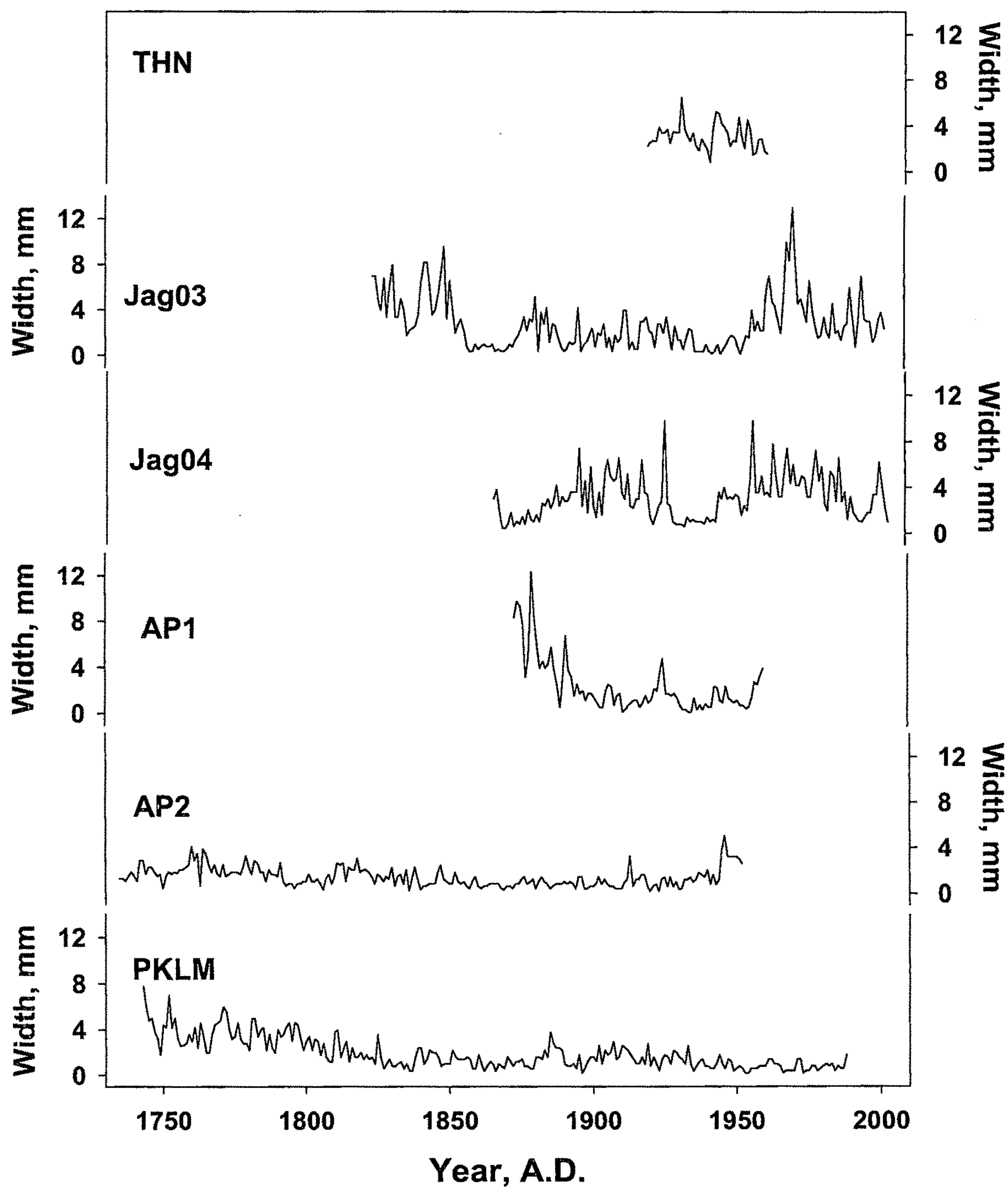

Fig.4.1. Time series of ring-width variations of all the samples.

