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The climatic significance of $\delta^{13}C$ in subalpine spruces (Lötschental, Swiss Alps)

A case study with respect to altitude, exposure and soil moisture

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ABSTRACT

Few stable carbon isotope studies exist from high mountain regions which consider both climatological and ecological influences. This study is the first presenting $\delta^{13}C$ tree ring records from the subalpine vegetation belt of the European Alps (Lötschental, Switzerland). Pooled late wood samples from several trees (*Picea abies*) per site were used for studies of spatial site comparisons with respect to altitude (upper timberline/valley floor), exposure (N/S) and soil moisture (dry/moist). This investigation aims to assess how much these site conditions influence the climatic signal of $\delta^{13}C$. The $\delta^{13}C$ site records (1946–1995 AD, late wood cellulose) show a decreasing long-term trend reflecting the atmospheric $\delta^{13}C$ decrease during this period. We apply a new method for the correction of this anthropogenically induced CO_2 trend which considers changes in the atmospheric $\delta^{13}C$ source value and plant physiological reaction due to changes in the partial pressure of atmospheric CO_2. The $\delta^{13}C$ relationship to all investigated months' climatic parameters (temperature, precipitation, relative air humidity) was found to be very strong with highest correlations in July/August, the time of late wood development (maximum $r_T = 0.74$, $r_{PPT} = -0.75$, $r_{RH} = -0.79$). In contrast to tree ring width and density studies the observed temperature signal is not related to the altitude of the sample sites. The precipitation signal extracted from the carbon isotope time series increases with decreasing altitude and it remains strong at the upper timber line. This indicates the suitability of this isotope proxy for reconstruction of atmospheric humidity. Single extreme events (pointer years) provide stronger and more uniform reactions for dry–warm than for cool–humid summer conditions. Furthermore, the sites with moderately dry or moist soil conditions react more strongly and consistently than the extremely dry and moist sites at high elevation. Site exposure influences the absolute $\delta^{13}C$ values (S-exposure high versus N-exposure low), but does not necessarily obscure the climatic signal of the stable isotope records.

1. Introduction

Tree rings are terrestrial archives of high temporal resolution and thus of fundamental importance for palaeoclimate research. The stable isotope ratio $^{13}C/^{12}C$ of cellulose is widely accepted as a suitable tree ring proxy (Becker et al., 1991; Leavitt et al., 1995; Schleser, 1995). One important requirement for any high-quality isotopic reconstruction is the precise knowledge of site-related influences which could possibly

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mask the climatic signal. Recently some investigations have indeed shown a strong correlation between soil moisture and isotope ratios. Comparing carbon isotope series from wet and dry sites of the Swiss Central Plateau, Saurer et al. (1997) found a closer interrelation and better correlation with climatic parameters at dry sites than at wetter sites. Laboratory experiments on cloned spruce seedlings also show the influence of soil moisture with clear stress reactions (higher isotope values) under dry conditions (Schleser and Makkonen-Spiecker in Schleser, 1995).

Presently, little is known about the influence of altitude on the carbon isotope ratios in tree rings, least of all in conjunction with climate signals. Tree ring width and density are well known climate proxies at extreme sites with only one growth limiting factor, such as temperature at the upper timber line (LaMarche, 1974; Schweingruber, 1996; Esper, 2000). How far a similar relationship holds for the $^{13}C/^{12}C$ signal of tree rings is not yet clear. Whilst the majority of carbon isotope studies have dealt with sites from temperate or arid regions (Leavitt et al., 1995; Lipp et al., 1991; Robertson et al., 1997; Saurer et al., 1997) a few isotope investigations exist from sites at high altitudes near the upper timber line (Zimmermann, 1998). Of these studies, the primary aim was to develop long time series at a site rather than to compare ecologically different sites. In this context it is an open question to what extent and in what relation to each other variations in temperature and humidity determine the isotope fractionation in trees from sites of different altitude.

The aim of this study was (a) to compare $\delta^{13}C$ variations of several sites with different altitudes (upper timber line/valley ground), exposures (NNW/SSE) and soil moisture levels (moist/dry), (b) to extract climatic signals from the $\delta^{13}C$ site records and (c) to investigate how much these different site conditions modify the climatic information of the $\delta^{13}C$ variations. To meet these requirements six sites in the central alpine valley Lötschental, Switzerland, were chosen to examine the climatic relevance of interannual $^{13}C/^{12}C$ variations in late wood cellulose. Subalpine spruces (*Picea abies* [L.] Karst.) were selected being the dominant tree species of this region. The step from area to space was realised by pooling the tree ring late wood for each year of all chosen individuals and radii per site (Leavitt and Long, 1984; Borella et al., 1998; Anderson et al., 1998). The resulting mean site records spanning the period 1946–1995 AD were used to compare carbon isotope variations from the different sites experiencing various climatic and ecological conditions. Notably, this study represents the only $\delta^{13}C$ work from subalpine upper timber line sites in Europe discussing their climatic significance with respect to altitude, exposure and soil moisture.

2. Isotope terminology

Isotope compositions are expressed in terms of δ-values, which are given as differences from a standard in parts per thousand. With R_t and R_{ref} as the ratios of $^{13}CO_2/^{12}CO_2$ from combustion of the tree material and reference, respectively, the δ-value reads as:

$$\delta^{13}C_t = \frac{R_t - R_{ref}}{R_{ref}} \times 1000(‰). \tag{1}$$

The reference is a fossil belemnite from the Pee Dee Formation, upper Cretaceous of South Carolina, USA. It is denoted as PDB, with $R_{ref} = 0.01124$ (Craig, 1957). The isotope shift between air, R_a, and tree material R_t, which is expressed by the discrimination Δ, is given by $\Delta = (R_a - R_t)/R_t$. In the δ-notation Δ results in

$$\Delta = \frac{(\delta^{13}C_a - \delta^{13}C_t)}{(1 + 10^{-3}\delta^{13}C_t)} (‰) \tag{2a}$$

In most cases $10^{-3}\delta^{13}C \ll 1$. Therefore, to a good approximation Δ is given by

$$\Delta \cong \delta^{13}C_a - \delta^{13}C_t. \tag{2b}$$

This expression clearly indicates that isotope variations of $\delta^{13}C_t$ can only be interpreted if the base value, namely atmospheric $^{13}CO_2/^{12}CO_2$, i.e. $\delta^{13}C_a$, is known or is otherwise constant.

3. Material and methods

3.1. Site selection

The sites were selected in the central alpine valley Lötschental, Vallais, Switzerland (Fig. 1). Climatically this valley is situated at the transition from the oceanic temperate-moist regime of the northern Alps to the continental central alpine character of the Vallais, which is one of the driest

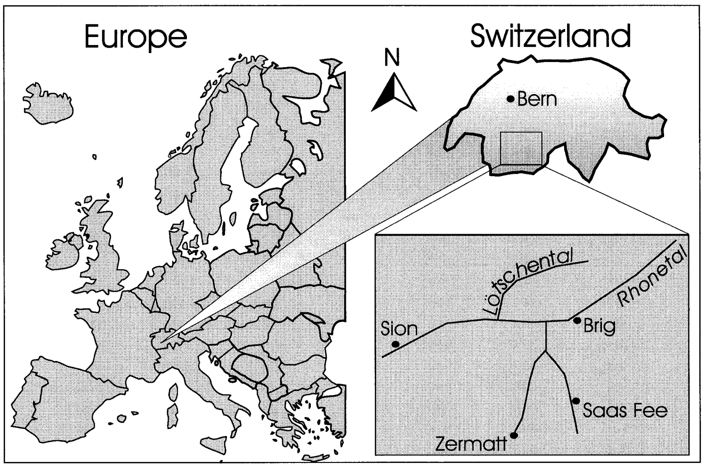

Fig. 1. Location of the Lötschental in the Swiss Alps.

regions in Switzerland (Beniston et al., 1994). The instrumental data used for calibration purposes are from the meteorological stations of Kippel and Ried (Lötschental, 1370 m and 1480 m asl) with a mean horizontal distance to the sites of 1–3 km. The temperature records of the Lötschental stations could be extended by the data base of Montana (about 30 km west of Lötschental, 1495 m asl). The mean annual precipitation amounts to 1010 mm (measured at Kippel) with a weak summer depression. The interannual differences in total precipitation are extremely high and may lead sporadically to a precipitation deficit during the vegetation period. The mean annual temperature is 5.7 °C (determined at Ried) with a strong increase from April to June and a maximum in July with 15.6 °C. At 1400 m asl the growth season generally ranges from the beginning of May until the middle of October (Ott, 1978).

