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$\delta^{18}O$ of tree rings of beech (*Fagus silvatica*) as a record of $\delta^{18}O$ of the growing season precipitation

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Abstract

The measurement of $\delta^{18}O$ in cellulose of tree rings is a potential means to reconstruct $\delta^{18}O$ variations of precipitation and climate. We present $\delta^{18}O$ data from cellulose of 3 beech trees (*Fagus silvatica*) growing on a relatively dry site in Switzerland where the roots do not have access to ground water, as well as data of 2 other groups of 4 beech trees each, one from a dry site and the other from a semi-dry site, respectively. The measurements cover the time period from 1934 to 1987 in 3-year-groups for the 1st site and 1965 to 1992 with a 1-year resolution for the other 2 sites. We find a high degree of common variance (61%) between the $\delta^{18}O$ variations of the 3 trees from the 1st location suggesting a common external cause. The comparison with climate data indicates that spring temperature (April/May/June) is the main influence for the long-term isotope variations, with a temperature coefficient of 0.33‰ per °C, whereas the short-term variations are mainly influenced by the relative humidity, with a coefficient of −0.13‰ per %. This latter value is about $\frac{1}{3}$ of the expected model value which points to leaf water pools with different $\delta^{18}O$ values influencing the isotopic composition of synthesised carbohydrates or to oxygen exchange with stem water. Tree ring $\delta^{18}O$ is correlated with $\delta^{18}O$ in precipitation, and the slope of the linear regression for different months most probably yield information about the growth rate function of the particular tree group. Our results confirm the potential of $\delta^{18}O$ measurements in tree ring cellulose for climate reconstruction, in particular information about $\delta^{18}O$ in precipitation can be gained.

1. Introduction

Relatively little is known about the relationship between $\delta^{18}O$ in tree ring cellulose and climate. This is partly due to the scarcity of data (because no automated sample preparation method is available), but is also related to the complexity of the isotope fractionation processes involved. Climatic information is contained in the oxygen isotope composition of precipitation (mainly on surface air temperature) and therefore such information may also be stored in $\delta^{18}O$ of tree rings. Yet it has to be taken into account that isotope fractionations occur between the uptake of soil water by the trees and cellulose synthesis. Tree ring $\delta^{18}O$ depends on the relative amounts of ground water and summer rain taken up by the roots of the tree, the leaf water ^{18}O enrichment and biochemical processes. In view of their complexity, it is necessary to study these processes for interpreting $\delta^{18}O$ measurements in tree rings (see Section 2). Concerning $\delta^{18}O$ data of trees in the literature, Burk and Stuiver (1981) and Edwards et al. (1985) measured mean $\delta^{18}O$ values of trees from sites with largely differing climatic conditions. They found a good agreement between experimental data and values predicted from a model where they incorporated $\delta^{18}O$ of precipitation and relative humidity and could thus confirm the climatic

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significance of $\delta^{18}O$ in trees. However, for the paleoclimatic interpretation of tree ring records the correlation between temporal changes of $\delta^{18}O$ in tree rings and climate at a given location is actually important. It can not a priori be expected that a temporal correlation will yield the same result as a spatial correlation with which the above mentioned publications are dealing. Only relatively poor knowledge is available concerning the latter type of calibration study. Ramesh et al. (1986) analysed a 30-year tree ring $\delta^{18}O$ record of a silver fir tree (*Abies pindrow*) from Kashmir, India. They found a significant relation to the relative humidity ($r = -0.5$), but unfortunately no $\delta^{18}O$ record in precipitation exists for this region.

Obviously, more data are needed in order to understand the climatic significance of $\delta^{18}O$ variations in tree rings and it is the aim of this study to contribute to this question. We chose 2 dry sites ('Twann Dry'=TWD, 'Krauchthal Dry'= KRD) and a semi-dry site ('Krauchthal Humid'= KRH) in Switzerland where trees have no or only minor access to groundwater. We measured $\delta^{18}O$ values of 3-year-ring groups from 3 beech trees of the dry site (TWD) for the period 1934 to 1987 and a mean $\delta^{18}O$ value of each of the other 2 sites (KRD and KRH) from 4 beech trees each for every year from 1965 to 1992. The results were compared with climate data as well as $\delta^{18}O$ data of precipitation which exist for several Swiss stations starting in 1971. Ramesh et al. (1985) report a high degree of coherence between $\delta^{18}O$ values along two radii of the same tree which was discussed in Ramesh et al. (1986). This is an important result because large isotope variations along the circumference of a single growth ring, as have sometimes been found for carbon isotopes, could obscure the climatic signal. Similarly, it would be important to know the degree of coherence of $\delta^{18}O$ signals in different trees from one site. We do not know about any study dealing with this problem and therefore it is another aim of this work to determine this coherence for our selected trees.

2. Processes

In this section, we discuss the fractionation processes which are relevant for the oxygen isotope composition in tree cellulose. We treat them in the order in which they occur naturally, i.e., we start with $\delta^{18}O$ in precipitation (2.1), go on to soil water (2.2), stem water and leaf water (2.3), and proceed with sucrose in the leaf and cellulose in the stem (2.4). This overview will facilitate the interpretation of $\delta^{18}O$ tree ring data. Fig. 1 illustrates the important steps and gives some typical values.