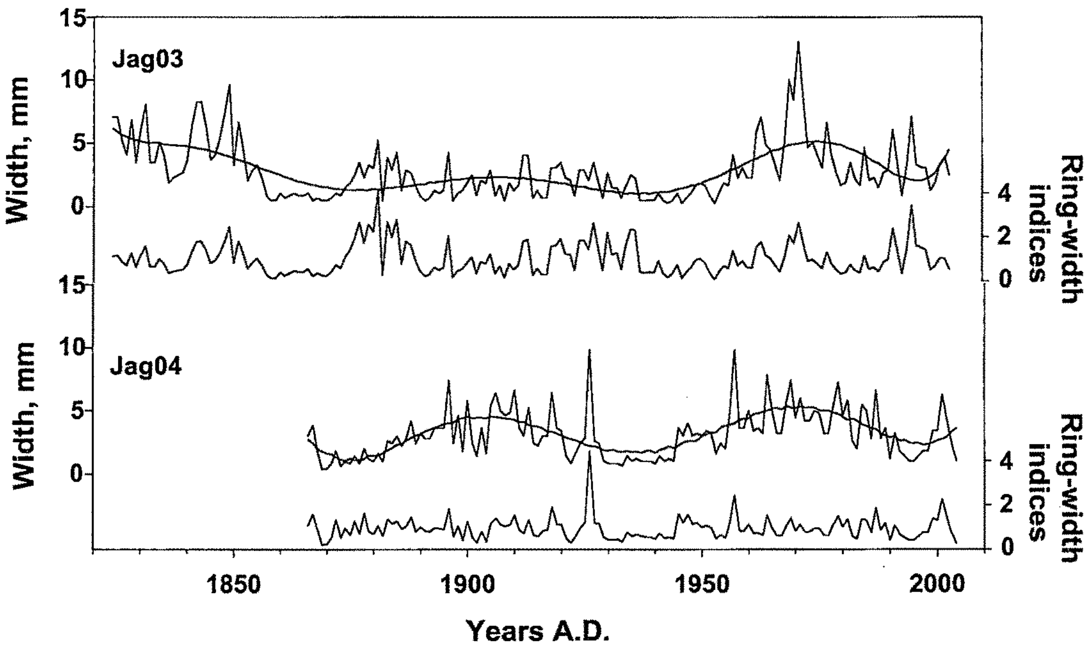

Fig.4.2. Time series of ring-widths and ring-width indices of Jag03 and Jag04.

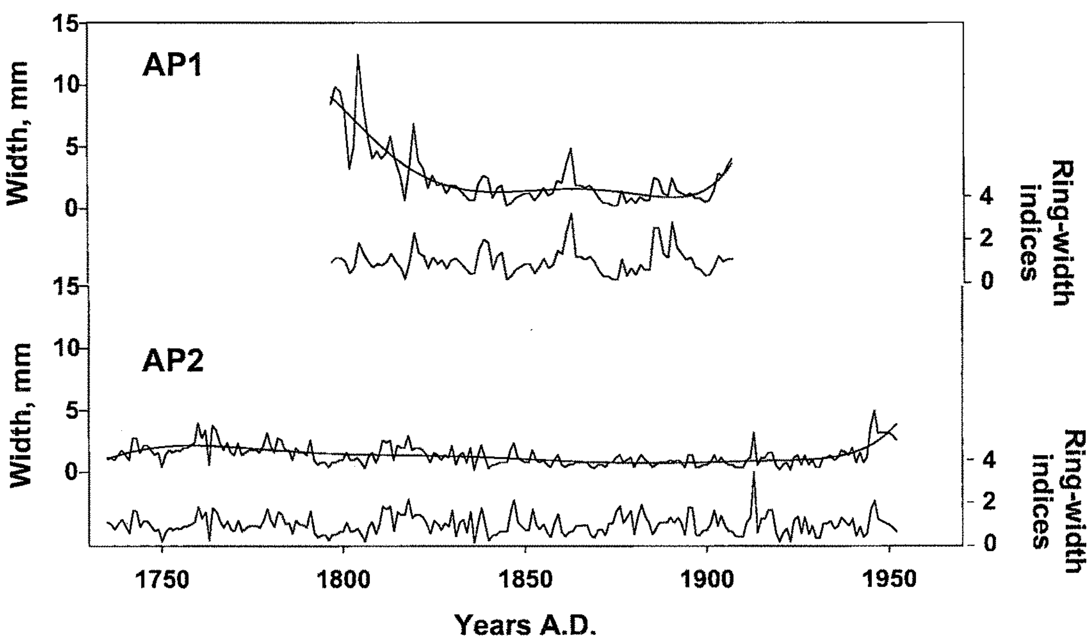

Fig.4.3. Time series of ring-widths and ring-width indices of AP1 and AP2.

