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-, mainand 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.