2.1. $\delta^{18}O$ in precipitation

$\delta^{18}O$ in precipitation is well correlated with temperature for polar and coastal stations with an average change in $\delta^{18}O$ of 0.7‰ per degree Celsius (Dansgaard, 1964). This is a correlation in a spatial sense, i.e., long term means of $\delta^{18}O$ and, of surface air temperature of the different stations have been compared. Besides the temperature there are many other influences on $\delta^{18}O$ in precipitation, like for instance changes in the origin of the water vapour, admixture of isotopically different water vapour, depletion due to continentality and due to altitude. A quantitative interpretation of $\delta^{18}O$ records of precipitation is

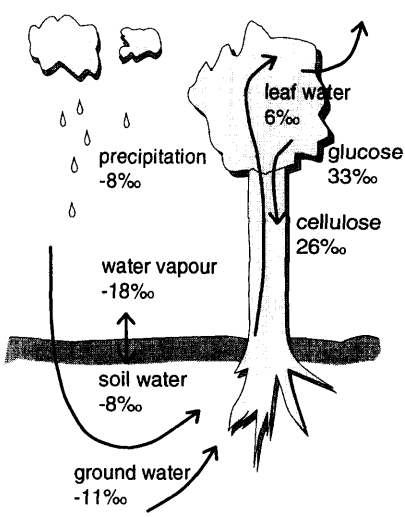

Fig. 1. The path of oxygen atoms of water into the plant and typical $\delta^{18}O$ values (versus SMOW). The indicated values of $\delta^{18}O$ in precipitation and shallow soil water are representative for summer in Switzerland, the values for ground water, water vapour, leaf water and glucose are estimated according to the theory in Section 2, and the value for cellulose is the mean of our data for beech trees.

therefore difficult. Another problem is that the correlation of long-term (interannual) changes of $\delta^{18}O$ and of temperature is less well investigated than the "spatial correlation" because of the lack of long time series (longer than 20 to 30 years) for $\delta^{18}O$ in precipitation (Rozanski et al., 1992). Yet temporal correlations are actually relevant for the interpretation of the proxy records which may be obtained from tree rings, from polar ice cores or from carbonate sediments in lakes. We calculated regression equations relating annual means of $\delta^{18}O$ and of temperature for several Swiss stations (see Table 1) from isotope data measured at our laboratory (see also IAEA, 1992). These stations were selected in view of the subsequent comparison with our tree ring results. The annual $\delta^{18}O$ means were computed as unweighted averages of the (amount-weighted) monthly values. The correlations are significant ($p<0.05$ according to t-test), but only 22% to 37% of the variability in $\delta^{18}O$ can be explained by temperature. The slopes for Bern and Grimsel are similar to the slope of 0.7‰/°C found for the spatial correlation (Dansgaard, 1964), but interestingly, the value for Locarno is significantly higher. On the one hand these results confirm the existence of a correlation between temporal changes of $\delta^{18}O$ in precipitation and temperature and on the other hand they make the uncertainties evident, e.g. regional differences may exist, which could stem from a different origin of rain-water. Similar results have been obtained by Rozanski et al. (1992) for several European stations (we obtained a better correlation for Bern than Rozanski et al., 1992, because we corrected the temperature data for a change of location of the weather station in 1978).

2.2. $\delta^{18}O$ in soil water

Concerning soil water a rough distinction between surface water and ground water can be made. During the vegetation period (spring/summer), surface water is in Switzerland about 3‰ more positive in $\delta^{18}O$ than groundwater because of the strong seasonal variation of $\delta^{18}O$ (Siegenthaler and Oeschger, 1980). Groundwater generally represents a long-term mean of $\delta^{18}O$ in precipitation and does not exhibit any significant variations. In relation to tree rings this difference in $\delta^{18}O$ between surface water and ground water means that the root distribution of a tree must be considered. White et al. (1985) measured δD of sap from the trunk of white pines growing at different sites. He found that after a rainfall the enrichment of the sap water clearly depended on the amount of groundwater available to the trees, only trees without groundwater access reflecting the rain δD in the sap δD. The situation could even be more complex if the unsaturated zone is not isotopically homogenous. Hesterberg and Siegenthaler (1991) measured variations of $\delta^{18}O$ of soil water from 30 cm and 80 cm below surface during 1½ year (grass-covered soil consisting of humus, sand and loam with embedded stones). The seasonal signal in the soil water was strongly damped and showed a phase lag relative to the precipitation signal, which amounted to about 6 months at 80 cm depth. Whether these findings are valid for forest ecosystems or not, we don't know, but for our dry or semi-dry sites we can exclude such an effect since most of the rain water is trapped by the tree root systems. This is confirmed by our correlation results (see section 4). Concerning tree ring $\delta^{18}O$ studies we conclude

Table 1. *Coefficients of variance (r^2) and slopes ($\pm 1\sigma$), comparing annual means of $\delta^{18}O$ in precipitation with temperature (temporal correlation)*

Location (altitude, m.a.s.l.)	Slope (‰/°C)	r^2	n (years)	β
Bern (572 m)	0.53 ± 0.21	0.22	24 (1971–1994)	0.05
Grimsel (1950 m)	0.62 ± 0.17	0.37	24 (1971–1994)	0.01
Locarno (379 m)	1.24 ± 0.31	0.44	22 (1973–1994)	0.001

n = number of years, significance level 1-β according to t-test. Bern is situated north of the Alps (46.56°N, 7.25°E, 572 m.a.s.l.), Grimsel in the centre of the Alps (46.34°N, 8.20°E, 1950 m.a.s.l.) and Locarno south of the Alps (46.10°N, 8.53°E, 379 m.a.s.l.).

from these findings that trees which use water from very different soil depths should not be used. Thus trees with a superficial root system may be best suited to record variations of $\delta^{18}O$ in precipitation or instead — for special purposes — trees which get their water from groundwater only.