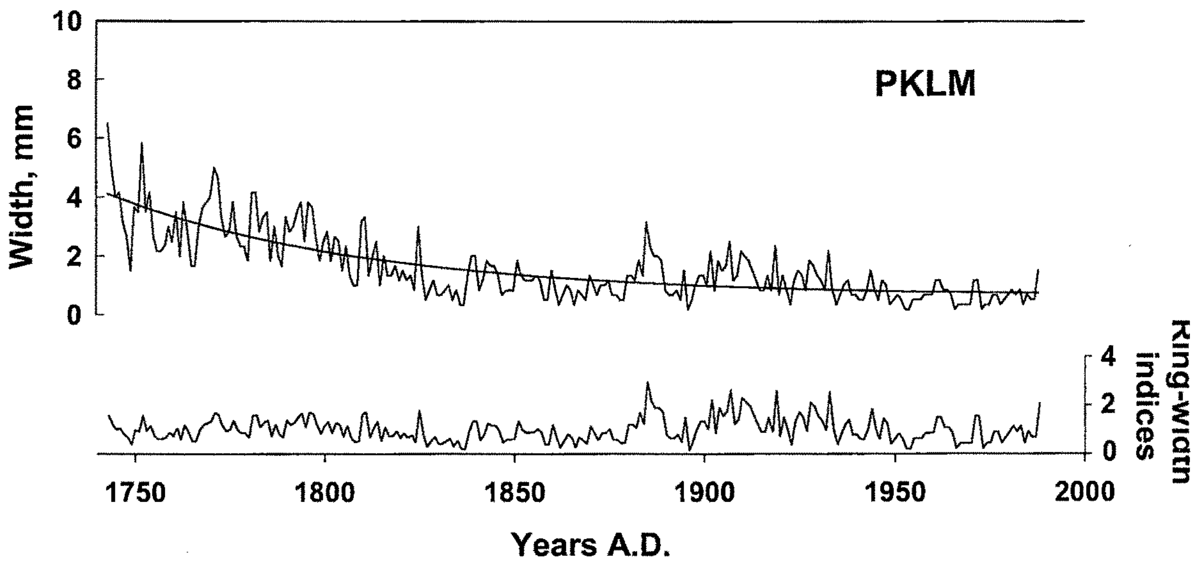

Fig.4.4. Time series of ring-widths and ring-width indices of the sample from Kerala, PKLM.