The Lötschental extends from ENE to WSW, and the study area is located in the upper part where the bottom of the valley ranges between 1350 m asl and 2000 m asl. The slopes receive strongly differing levels of insolation in relation to their exposure. The SSE-exposed sunny slope has been largely cleared due to the favourable thermic conditions for agricultural land use and settlement. Closed natural forest stands are confined to regions above continuous settlements for protection against avalanches. Soils are not well developed and mostly classified as podzolic cambisols. The whole NNW-exposed shady slope is covered by forest as a result of lower human impact. Soil conditions are more humid and mostly classified as ferric podzols.

Because of its altitude the entire Lötschental is situated in the subalpine belt of spruce–larch forests (*Larici–Piceetum*; Ellenberg, 1996) which grow between 1400 and 2000 m asl. Between 1900 and 2000 m asl spruce is gradually being replaced by larch–stone pine societies (*Larici–Pineatum cembrae*; Ellenberg, 1996) forming the upper timber line, which is located presently at about 2200 m asl.

Fig. 2a shows the six selected test plots: four near the upper timberline at about 1900–1950 m asl (Nos. 1 and 2; Nos. 5 and 6) with one relatively dry and one relatively moist stand at each exposure and two near the valley ground at about 1400–1450 m asl (Nos. 3 and 4). Thus the vertical distance between low and high located sites is about 500 m. This should mean a temperature decrease of at least 3 °C, and thus a significantly shorter vegetation period at the upper timber line. The terms "moist" and "dry" refer mainly to the herb layer. Moist site conditions are expressed by the dominance of grasses such as *Calamagrostis villosa*, a dense dwarf shrub layer with *Vaccinium myrtillus* and some broad leaf herbs like *Adonostyles alliariae* (Nos. 2, 4 and 6). On dry sites the herb cover is mostly low or *Calamagrostis arundinacea* dominated (Nos. 1, 3 and 5). Broadleaf herbs are always absent. Therefore, this classification "moist" or "dry" is of relative character.

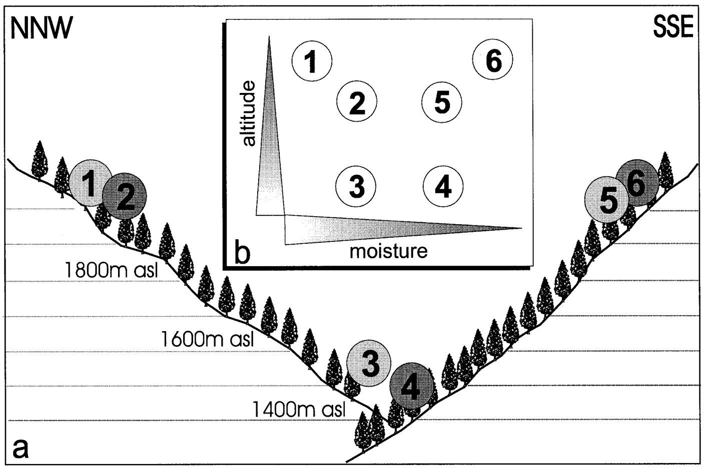

Fig. 2. (a) Location of the six test plots in the Lötschental and (b) their allocation in an ecogram. The light grey shaded sites Nos. 1, 3 and 5 have been classified as relatively dry, the dark grey shaded sites Nos. 2, 4 and 6 as relatively moist.

With these classifications a schematic ecogram may be depicted (Fig. 2b).

3.2. Sampling and laboratory analysis

We selected four to five co-dominant spruce trees (*Picea abies* [L.] Karst.) of similar age (more than 90 years old) per site which apparently had the same growth conditions and were least influenced by geomorphological processes. We cored each tree at about 1.5 m above ground from two opposite positions using an increment corer of 5 mm diameter (Suunto, Finland). In order to test the pooling method (see below) 10 mm diameter cores for single tree analysis were taken at one test site (No. 4). All cores were carefully cross-dated, and ring widths were measured on a semi-automated system (Aniol) with a resolution of 0.01 mm. Early and late wood were separated from all cores for 50 years (1946–1995 AD). The late wood of the different radii and trees was pooled year by year. The samples were ground with an *Ultrazentrifugalmuehle* (Retsch ZM1) using a mesh size of 0.5 mm to assure homogeneity. In particular, for measurements of small sub-samples a good homogeneity of the wooden material must be guaranteed because coarsely milled samples could lead to an overrepresentation of one tree ring (Borella et al., 1998). It was important to provide mean annual isotope values such that individual trees were equally represented. Therefore, the problems associated with a tree demonstrating temporarily rapid growth and an anomalously large late-wood contribution were addressed as follows: a pooled sample $\bar{\delta}_{\text{pool}}$ comprising n individual rings of several trees with isotope values $\delta_1, \delta_2, \delta_3 \ldots$ is given by

$$\bar{\delta}_{\text{pool}} = \left(\sum_{i=1}^{n} m_i \delta_i \right) \Big/ \sum_i m_i \qquad (3)$$

with m_i being the contribution of late wood mass from the ith tree ring. Ideally, the contribution of late wood is the same for all rings, and the expression reduces to the same $\bar{\delta}$ which applies for *individually* measured tree ring isotopes, $\bar{\delta}_{\text{ind}}$. One would, therefore, expect the same results independent of whether pooled samples are analysed or individually measured ring samples are averaged:

$$\bar{\delta}_{\text{ind}} = \left(\sum_{i=1}^{n} \delta_i \right) \Big/ n. \qquad (4)$$

Occasionally, however, one tree ring width of a sample set may deviate strongly from the others. In this case the corresponding tree ring would either be strongly over- or under-represented. Test measurements over a wide variety of rings and trees resulted in a maximum isotope difference between individuals of 3.1‰ (−24.9 and −21.8‰)

and an almost threefold broader ring width. The corresponding difference between pooled and individually measured samples of four trees, assuming for simplicity three trees to have the same values, would lead to:

$$\bar{\delta}_{\text{pool}} = \frac{-21.8‰ + \frac{1}{3} \times (-24.9‰) \times 3}{1 + \frac{1}{3} \times 3} = -23.3‰ \tag{5a}$$

$$\bar{\delta}_{\text{ind}} = \frac{-21.8‰ + 3 \times (-24.9‰)}{4} = -24.1‰ \tag{5b}$$

Deviations of a similar order could be produced if one ring width were just a third of the others. In single extreme years this would mean an average change of up to 0.8‰. In view of the strikingly reduced expenditure and the fact that such differences rarely exist, this discrepancy can be accepted for the purpose of climatic and ecological investigations.

From every wooden sample the α-cellulose was extracted to avoid isotope variations that are purely based on changes in the relative abundance of individual constituents of the wood, each having different isotope signatures. The extraction method is based on the treatment of wood with sodium hydroxide and sodium chlorite (Sohn and Reiff, 1942). Details of preparation follow Wiesberg (1974). Carbon isotopes were measured as CO_2 by combusting the cellulose samples in an elemental analyser interfaced to a dual-inlet isotope ratio mass spectrometer (Micromass-Optima). The precision is better than 0.1‰, a value which is much smaller than the isotope inhomogeneities of most samples.