2.3. $\delta^{18}O$ in leaf water

No significant fractionation seems to occur during uptake of water by the roots and the subsequent transport of water from the roots to the leaves (White, 1985). However, large isotopic enrichment takes place in the leaf due to transpiration. A model has been developed to describe this effect (Dongmann et al., 1974):

$$\delta_l \approx (1-h)(\delta_s - \delta_v + \varepsilon_k) + \varepsilon_e + \delta_v , \quad (1)$$

where $\delta_l = \delta^{18}O$ of leaf water, $\delta_s = \delta^{18}O$ of soil water, $\delta_v = \delta^{18}O$ of atmospheric water vapour, $\varepsilon_e =$ equilibrium fractionation due to the change of phase from liquid to vapour; $\varepsilon_e = 9.8‰$ at 20°C (Majoube, 1971), $\varepsilon_k =$ kinetic fractionation due to the diffusion of vapour into undersaturated air; ε_k is dependent on the degree of turbulence in the leaf-boundary and on the ratio of the resistance for diffusion through the stomata to the resistance for diffusion through the leaf-boundary; $\varepsilon_k \approx 26.5‰$ according to Farquhar et al. (1989), $h =$ relative humidity; h refers to leaf temperature T_l, i.e., $h = e/e_{sat}(T_l)$, where $e =$ water vapour pressure of the air, $e_{sat}(T_l) =$ saturation vapour pressure at T_l.

A large number of experimental data support the linear relation between δ_l and h (Dongmann et al., 1974; Farris and Strain, 1978; Brenninkmeijer, 1983), at least a semi-quantitative interpretation of leaf water $\delta^{18}O$ is possible. Under normal European summer climate conditions the water vapour is on average approximately in isotopic equilibrium with soil water (Förstel and Hützen, 1983), and so one variable in eq. (1) can be eliminated since $\delta_v = \delta_s - \varepsilon_e$. Hence:

$$\delta_l - \delta_s \approx (1-h)(\varepsilon_k + \varepsilon_e). \quad (1')$$

As an example, for a daytime relative humidity of $h = 0.59$ (the long-term mean (1965–1992) during the vegetation period in Bern) we get a theoretical value of $\delta_l - \delta_s = +14.9‰$, thus a remarkable enrichment is expected to take place in the leaf. Yet sometimes the $\delta^{18}O$ values calculated in this way are too high compared to measured leaf water values, and this difference between theoretical and experimental values is related to the transpiration rate (Flanagan and Ehleringer, 1991). An important point which is neglected in eq. (1) is that leaf water is not well mixed. This is allowed for in recent models of leaf water dynamics: a diffusion/advection model yields an exponential isotope gradient from water at the evaporating sites to water in the chloroplasts (Farquhar and Lloyd, 1993), and an alternative model assumes 2 distinct water pools ((i) apoplastic water, i.e., water subject to transpiration and (ii) symplastic water) which exchange water at a certain rate (Yakir et al., 1990). Both models yield less enriched total leaf water and accordingly less enriched chloroplast water compared with eq. (1) (unless chloroplast water is directly subject to transpiration, as suggested in Farquhar et al., 1993). This is important with respect to tree ring analysis because it is the chloroplast water which determines the $\delta^{18}O$ of the photosynthetic products. The influence of the relative humidity on $\delta^{18}O$ in leaf organic matter may therefore not be as strong as given by eq. (1) or (1′).

2.4. Biochemical isotope fractionation

The oxygen isotope composition of cellulose in the leaf is not influenced by the $\delta^{18}O$ of CO_2 or of O_2 but is determined by the $\delta^{18}O$ of the water in the leaf (more precisely: in the chloroplasts). This was shown by experiments with labelled CO_2 (DeNiro and Epstein, 1979) and labelled O_2 (Cooper and DeNiro, 1989), respectively, because no effect of the labelled gases on the $\delta^{18}O$ of cellulose was found. However a difference of about 27‰ between the $\delta^{18}O$ of cellulose and water at the site of synthesis was found (DeNiro and Epstein, 1981). This value for the "biochemical" fractionation was obtained for a variety of plants and seems to be more or less constant (±3‰). The process responsible (as is now widely recognised) is the isotopic exchange of carbonyl oxygen atoms of organic molecules with water during hydration reactions (Sternberg and DeNiro, 1983; Sternberg et al., 1986), thus reactions with intermediate products of photosynthesis during cellulose synthesis. This has important implications for the interpretation of $\delta^{18}O$ in cellulose of tree rings, because sucrose transported

from the leaves to the stem may exchange part of the oxygen atoms with stem water during cellulose build-up. No quantitative estimate for trees can yet be made about the percentage of oxygen atoms which will undergo this exchange. From experiments with cellulose-producing bacteria Sternberg (1990) estimated a value of 47% which principally could also hold for trees. Therefore, considerable uncertainty exists regarding the relative influence of stem water and of (more enriched) leaf water on the $\delta^{18}O$ in tree ring cellulose. A high percentage of exchange with stem water would also, as above, reduce the influence of the relative humidity on the isotopic composition of stem cellulose.

The 4 most important processes, discussed above, that influence the ^{18}O content of the cellulose are summarised in Fig. 1: the water taken up by the roots is a mixture of ground water and summer months' precipitation with an isotopic composition influenced by climatic factors such as temperature. This mixture is transported without any isotopic fractionation to the leaves, where an enrichment, that depends on the relative humidity, due to evapotranspiration takes place. As the result of a biochemical fractionation, sucrose in the leaf is further enriched in ^{18}O. Cellulose in the stem might be less enriched because of a possible oxygen exchange of sucrose with stem water during cellulose build-up.