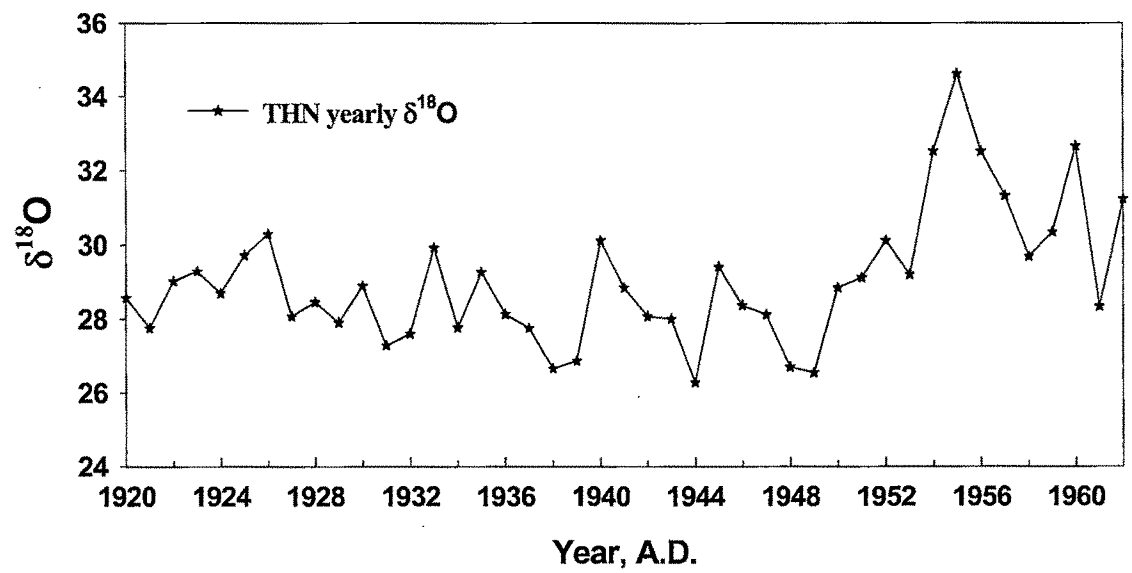

Fig.4.5. Time series of cellulose $\delta^{18}O$ variations of the sample from Thane, THN.

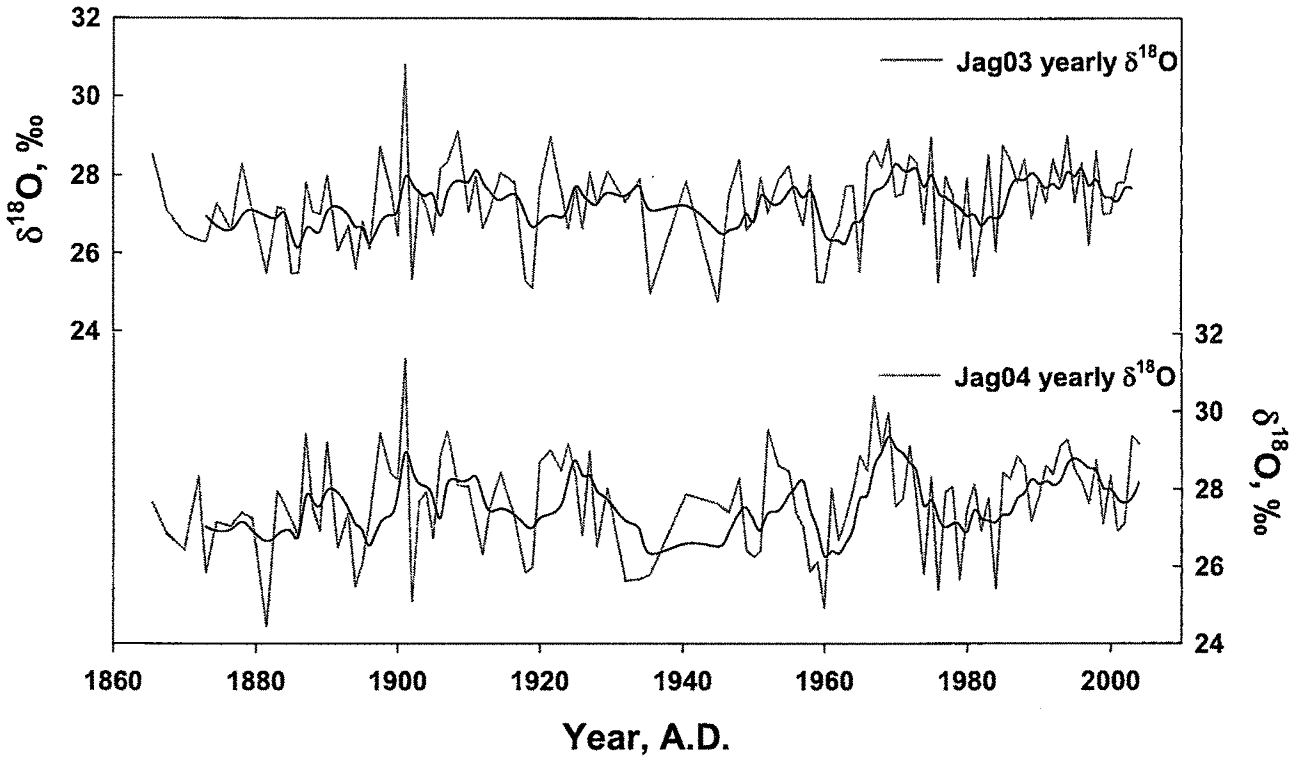

Fig.4.6. Time series of cellulose $\delta^{18}O$ variations of the samples from Jagdalpur, Jag03 and Jag04.