3.3. Data processing

3.3.1. CO_2-correction. Since the beginning of the 19th century, the atmospheric carbon dioxide concentration has increased and the carbon isotope ratio ($\delta^{13}C_{atm}$) of atmospheric CO_2 has decreased (Stuiver, 1978). Both effects influence the δ^{13}C ratio of plants because the carbon isotope composition of photosynthetically produced organic matter is determined by the δ^{13}C value of the atmospheric CO_2 and the leaf intercellular to atmospheric CO_2 concentration (Farquhar et al., 1982). These effects mask the natural climatic signal to a greater or lesser degree. Therefore, they have to be eliminated for reasons of calibration when reconstructing past climatic conditions. Currently corrections are restricted to atmospheric δ^{13}C changes, mostly after Keeling et al. (1979, 1980), Friedli et al. (1986) and Francey et al. (1995). Some recent studies report suggestions for possible atmospheric $p(CO_2)$ corrections ranging from −0.02‰ to −0.007‰ per ppmv (Feng and Epstein, 1995; Kürschner, 1996). This range of discrimination increase is similar to our own results on greenhouse experiments (unpublished). By using these rates of discrimination changes (0.007‰/ppmv) and the changes of the source value, namely $\delta^{13}C_{atm}$ per year, a novel correction can be applied for the last 50 years. For the $\delta^{13}C_{cell}$ records this correction factor eliminates the declining trend observed for this period, and in most cases leads to better climate–tree ring correlations than the commonly applied correction (Treydte et al., in preparation).

3.3.2. Pointer year analysis. By focussing on selected single values of the δ^{13}C records, a classical dendrochronological approach is applied which is not common in isotope analysis (Schweingruber, 1996). The aim of this approach is to obtain more differentiated information about the climate–tree ring relationship by interpreting single extreme events based on the assumption that the climate–growth relationship is not static (Schweingruber et al., 1990). As a threshold for defining extreme events, the single standard deviation of a given period is used (Cropper, 1979; Hüsken, 1994; Hughes, 1982). Values crossing this threshold (calculated after standardisation) are defined as pointer values, keeping in mind that the pooling method already averages several single trees (for details see Schweingruber et al., 1990). These pointer values are compared with the meteorological data of the corresponding and the previous year, searching for similarities with weather conditions that could explain the reactions.

3.3.3. Time series analysis. Continuous time series analysis quantifies statistically climate–tree ring relationships by comparing the whole δ^{13}C records with the corresponding records of different climatic parameters. For optimal trend elimination various approaches are used (Cook and Kairiukstis, 1990; Fritts, 1976). By calculating the yearly residuals from the 5-year weighted running mean, we chose a very common and transparent method to enhance the short term signal while suppressing low frequencies both in the $\delta^{13}C$ records as well as in the meteorological data (Baillie and Pilcher, 1973; Fritts, 1976; Hüsken, 1994):

$$z_i = \frac{x_i - t_i}{t_i} \tag{6}$$

where z_i is the index value, x_i the raw value and t_i the trend value of the ith year.

An initial indication of a common external forcing identifiable in the isotope data is the similarity of the non-standardised $\delta^{13}C$ isotope records of different trees respectively sites. As a measure of this similarity the *Gleichlaeufigkeit* G_{xy} is used, which describes the comparable year-to-year trends between two records. It is defined as the percentage of cases of agreement (Schweingruber, 1988; Esper et al., 2001). By simple linear regressions the $\delta^{13}C$ data representing certain time intervals of the vegetation period were correlated with monthly data of mean temperature, precipitation sums and mean relative humidity, which were detrended by the same standardisation method. The short temperature series of the Lötschental and the longer series from Montana (1495 m asl) were selected for development of the temperature models. The precipitation model was constructed using the combined records from the Lötschental meteorological stations Kippel (1370 m asl) and Ried (1480 m asl). For the relative humidity model a limited record from Ried was available covering 22 years only (Neuwirth, 1998; Treydte, 1998).

4. Results

4.1. $\delta^{13}C_{cell}$ data of individual trees

The mean tree ring width of the four spruce trees at site No. 4 which have been chosen for single-tree isotope analysis ranges from 1.29 to 2.38 mm, and the mean G_{xy} is 64% (Fig. 3a). No tree shows a strikingly deviating ring width record which could be a hint to ecologically indicated different micro-site conditions of an individual.

The $\delta^{13}C$ short-term variations, i.e. the high-frequency domain of the individuals at test site No. 4, show a remarkable synchronicity over the whole period (Fig. 3b). This is expressed by G_{xy} values between 80% and 88% (21% substantially higher than G_{xy} of the ring width series). The mean $\delta^{13}C$ values of all trees, averaged over the whole period, are close together with tree I = −20.96‰, tree II = −22.39‰, tree III = −21.15‰ and tree IV = −21.67‰, with a maximum difference between tree I and tree II of only 1.43‰. In some years $\delta^{13}C$ differences of up to 3.5‰ occur (1951 AD), but altogether the similarity of the individuals is so high that all trees were considered when calculating a representative mean site record.

4.2. Mean site record versus pool records

The $\delta^{13}C$ mean site curve of site No. 4 calculated from the four individually analysed trees and two pool curves ($4_{fourfold}$ and $4_{eightfold}$) produced by mixing late wood samples of the same individuals are compared in Fig. 4. These pool records are characterised by different degrees of replication: $4_{fourfold}$ includes material from the four cores (one per tree), which have also been prepared for individual tree analysis, and $4_{eightfold}$ includes two cores per tree (opposite position). Comparing the curves, it follows that the calculated mean of the individual data sets and the two pool curves show almost identical levels and year-to-year trends. Only for the time period 1968–1972 AD does pool curve $4_{eightfold}$ diverge slightly from the other series by more negative isotope values [0.3‰ (1971) to 0.6‰ (1970)]. Nevertheless, the year-to-year trends remain the same. However, in this interval $4_{fourfold}$ complies with 4_{mean}, so it has to be assumed that the more negative values from the second cores per tree are due to within-tree variations of $\delta^{13}C$ most probably with regard to circumferential variations (Schleser, 1999). Marginal divergences between pool and mean values are attributed to insignificant inhomogeneities of the mixed samples. Nevertheless, the trends remain stable, so the validity of the pooling method is strongly confirmed and its application for the other sites is justified.

4.3. $\delta^{13}C$ site records

The annual late wood of four to five trees (two cores per tree) was pooled for each site. Fig. 5 represents the pool records of the six sites in the Lötschental, characterised by different altitudes,

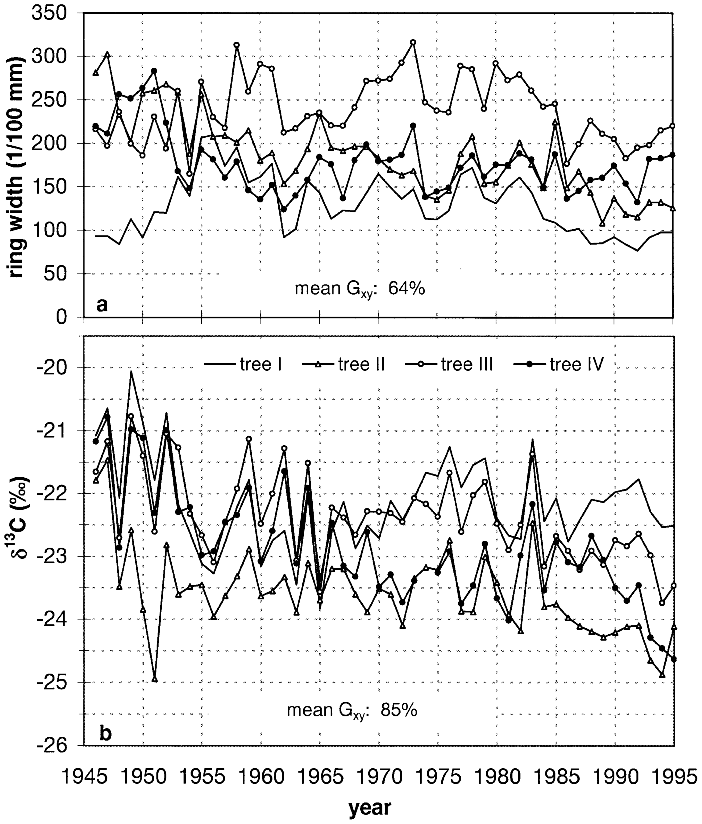

Fig. 3. Tree ring width and $\delta^{13}C$ late wood cellulose data of four individual spruce trees at site No. 4.