3. Materials and methods

The first sampling site ("Twann Dry" = TWD) is situated on a south-eastern slope of the Jura mountain chain near Twann (600 m.a.s.l.) in Switzerland. The beech trees (*Fagus silvatica*) on this dry site with a shallow humus layer have a relatively superficial root system (Saurer et al., 1995). Cores from 3 co-dominant trees from an area not larger than 50 m × 50 m were taken and cut into pieces including 3 tree rings each. The investigated period is from 1934 to 1987 and no tree was younger than 30 years in 1934, so that any juvenile effect can be excluded. Ring widths were measured on separate cores. The two other sites are situated near Krauchthal on the Swiss Plateau, about 12 km north-east of Bern and 30 km south-east of Twann. The very dry site ("Krauchthal Dry" = KRD) is on a hill with a shallow humus layer (700 m.a.s.l.), whereas the semi-dry site ("Krauchthal Humid" = KRH) is north-west exposed and has a deep humus layer (600 m.a.s.l.). From each of the 2 latter sites 2 cores from 4 beech trees (*Fagus silvatica*) were taken, and ring widths were measured. Then the cores were cut into pieces representing 1 year for the period 1965 to 1992. Corresponding pieces of all 4 trees from the same year and site were mixed together. Cellulose was extracted from the wood samples according to a method described by Brenninkmeijer (1983). To obtain CO_2, for isotope analysis, a modified nickel pyrolysis method was used, similar to that originally developed by Thompson and Gray (1977) and further improved by Brenninkmeijer (1983). The principle of the procedure is that cellulose (together with nickel-powder) is heated to about 1000°C in a nickel-tube. The cellulose decomposes among others to H_2, CO and CO_2, hydrogen diffuses through the nickel-walls and a CO/CO_2-mixture remains. In the next step at a temperature of about 350°C the nickel-powder acts catalytically to convert CO to CO_2. In our system we use a nickel-tube of 200 mm in length and with a 21 mm outer diameter (wall thickness 3 mm) which is provided with a resealable opening and a valve for easy gas handling. The temperature at the seal and valve during the pyrolysis doesn't exceed the permitted 400°C for the valve because of the relatively large dimensions of the tube. A disadvantage of the method is that the nickel-powder has to be carefully prepared: nickel-powder is sintered at 900°C to allow the subsequent separation of pieces of 4 g which are needed for one pyrolysis. The pieces are then reduced with H_2 at 400°C for 1 h and degassed under vacuum at 900°C. In a glove-box flooded with N_2 one nickel-piece is placed in the uppermost part of the nickel-tube and a cellulose sample in the lower part. Several nickel-tubes may be simultaneously processed during the following steps. Cellulose and nickel-powder are degassed under vacuum at 80°C and 350°C, respectively, in the nickel-tube which is horizontally positioned. The pyrolysis temperature of 1090°C is kept for 45 min. For the final CO/CO_2-conversion the tube is in vertical position at 350°C for 2 h. Impurities are pumped off, the CO_2 collected and measured by a mass spectrometer. The CO_2-yield is 95% ± 1% and the reproducibility in $\delta^{18}O$ for standard cellulose is 0.2‰ (the cause of the CO_2-

yield being $<100\%$ could be a partial oxidation of the nickel during the catalysis). The $\delta^{18}O$ values of cellulose are given relative to PDB and the $\delta^{18}O$ values of water relative to SMOW. The 2 standards are related by $\delta^{18}O_{PDB}=(\delta^{18}O_{SMOW}-41.45‰)/1.04145$ (Brenninkmeijer, 1983). $\delta^{13}C$ was also measured on the same cellulose samples as well as on an additional tree from the TWD site (Saurer et al., 1995).

4. Results and discussion

We first test the ability of the accepted models (leaf-water enrichment and constant biochemical fractionation) for explaining the measured $\delta^{18}O$ of cellulose when all rings and all trees are pooled. The mean values for the 3 sites in study are $-12.30‰\pm0.44‰$ (TWD), $-12.26‰\pm0.19‰$ (KRH) and $-12.47‰\pm0.13‰$ (KRD) (versus PDB). The mean $\delta^{18}O$ value for precipitation at the sampling site during the growing season is about $-7.5‰\pm0.5‰$ (versus SMOW, $-47.0‰$ versus PDB, respectively) and therefore the overall fractionation between cellulose in tree rings and precipitation is about $-12.3‰$ PDB $-(-47.0‰$ PDB$)=34.7‰$ ($\pm1‰$). A theoretical value can be calculated using eq. (1). We add the estimated leaf water enrichment of 14.9‰ for the site in this study (see Section 2) to the biochemical fractionation of 27‰ ($\pm3‰$) which yields $41.9‰\pm3‰$. This theoretical estimate is too high when compared with the measured value of $34.7‰\pm1‰$. Possible explanations for this discrepancy might be (i) that the diurnal isotope variation in the symplastic water pool is damped compared to that in the transpiration pool (Yakir et al., 1990) and (ii) that sucrose exported from the leaf exchanges oxygen atoms with stem water during synthesis of cellulose. Our results from the correlation analysis between $\delta^{18}O$ of cellulose and relative humidity (see later in this section) indicate that the influence of humidity is smaller than predicted by a factor of about 3. If we repeat the above calculation using 5‰ for the evaporative leaf water enrichment (i.e., $\frac{1}{3}$ of 14.9‰) we find an agreement with our measured mean $\delta^{18}O$ value of the investigated trees within the error limits. Such a calculation might give further insights, if the value for the biochemical fractionation for beech would be more precisely known.

The mean $\delta^{18}O$ values of the investigated period of the three trees from TWD are $-11.94‰$ (no. 1), $-12.17‰$ (no. 2) and $-12.79‰$ (no. 3), respectively. We calculated pairwise differences in the following way: ring 1934 of tree no. 2 minus ring 1934 of tree no. 3 etc. The mean differences are $0.23\pm0.30‰$ (no. 2–no. 1), $0.62\pm0.23‰$ (no. 3–no. 2) and $0.85\pm0.38‰$ (no. 3–no. 1) which are all significant at $p<0.01$ (significance level as determined from the t-test). These differences between the trees are rather difficult to interpret in terms of the theory outlined in Section 2, because the growth conditions are very similar for all trees. In particular, the $\delta^{18}O$ of the rain water is identical for the investigated trees which are standing close together. Possible causes might involve (i) differences in the maximal depth the roots are reaching and hence in the age distribution and the isotopic signature of the water taken up, (ii) different crown structure and exposition and consequently different transpiration and $\delta^{18}O$ of leaf water or (iii) different biochemical fractionations.