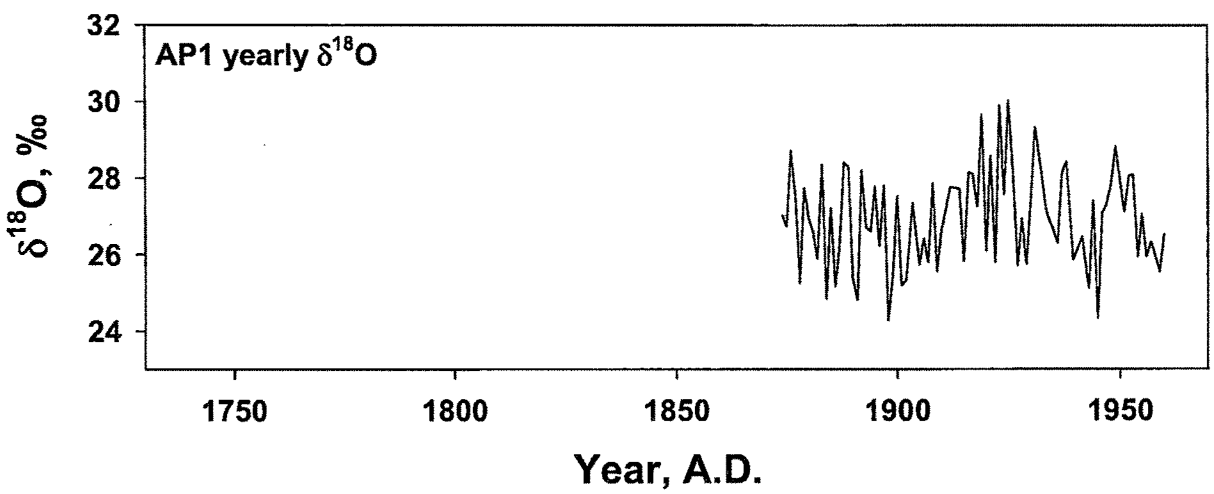

Fig.4.7. Time series of cellulose $\delta^{18}O$ variations of sample AP1, from Andhra Pradesh.

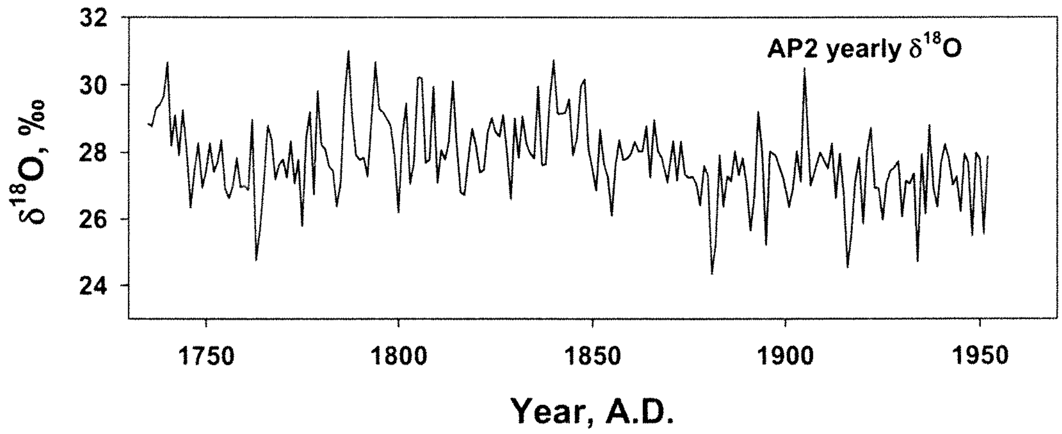

Fig.4.8. Time series of cellulose $\delta^{18}O$ variations of sample AP2, from Andhra Pradesh.