exposures and soil moisture levels. Again the similarity of the trends is apparent. In particular the years AD 1947–1951, 1962–1965 and 1982–1985 are striking because of the synchronous trends with large year-to-year variations. These analogous high-amplitude excursions apparently alternate in 9- to 12-year periods with less uniform and weaker, more negative periods. The pool curves of all sites differ in their average values by only 0.9‰ (site No. 1 = −22.3‰, No. 2 = −22.1‰, No. 3 = −22.0‰, No. 4 = −22.8‰, No. 5 = −22.6‰, No. 6 = −22.9‰). Nevertheless, the different means reflect a clear exposure phenomenon: site chronologies Nos. 1–3 on the SSE exposed sunny slope (mean −22.1‰) are more positive by 0.7‰ than those from Nos. 4–6 of the NNW exposed shady slope (mean −22.8‰).

A decreasing trend is observed in almost all of the pool site curves. At five out of six sites (except site No. 1) the $\delta^{13}C$ values become more negative by 0.9–1.1‰, reflecting the atmospheric $\delta^{13}C$ decrease of approximately 1‰ in the same period. With our deterministic approach *all* site records are detrended by the CO_2 correction. Thereafter, the majority of curves show a nearly constant level except site No. 1, which increases (Fig. 5).

For site comparisons of the $\delta^{13}C$ records the correlation coefficient r_{xy} and the *Gleichläufigkeit* G_{xy} are used. The r_{xy} values show strong interrelationships between all sites with a significance level of at least 95% (No. 1/No. 6) but mostly at the 99% level (Table 1). After standardisation and detrending the low-frequency signal, the r values further increase, mostly exceeding the 99.9% significance level. This supports the strong similarity of tree response to environmental signals at all sites, especially in the high frequency domain.

Further differentiated information can be gained from inter-site correlations (Fig. 6). The highest correlation can be found between sites Nos. 2 and

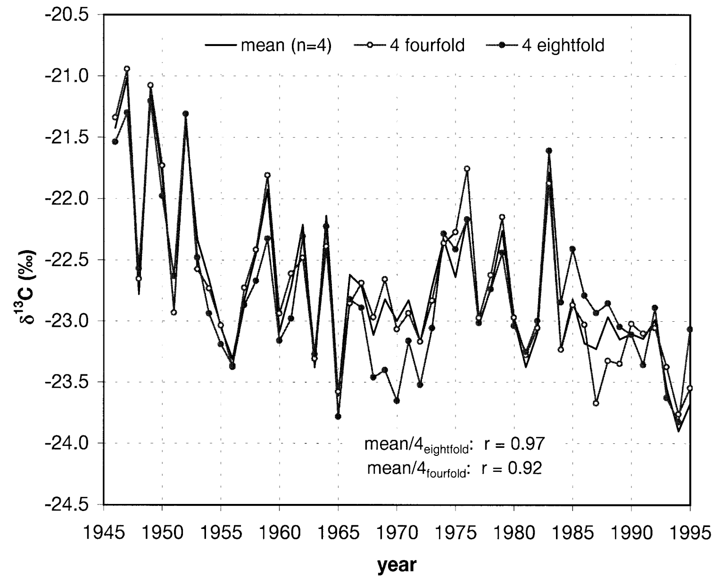

Fig. 4. δ^{13}C mean site record and pool records at site No. 4.

5 with minimal $r = 0.78$ and maximal $r = 0.83$. Site No. 1 (upper timber line, SSE exposed, dry) and site No. 6 (upper timber line, NNW exposed, moist) exhibit the lowest correlations. Projected on the ecogram in the Lötschental, the moderately dry and moist sites constitute a homogenous group, whereas the two extremes, namely high/dry and high/moist, are deviating.

4.4. Climatic signals in the $\delta^{13}C$ site records

4.4.1. Interpretation of single extreme years. The catalogue of all pointer values is given in Table 2. Positive pointer years (high δ^{13}C values, "+") dominate, negative pointer values ("−") are less frequent. Periods with frequently occurring extreme deviations, e.g. 1947–1952 AD or 1960–1964 AD, alternate with periods without any extreme events. This behaviour cannot clearly be associated with particular groups, e.g. upper timberline/valley floor, sunny/shady slope or dry/moist sites.

Four representative pointer years are shown in Fig. 7. Within the investigated time span of 50 years, the strongest positive reaction of all sites occurs for 1983 AD. For this year temperature as well as precipitation varied greatly during all seasons. The vegetation period begins rather humid and cool; especially striking is May followed by an unusually dry summer. Additionally July is very warm. At the end of the vegetation period the conditions become "normal" (long-term average). In 1949 AD again all sites show strong positive pointer values. After a dry–warm winter the vegetation period starts with very favourable conditions in April (moist and very warm). In contrast to 1983 AD, May 1949 AD is inconspicuous but the summer is comparable even though temperatures are high for *all* summer months and the precipitation is always below the average. Again July is noteworthy because of its dryness. The end of the vegetation period is very warm and dry. Both years have in common lower precipitation in summer and higher temperatures, especially in July when late wood development is most intense. The other positive pointer years basically confirm this influence of dry–warm summer conditions. Spring and autumn appear to modify the intensity of the reactions.

The negative pointer values are less uniformly spread and the reactions are weaker. 1948 AD shows the strongest reactions at all sites. Over the whole year there are favourable weather conditions. High precipitation sums in winter result in a thick snow cover followed by a dry but very warm spring with a large melt water supply. The beginning of the vegetation period was therefore