In the following, we will discuss the temporal patterns of the $\delta^{18}O$ curves. The coherence of the $\delta^{18}O$ signal between the three beech trees from TWD was determined by calculating the deviations from the mean of the respective series, referred to as $\delta^{18}O$ anomalies in the following. These anomalies are shown in Fig. 2 covering the time period from 1934 to 1987. A strong similarity between the $\delta^{18}O$ series of the trees is visible which suggests an external common cause. To give a measure for this similarity we calculated the variance common to the three $\delta^{18}O$ records according a procedure for analysis of variance (Fritts, 1976). The common variance turned out to be 61% and accordingly the noise in the data is 39%. For comparison, the much lower value of 33% calculated for the common variance for $\delta^{13}C$ anomalies among the same trees may be considered, and 46% for ring width anomalies (also 3-year-ring groups have been calculated, data from Saurer et al., 1995). Thus, $\delta^{18}O$ is affected relatively little by biologically induced noise. This can further be made evident by considering the standard deviations s_i of $\delta^{18}O$ of the three trees for every 3-year-ring group (for instance $s_{1935}=0.08‰$, see Fig. 2). The mean standard deviation (square root of $(1/n)$ Σ $(s_i)^2$) is 0.21‰ and is of the order of the magnitude of the $\delta^{18}O$ measurement precision (0.2‰). The intra-species variation among beech

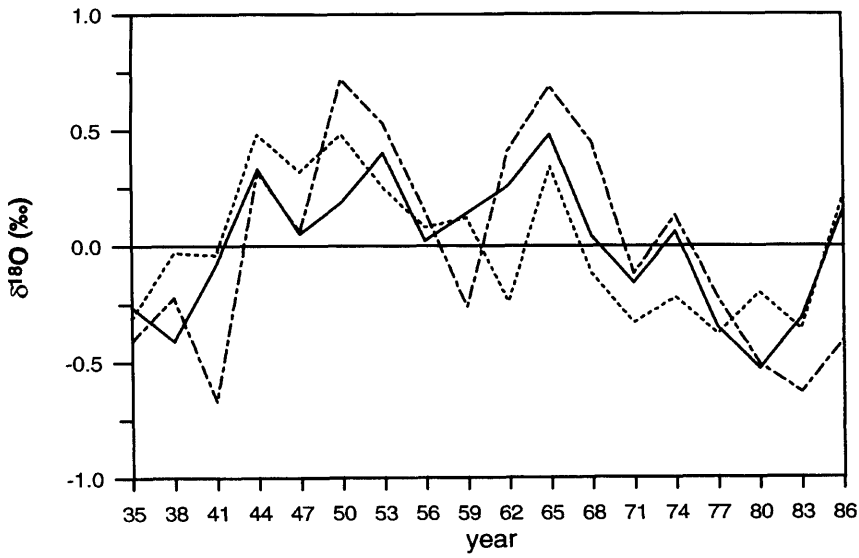

Fig. 2. $\delta^{18}O$ anomalies of the three beech trees from TWD, defined as deviations from the mean of the respective series. Each sample consists of three consecutive tree rings (*x*-axis notation corresponds to the central year).

trees at our site (TWD) is therefore relatively small for $\delta^{18}O$ and the average of the three $\delta^{18}O$ series may well represent a climatically meaningful signal. This will be discussed in the following.

We took monthly data of precipitation amount, temperature and relative humidity from the meteorological station of Bern for 1934 to 1987 (for TWD, 1965 to 1992 for KRD and KRH) and calculated means for periods of one to twelve months. For instance, the series with four months include the periods from January to April, from February to May and so on. The corresponding 3-year means (1-year, respectively) of these climatic data sets were then correlated with the mean curve of the tree ring $\delta^{18}O$ anomalies from TWD (KRH and KRD, respectively). The best correlation for the site TWD was obtained for the temperature of the 3-month-period from April to June ($r=0.70$, $p<0.01$), i.e., the temperature of a time interval of the growing period. The slope of the regression line is $+(0.33\pm0.09)$‰ per °C. It is apparent in Fig. 3that the long-term variations of tree ring $\delta^{18}O$ and of spring temperature are fairly similar. For instance, the decline from 1965 to about 1980 exists for both curves. On the other hand there are some discrepancies like the relatively low temperature in the 3-year-period from 1955 to 1957 which is not reflected in a lower $\delta^{18}O$ value. Relative humidity could interfere, but no significant improvement of the correlation coefficient could be achieved by multiple regression analysis with two or three climatic parameters, and further, no significant correlation with $\delta^{13}C$ and ring width was found.

We found different results for KRH and KRD compared to TWD, which is most probably due to the different time resolutions. The series of KRH and KRD are shorter and therefore not suited to detect long-term changes, whereas the 3-year-means of TWD strongly damp the short-term variations. The same analysis as above for the 2 other sites (KRH, KRD) shows no significant correlation with temperature but a good correlation with the relative humidity. The best correlation coefficient has been found for the comparison between $\delta^{18}O$ of KRH and the daytime (13 h) humidity from July. The correlations between the first differences (i.e. data for one year minus data for the former year), which better represent short-term variations, give somewhat better regressions as the direct correlations (Fig. 4). In both cases we found slopes of about -0.13‰/%, which is about one third of the modelled value in section 2.3 ($d\delta_l/dh=\varepsilon_k+\varepsilon_e\approx-0.36$‰/%). As pointed out before this could be caused by the inhomogeneity of the leaf water or by the exchange with stem