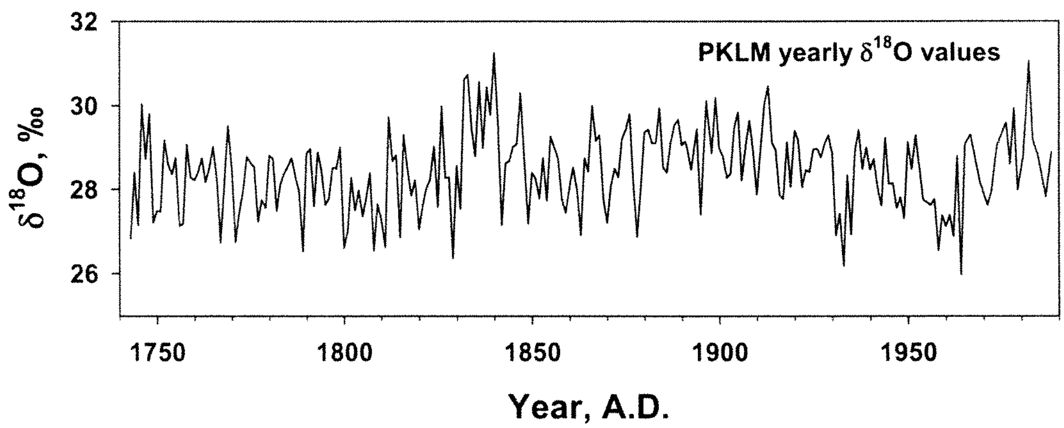

Fig.4.9. Time series of cellulose $\delta^{18}O$ variations of the sample from Kerala, PKLM.

4.2 Discussion

The present discussion starts with a general description of ring-width and cellulose $\delta^{18}O$ variations observed in the samples. A subsequent section deals with finding similarity in ring-width as well as cellulose $\delta^{18}O$ 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.

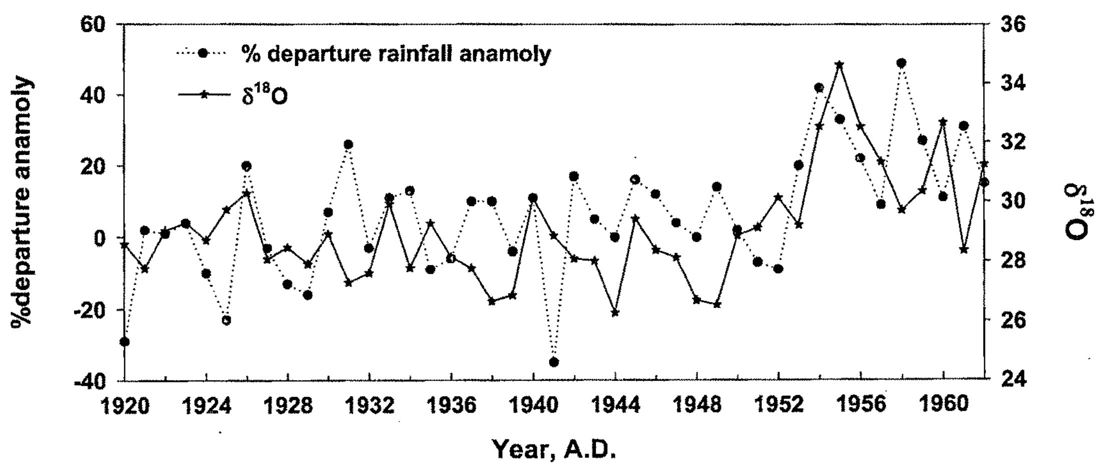

Fig.4.10. Comparison of percentage rainfall anomaly (dotted line) and cellulose $\delta^{18}O$ record (solid line) of sample THN.

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.