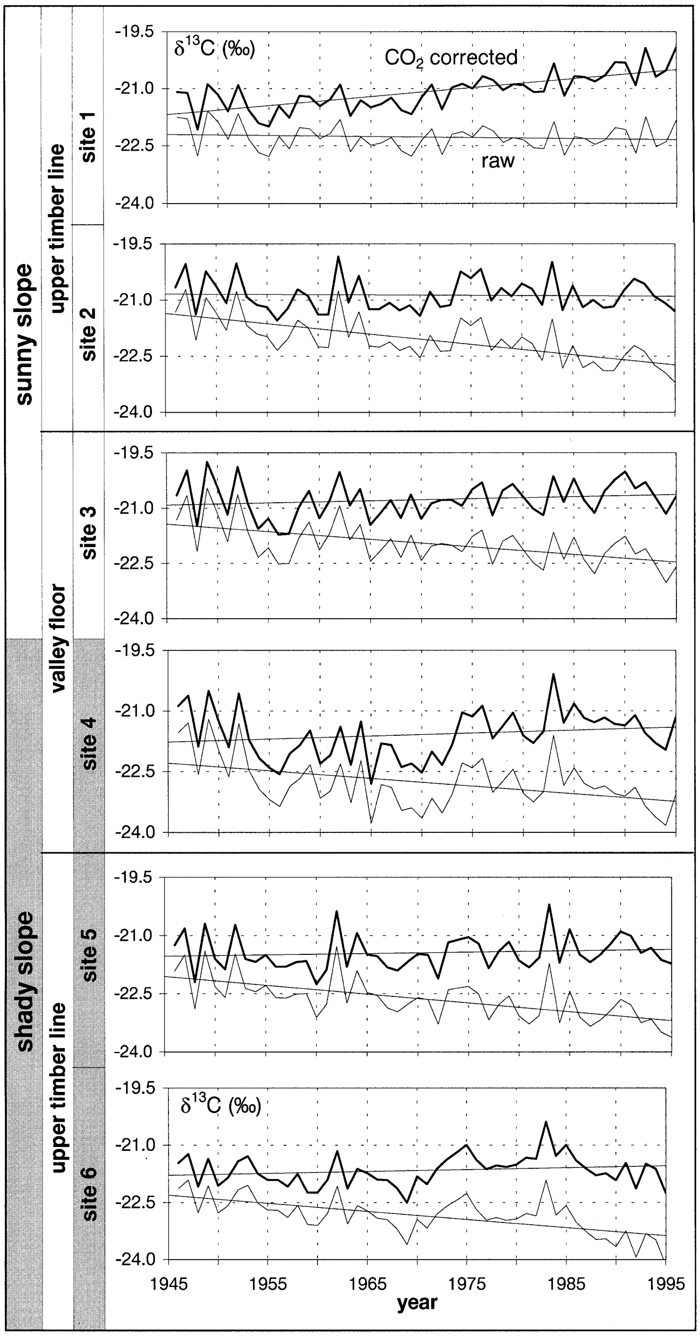

Fig. 5. $\delta^{13}C$ pool records of the six sites in the Lötschental, raw and CO_2-corrected.

Table 1. *Inter-site correlations* r_{xy} *and* Gleichlaeufigkeit G_{xy} *of the* $\delta^{13}C$ *site records – non-standardised and standardised*

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
No. 1	1	65	69	75	65	59
No. 2	0.38	1	71	77	71	69
No. 3	0.59	0.74	1	77	75	53
No. 4	0.59	0.73	0.77	1	77	59
No. 5	0.48	0.79	0.74	0.71	1	69
No. 6	0.31	0.6	0.39	0.62	0.67	1

G_{xy}

r_{xy} (non-standard records)

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
No. 1	1	65	69	75	65	59
No. 2	0.62	1	71	77	71	69
No. 3	0.67	0.78	1	77	75	53
No. 4	0.67	0.82	0.82	1	77	59
No. 5	0.67	0.83	0.79	0.81	1	69
No. 6	0.37	0.63	0.45	0.5	0.73	1

G_{xy}

r_{xy} (standard records)

$0.30 = t_{critical}$ for $p = 0.05$.
$0.39 = t_{critical}$ for $p = 0.01$.
$0.49 = t_{critical}$ for $p = 0.001$.

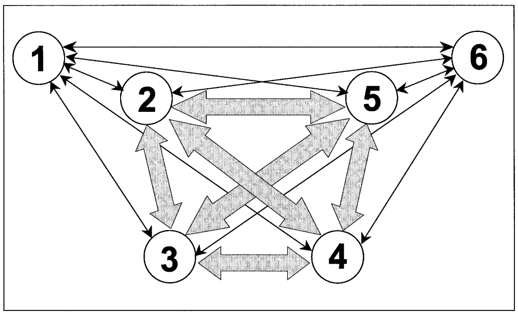

Fig. 6. Correlations between the standardised $\delta^{13}C$ site records. The thickness of the arrows represents the strength of the relationships based on r_{xy} and G_{xy}.

likely to have been early in the year. However, it has to be considered that at high altitudes even in extremely warm years tree growth only starts at the beginning of June (Müller, 1981). At the most extreme tree stands of the northern and subalpine timber lines the growth period is presumably not longer than a month (Schweingruber,

Table 2. *Catalogue of* $\delta^{13}C$ *pointer values in the Lötschental*

	Sunny slope				Shady slope	
	utl		vf		utl	
Years AD	1	2	3	4	5	6
1946						
1947		+	+	+	+	+
1948	−	−	−	−	−	−
1949	+	+	+	+	+	+
1950						
1951	−	−	−	−	−	
1952	+	+	+	+	+	
1953						
1954		−				
1955						
1956						
1957						
1958		+				
1959			+	+		
1960		−	−	−	−	−
1961		−				
1962	+	+	+	+	+	+
1963	−	−		−	−	−
1964		+	+	+		
1965			−	−		
1966						
1967						
1968						
1969						−
1970						
1971		+				
1972		−			−	
1973						
1974			+			
1975						+
1976						
1977						
1978		−	−	−	−	
1979						
1980						
1981						
1982		−	−			
1983	+	+	+	+	+	+
1984	−	−		−	−	−
1985			+		+	
1986						
1987			−			
1988						
1989						
1990						
1991	−					+
1992	+					−
1993	−					+
1994						
1995						

+, values crossing the single positive standard deviation; −, values crossing the single negative standard deviation. utl is the upper timber line, vf is the valley floor. Note that positive $\delta^{13}C$ pointer values indicate small stomata apertures and, therefore, must be interpreted differently from positive ring width pointer values.

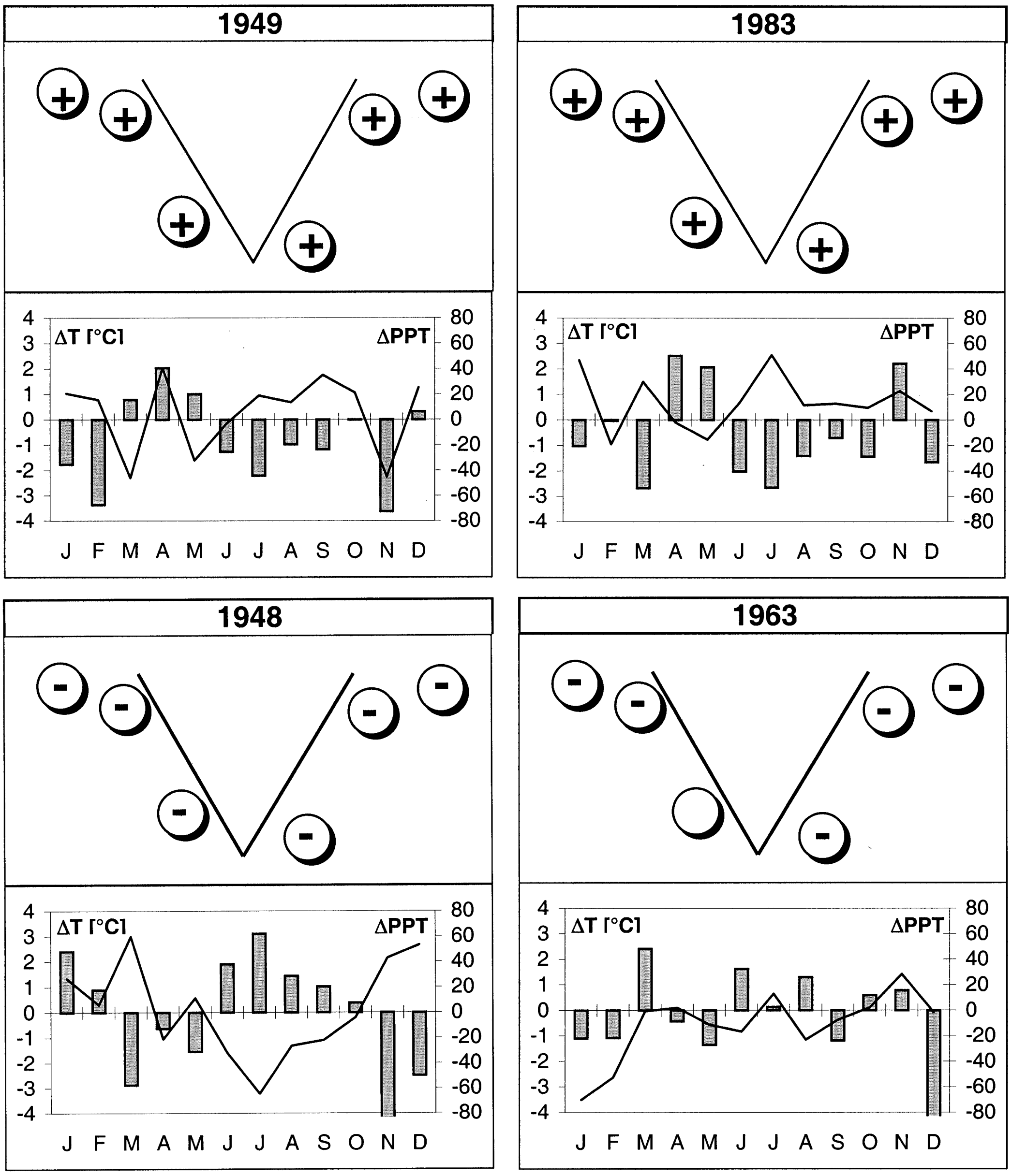

Fig. 7. Positive and negative $\delta^{13}C$ pointer years in the Lötschental.