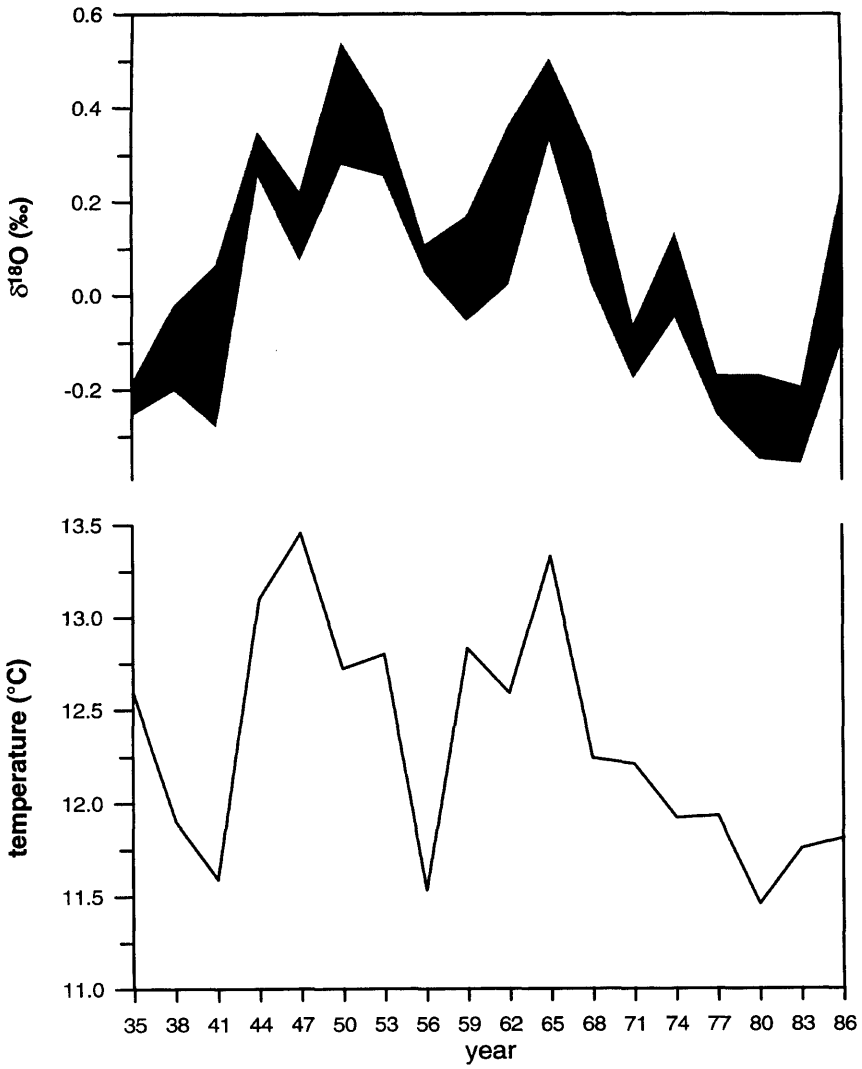

Fig. 3. Upper curve: mean $\delta^{18}O$-curve of the three trees from TWD (anomalies) with standard deviation (width of the band). Lower curve: mean temperature of the months April/May/June at the weather station of Bern.

water during ring formation. A calculation of a multiple regression with the months May to September leads to unrealistic results, some regression coefficients are even positive, which contradicts the theory in Section 2. Therefore we performed a multiple regression with $\delta^{18}O$ of precipitation and the humidity data to disentangle the influences of these 2 main parameters to the isotope composition of cellulose. However it also did not improve the result, but we found the cause for this unexpected problem: a significant correlation is present between the humidity and the $\delta^{18}O$ of precipitation for the months May to July.

To summarise, we have found a correlation between the long-term (>10 years) variations of the temperature from the growing season and the $\delta^{18}O$-values of the cellulose, as well as a correlation between short term variations of the relative humidity and $\delta^{18}O$ of the cellulose. This does not exclude, of course, that the relative humidity also

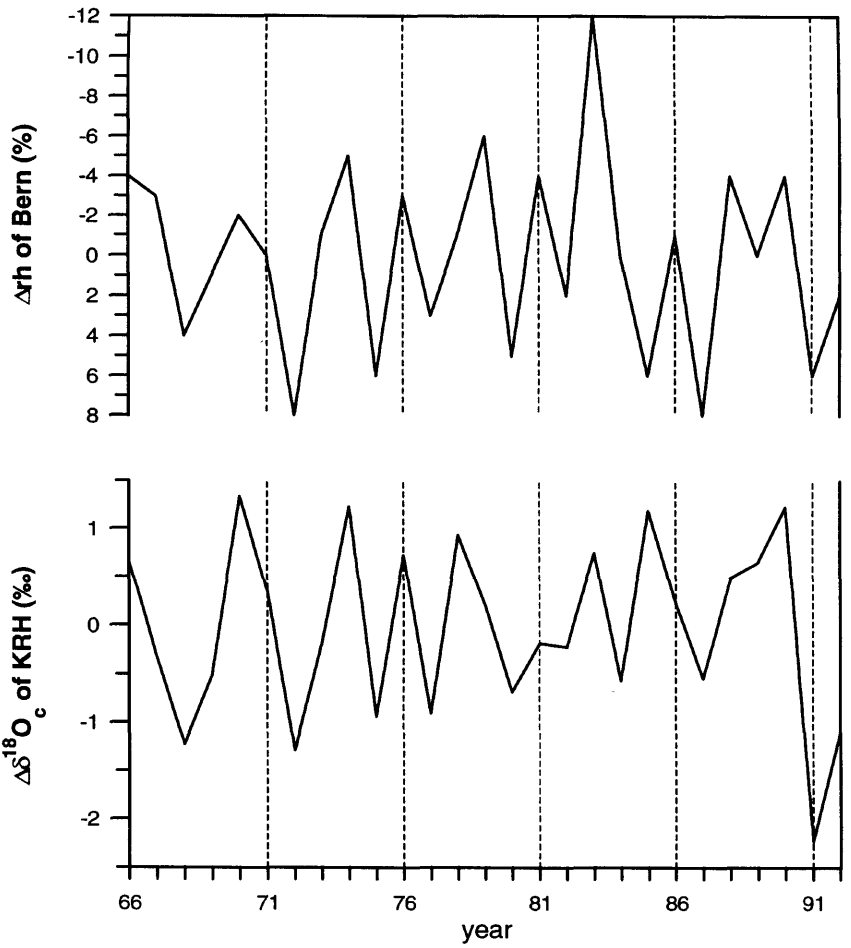

Fig. 4. First differences (i.e., data from one year minus data from the former year) of the relative humidity data at 1 p.m. in Bern (upper curve) and of the cellulose-$\delta^{18}O$ from KRH (lower curve). Note the inverse scale for the humidity data.

has an influence on the oxygen isotope composition on a larger time scale. Yet, this influence may be difficult to detect when several rings are lumped together (as was the case for TWD) because the width of variation of the signal is reduced.