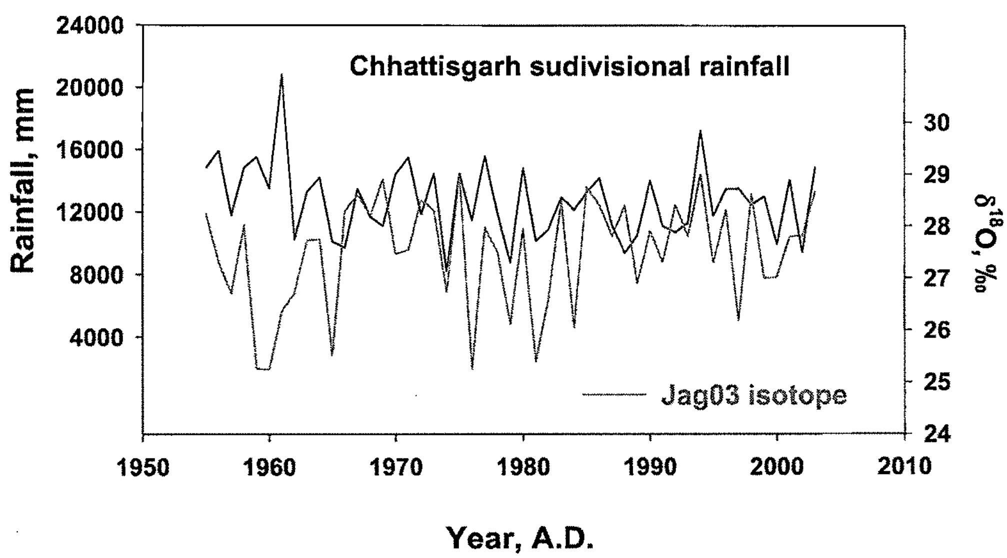

Fig.4.11. Comparison of cellulose $\delta^{18}O$ record of Jag03 (gray lines) and Chattisgarh sub-divisional rainfall (solid line). See text for explanation of sub-divisional rainfall.

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 $\delta^{18}O$.

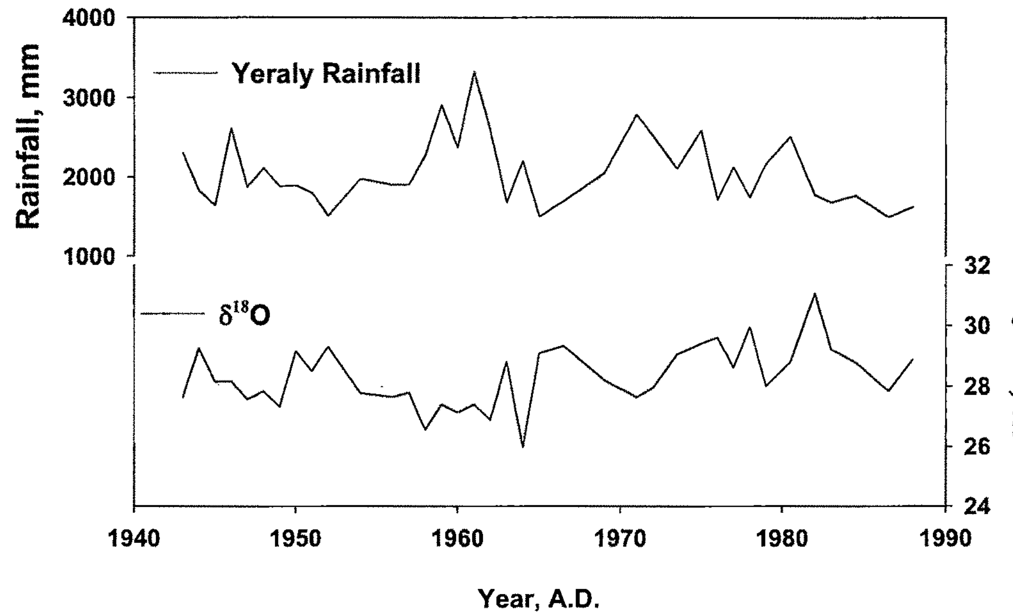

Fig.4.12. Yearly rainfall of Palakkad (upper panel) and cellulose $\delta^{18}O$ record of sample from southern India, PKLM (lower panel).