1996). The whole summer (June–September) is characterised by high precipitation sums and low temperatures with their extremes in July. October is warm and dry. In 1963 the weather conditions of winter and spring differ from 1948 with a more "normal" beginning of the vegetation period. Again the summer is humid and cool, especially in June and August, even though with less intense deviations in July. The latter could be the reason for the less pronounced $\delta^{13}C$ reactions.

The pointer years apparently emphasise dry–warm weather conditions during the summer months through extreme isotope excursions. The influence of humid–cool weather conditions is a little more ambiguous. In both situations precipitation seems to play the dominant role. We could not find any connections between the $\delta^{13}C$ pointer values and the weather conditions of the previous year, presumably because late wood is formed from photosynthates fixed after this period.

4.4.2. Results of the time series analysis. The correlation coefficients of the CO_2 corrected isotope records based on 22 and 50 pairs of values are given in Fig. 8a,b. Each bar represents one site giving the relationship (r_{xy}-value) between temperature and site $\delta^{13}C$ in the corresponding month of the vegetation period. Correlation with the short 22-year records (1974–1995 AD) shows a rather irregular pattern with few values crossing the 95% significance level. Extending the time series to 50 years (1946–1995 AD) improves the relationship considerably. In the majority of cases positive relationships prevail with the 95% significance level easily reached in July and August. Therefore, the importance of an adequate database comprising enough values has emphatically to be stressed. After standardisation (taking residuals of the 5-year weighted running mean) the $\delta^{13}C$–climate relationship becomes even more pronounced (Fig. 8c). Additionally, the main tendencies of the raw records are further accentuated, with only positive responses during summer. The correlation of standardised values of July and August show a particularly striking increase and easily surpass the 99.9% level with highest values at site No. 4 in July ($r = 0.69$) and site No. 2 in August ($r = 0.71$). The valley sites Nos. 3 and 4 show the strongest dependency on temperature of July, while the upper timber line sites exhibit stronger signals for August. We assume the reason for the later response at the upper timber line is a product of delayed late wood formation.

The correlation coefficients between $\delta^{13}C$ and precipitation (based on 50-year standardised records) (Fig. 8d) appear approximately inverse to

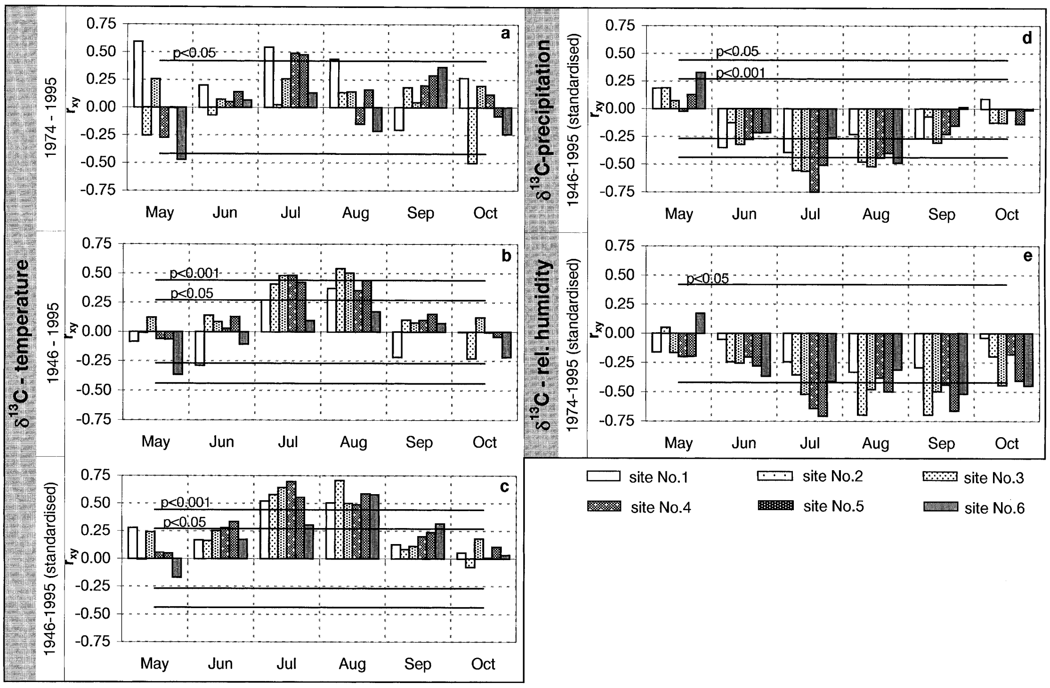

Fig. 8. Correlation between site $\delta^{13}C$ (CO_2 corrected) and (a–c) monthly mean temperature: (a) non-standardised records 1974–1995 AD, (b) non-standardised records 1946–1995 AD, (c) standardised records 1947–1995 AD, (d) monthly precipitation sums: standardised records 1946–1995 AD and (e) monthly mean relative humidity: standardised records 1974–1995 AD.

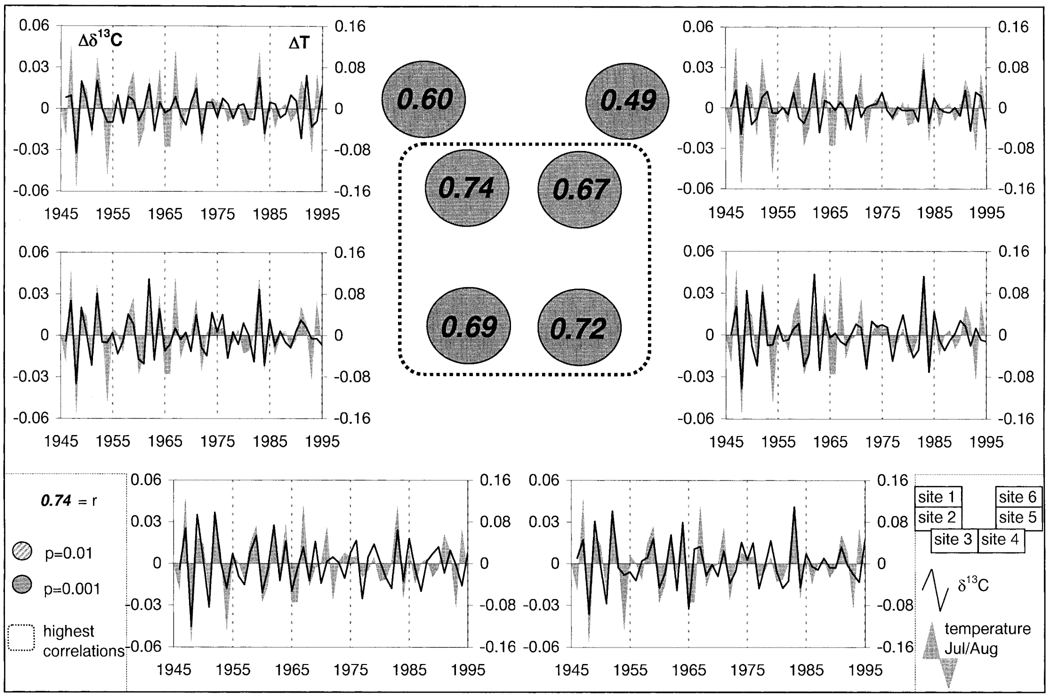

Fig. 9. Site-dependent relationships between $\delta^{13}C$ and temperature of July/August (1946–1995 AD). Δ describes the residuals from the 5-year weighted running mean, $\delta^{13}C$ is noted as per mill, *T* (temperature) as °C; note that the altitudinal differences between the high elevation sites are not as large as the figure implies (see Fig. 2)!

the $\delta^{13}C$ temperature relationships. Again the different sites react similarly. At the 95% significance level, the values are mostly negative, with July and August showing the strongest relationships (site No. 4: $r = -0.75$ in July). Note that at the upper timber line (predominately sites Nos. 2 and 5) the correlations are still significant during these months.