The most likely explanation for the correlation between temperature and $\delta^{18}O$ in cellulose, as found above, is that the $\delta^{18}O$ in precipitation is recorded in the tree rings (because $\delta^{18}O$ in precipitation is influenced by temperature). $\delta^{18}O$ of soil water represents $\delta^{18}O$ of recent precipitation events or maybe of several months depending on the size of the soil water reservoir. Therefore, we compared our $\delta^{18}O$ data from cellulose with the averaged $\delta^{18}O$ from precipitation of 1- to 12-months periods. $\delta^{18}O$ from precipitation has been measured in Bern since 1971, so only the comparison with the data from KRH/KRD (1 year resolution) is performed, since the 3 year resolution for the TWD site corresponds only to 6 data points. The best correlation coefficients we find are $r=0.74$ (0.68, respectively) for the averaged precipitation data from May to August (June solely, respectively) and the cellulose data from KRH (KRD, respectively) (Fig. 5). Therefore, we conclude that $\delta^{18}O$ from summer precipitation is rather well recorded in $\delta^{18}O$ from cellulose from beech trees from dry and semi-dry sites.

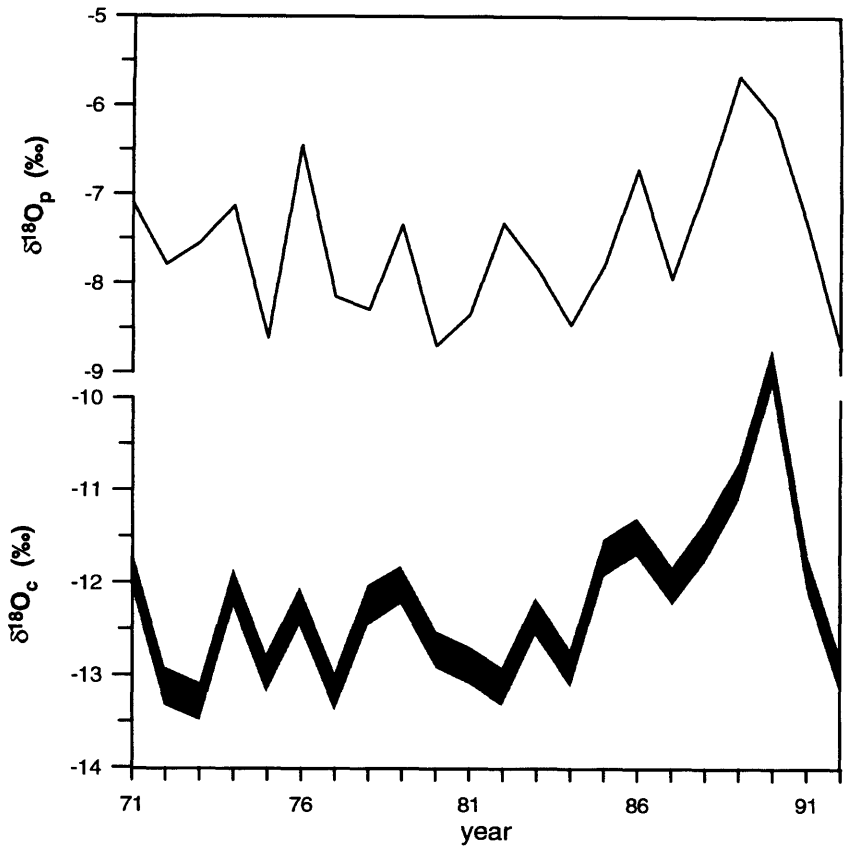

Fig. 5. Upper curve: mean $\delta^{18}O_p$ of precipitation from May to August at Bern. Lower curve: mean $\delta^{18}O_c$-curve of the cellulose of the three beech trees from KRH with measurement precision indicated as width of the band.

Surprisingly, the slopes of the linear regressions are 0.76 ± 0.15 ‰ (0.31 ± 0.08 ‰, respectively), i.e., significantly less than 1, which we would expect for an undisturbed signal transfer between precipitation and cellulose. A possible explanation is presented below.

The signal seen in the trees may not be simply the $\delta^{18}O$ signal of precipitation during the growing season, but could be weighted with the growth rate. Secondly, precipitation from earlier months and from the last year growing season may have an influence too, since a part of the cellulose could be produced with conserved material photosynthesised in the previous year. These facts can be taken into account as follows:

$$\delta_c = \sum_i W_i(\delta_{si} + \varepsilon_i), \qquad (2)$$

with:

δ_c: mean $\delta^{18}O$ of the cellulose from one year
δ_{si}: $\delta^{18}O$ from soil water during the month i
ε_i: fractionation factor between soil water and cellulose for month i (ε_i can vary in a wide range due to differences in climatic condition, like humidity, or in the biochemical fractionation and other unknown factors)
w_i: growth rate for month i;
and:

$$\delta_{si} = \sum_{j \le i} w'_j \delta_{pj}, \qquad (3)$$

where
δ_{pj}: $\delta^{18}O$ from precipitation from month j
w_j: weights to account for the mixing of older water in the soil.