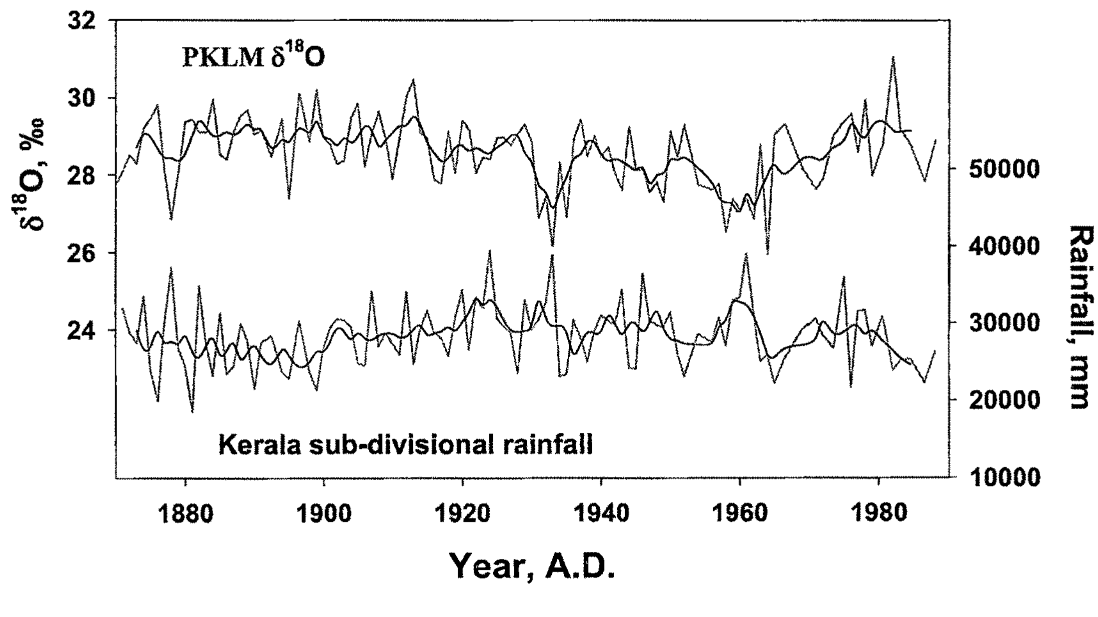

Fig.4.13. Comparison between PKLM cellulose $\delta^{18}O$ record and Kerala sub-divisional rainfall. See text for explanation regarding sub-divisional rainfall.

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.).

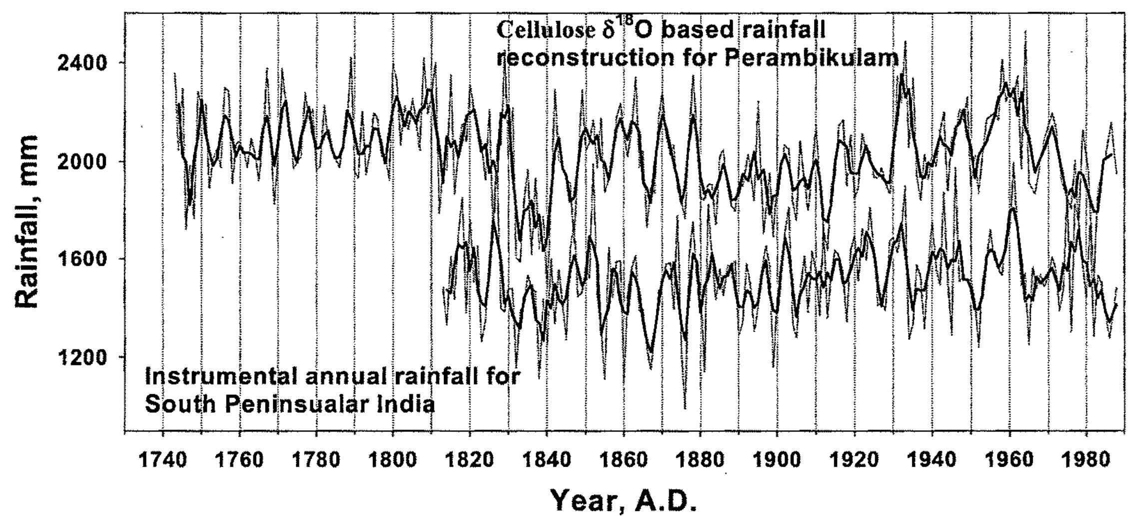

Fig.4.14. Reconstructed past rainfall for Perambikulam region using cellulose $\delta^{18}O$ record of PKLM (upper graph). Instrumental rainfall record for the south peninsular India from Sontakke et al., (2008) (lower graph). Gray and black lines are yearly and 3-yearly variations, respectively.

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**).