Relative humidity is believed to be the major climatic factor governing stomatal conductance and thus the isotope composition of leaf organic matter. Unfortunately, for the correlation calculations of this study only the short 22-year time series were available. Therefore, as discussed above, our results have to be treated somewhat more carefully because the calibration is less representative and perhaps should be used to indicate tendencies. Fig. 8e identifies July–September as the months being most significantly correlated. Although the correlations are lower than those with regard to temperature or precipitation (most probably because of the minor data set), the results suggest a strong influence of this meteorological parameter during the whole summer.

Next all possible combinations of months were correlated with the $\delta^{13}C$ records. The strongest climate–tree ring relationships emerge during the period from July to August, i.e. late summer. Figs. 9–11 show the site dependent relationships of $\delta^{13}C$ versus temperature, precipitation and relative humidity, expressed in terms of correlation coefficients and direct comparison of the curves.

With regard to temperature (Fig. 9) the correlation calculation with July and August leads to high positive values for all sites (above the 99.9% significance level). In contrast to results of tree ring widths and density studies the temperature signal as represented by $\delta^{13}C$ does not decrease with lower elevation. However, sites Nos. 1 and 6, at the outer extremes of the ecogram (Fig. 2b), show lower correlations than the moderate sites. Both curves are characterised by lower variations (and fewer pointer values) than the others, especially between the years 1946 AD and 1953 AD. At

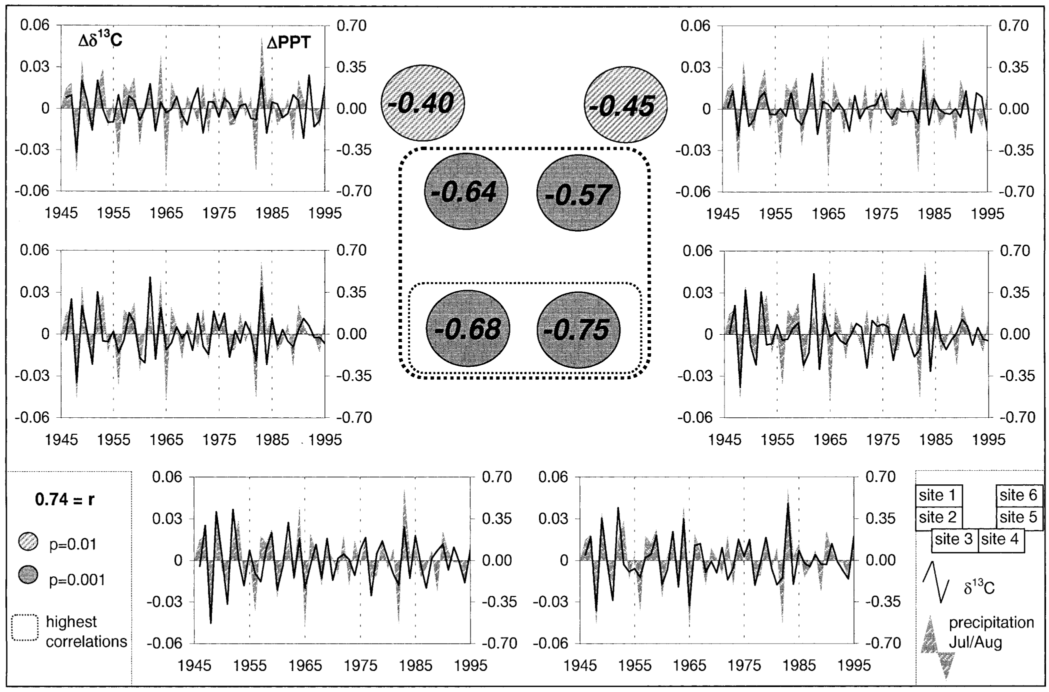

Fig. 10. Site-dependent relationships between $\delta^{13}C$ and precipitation of July/August (1946–1995 AD). Δ describes the residuals from the 5-year weighted running mean, $\delta^{13}C$ is noted as per mill, PPT (precipitation) as mm; note that the altitudinal differences between the high elevation sites are not as large as the figure implies (see Fig. 2)!

site No. 6 in particular, the strong temperature variations of this period are mirrored by the interval trends of the records but less by the amplitudes. Between the periods 1976–1982 AD and 1987–1995 AD both records do not reflect temperature variations.

The correlation coefficients between $\delta^{13}C$ and precipitation during July and August (Fig. 10) are likewise high, except for those of sites Nos. 1 and 6. The lower altitude sites Nos. 3 and 4 are better correlated than those at the upper timber line (average of Nos. 3 and 4 = −0.72 versus average of Nos. 2 and 5 = −0.60). Nevertheless, the still high $\delta^{13}C$–precipitation relationships at the upper timber line are striking. Comparing the reactions on temperature and precipitation, the upper timber line trees (except for the outside extremes) react 10% stronger on temperature than on precipitation. At the lower sites the relationships to temperature and precipitation become very similar (average of Nos. 3 and 4 for $r_T = 0.71$ and for $r_{PPT} = 0.72$).

For relative humidity from July to September (Fig. 11) a similar picture emerges with sites Nos. 1 and 6 showing the lowest values. The timber line sites Nos. 2 and 5 seem to react 14.5% stronger (absolute differences) than the lower altitude ones, with the highest values of all at site No. 5 (−0.79). We anticipate these correlations should become still better when extending the time series.

5. Discussion

This study presents the first $\delta^{13}C$ tree ring records from the European Alps (Lötschental, Vallais, Switzerland), namely the high altitude subalpine vegetation belt (1400–2000 m asl). Spatial site comparisons under climatological and ecological aspects were made possible through pooling of the material from several individuals per site.