If the soil is shallow enough that we can assume that no water can accumulate more than 1 month,

eq. (3) is trivial, and we can replace δ_{si} with δ_{pi} in the first equation. In this case, the slopes (w_i) of a linear regression analysis between δ_c and δ_{pi} for different months (i) would give us monthly means of the tree growing function during a year. The regression coefficients calculated in this way can only be determined with a large uncertainty due to an additional variability of δ_c mainly given by other influencing factors, such as the other δ_{pj} and ε_i. A multiple regression analysis will eliminate the accidental intra-correlations of the δ'_{pi}s, but it's necessary to determine which months' precipitation have an influence on δ_c, because the degree of freedom of the regression would be too low if all months are taken into consideration. The single correlations between δ_c and δ_p from different months (as well as an approximate knowledge of the growing period of beech trees in Switzerland) make clear that we can restrict the months for a multiple regression between May and September. Table 2and Fig. 6 show the results from this multiple regression.

The results from the multiple regression analysis are not significantly different from those from the

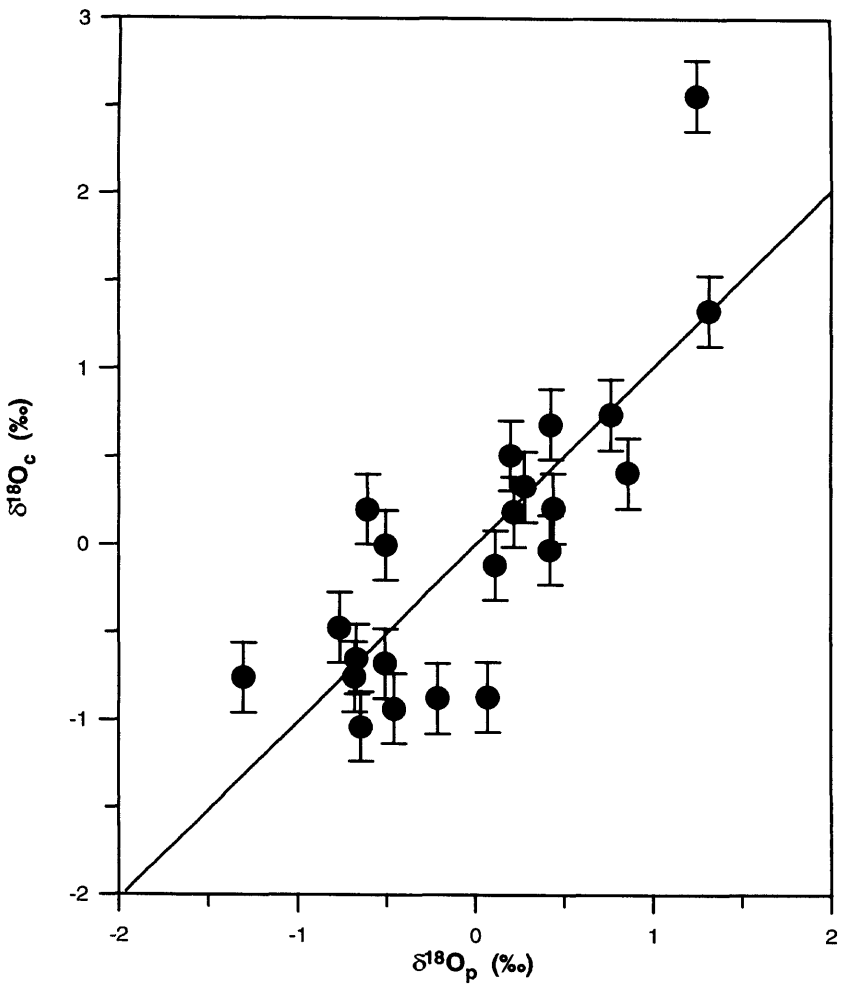

Fig. 6. $\delta^{18}O_c$ in tree rings from KRH versus $\delta^{18}O_p$ in precipitation (the different months are weighted as suggested in Table 2) (anomalies). Standard deviation (1σ) of the $\delta^{18}O$-measurement is indicated for $\delta^{18}O$ in tree rings. The solid line is the regression line.

single regression analysis, but they should be more reliable because the influence of the other months is taken into account by the calculation of the regression coefficient for each month. A comparison between the results for KRH and those for KRD indicates that the growing season is shorter at the drier location, which is consistent with an increased water stress.

5. Conclusions

We conclude from our results that for dry and semi-dry sites $\delta^{18}O$ of summer precipitation is the main influence on $\delta^{18}O$ in cellulose of beech. Accordingly, a temperature information is stored in $\delta^{18}O$ of tree rings. By comparison with climate data we found spring temperature to be most important for explaining the long term (> 10 years) variations of $\delta^{18}O$ in tree rings, with a temperature coefficient of 0.33‰ per °C. The relative humidity has more influence on the short term variations of $\delta^{18}O$ in tree rings, with a coefficient of −0.13‰/%, which indicates that the influence of the leaf water enrichment is probably damped by a factor of 3. Although the mean $\delta^{18}O$ value of cellulose in tree rings can roughly be explained with the available models, clearly more data about fundamental processes related to the biochemical isotope fractionation are needed for the quantitative interpretation of $\delta^{18}O$ in tree rings. Yet our results confirm the potential of $\delta^{18}O$ measurements in tree ring cellulose for climate reconstruction.

Table 2. *Slope coefficients for the multiple regression analysis between $\delta^{18}O$ of cellulose and $\delta^{18}O$ of precipitation of the months May to September*

	Slope coefficients (‰/‰)	
Month	KRH	KRD
May	0.12 ± 0.06	0.07 ± 0.05
June	0.24 ± 0.10	0.28 ± 0.09
July	0.31 ± 0.09	0.08 ± 0.08
August	0.20 ± 0.07	−0.03 ± 0.07
September	0.05 ± 0.09	−0.05 ± 0.08

The correlation coefficient is $r^2 = 0.66$ ($r = 0.81$) for KRH, $r^2 = 0.56$ ($r = 0.75$) for KRD.

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