The decreasing long-term trend in five of the

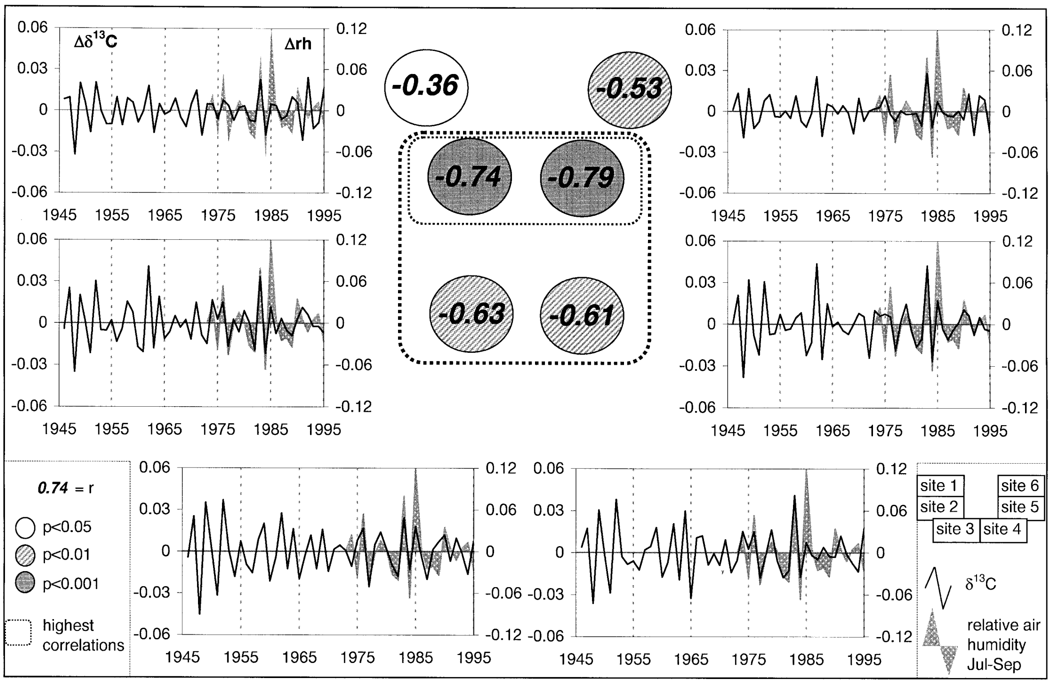

Fig. 11. Site-dependent relationships between $\delta^{13}C$ and relative humidity of July–September (1974–1995 AD). Δ describes the residuals from the 5-year weighted running mean, $\delta^{13}C$ is noted as per mill, rh (relative air humidity) as per cent; note that the altitudinal differences between the high elevation sites are not as large as the figure implies (see Fig. 2)!

six isotope raw records ($\Delta\delta = 0.9$–1.1‰) mirrors the rising atmospheric CO_2 concentration [$p_{atm}(CO_2)$] (290–360 ppmv during the last 100 years) and its associated decrease in the $\delta^{13}C$ values (Keeling et al., 1980; Keeling and Whorf, 1999). This anthropogenically induced atmospheric carbon isotope depletion has been observed in a number of study areas (Feng, 1999; Freyer and Belacy, 1983; Kitagawa and Matsumoto, 1993; Leavitt and Long, 1989; Leavitt and Lara, 1994; Lipp et al., 1991; Liu et al., 1996; Zimmermann, 1998). At other sites, however, no trend was observed, including several European locations (Anderson et al., 1998; Francey, 1981; Robertson et al., 1997; Stuiver, 1978; Tans and Mook, 1980). Anderson et al. (1998) explain the missing CO_2 trend in their records of relatively dense spruce stands with canopy effects, i.e. reassimilation of respired CO_2. This reasoning does not hold for our trees also selected from spruce stands with mean distances of the individuals to each other of less than 5 m. Therefore, a careful selection of trees should be the main criterion to obtain signals of the free atmosphere. Choosing dominant individuals with the major parts of the crown reaching the open atmosphere suppresses canopy effects. It should be mentioned that meagre soils emit less CO_2, thus providing less favourable conditions for masking the CO_2 trend (Schleser and Jayasekera, 1985). Additionally, we assume altitude to be a dominant factor for recording a CO_2 trend in the $\delta^{13}C$ values of tree rings, since with increasing altitude the atmospheric carbon dioxide supply decreases (Körner et al., 1991). Therefore, trees of high mountain regions react more sensitively to changes in the CO_2 concentration. Presently there exist few investigations from high regions which, however, confirm this hypothesis (Zimmermann, 1998).

The site-related $\delta^{13}C$–climate relationships of our records are high in relation to *all* investigated climatic parameters. The weather conditions during the summer months July, August and

September play the dominant role. Therefore, we propose that for climate reconstruction of summer conditions the analysis of late wood should be preferred (if the tree ring width permits separation of this fraction). In doing so adulteration of the signal through the remobilization of stored photosynthates (mostly starch) from previous years during early wood formation is minimised. This is confirmed by other investigations, e.g. by Lipp et al. (1991), based on late wood cellulose samples from the Black Forest (Germany) which revealed August as the main time interval for best climate–δ^{13}C correlations. In contrast to our results of the Swiss high mountain region, Saurer et al. (1997) working at the Swiss Central Plateau found best correlations of δ^{13}C with early summer months, i.e. May–July. In these cases, however, whole tree ring cellulose of 3-year segments from beech were used. In the same region (Swiss Central Plateau) Anderson et al. (1998) found June, July and August to have the highest degree of correlation with the isotopic records when studying spruce at an annual resolution.

The temperature signal in the carbon isotope records of the Lötschental seems to be independent of elevation. The high r values at the lower sites convincingly identify the potential for temperature reconstruction from late wood δ^{13}C values independent of altitude. The strong precipitation signal at the upper timber line is clearly in contrast to dendrochronological investigations on tree ring width or late wood density. According to current knowledge temperature is the dominant growth limiting factor at the upper timber line (Schweingruber, 1988; Meyer, 2000). Moisture-related conditions, strictly speaking the vapour pressure difference between atmosphere and the intercellular air spaces of leaves, directly determine the stomatal aperture and thus leaf internal CO_2 concentration c_i, which governs δ^{13}C (Farquhar et al., 1982). Consequently, relative humidity and partly precipitation should have a similar or even stronger influence on δ^{13}C than temperature (Anderson et al., 1998; Edwards et al., 2000; Saurer et al., 1997; Schleser, 1995; Schleser et al., 1999). Therefore, depending on the type of climate, especially during the summer season, correlations between δ^{13}C and temperature can be the result of intercorrelations between temperature and precipitation ($r = -0.5$ for the period July–August) or relative humidity, respectively. The somewhat lower correlation with precipitation than with temperature at the upper timber line could be caused by the high temporal and spatial variability of precipitation that is expressed insufficiently in monthly values. In a dry month, a few major precipitation events with rapid overhead flow could result in the same total monthly precipitation as a continuously moderate humid month. Owing to the increasing amount of precipitation with altitude the valley ground sites should experience drought stress earlier during the summer months than those at the timber line. The higher precipitation relationships at the lower sites thus indicate the stronger sensitivity on precipitation.

Regarding "dry" and "moist" sites it should be remembered that the entire central alpine Lötschental is characterised as a dry region. Therefore, the differentiation between sensitive dry versus less sensitive moist sites as found e.g. by Saurer et al. (1995; 1997) does not apply to our records. Considering the ecogram (Fig. 2b), the relatively moderate dry/moist sites with no extreme local ecological conditions react more uniformly and strongly than the outside located extremes high/dry (site No. 1) and high/moist (site No. 6). At site No. 1, southerly exposure combined with 45° slope leads to very high insolation during the growth period, resulting in shallow soils and extremely dry site conditions. The trees suffer permanent drought stress and keep their stomata aperture narrow throughout the whole summer. Therefore, the potential for varying the aperture in relation to weather conditions is limited. Only temperature has a marked influence. The extreme local site conditions are generally expressed by low annual variations in the records. It follows, therefore, that in contrast to classical dendroclimatological approaches, there is no necessity for δ^{13}C studies to go to the real *tree* line to get the best archives, especially if the climate of lower altitudes is to be reconstructed. Altogether moderate sites at the upper timber line *belt* may provide adequate material for carbon isotope investigations. At site No. 6 (high/moist) the poorer δ^{13}C–climate relationship is probably due to the most humid of all selected sites in the Lötschental. Because of relatively high soil moisture the trees here do not have to close their stomata as much as those at other sites even when lower atmospheric humidity conditions prevail. This results in not only the lowest average δ-values but also in lower annual amplitudes of the isotope records (Fig. 5).

The influence of exposure is mainly reflected by higher δ^{13}C values of the SSE-exposed sunny sites with more shallow soils. In order to maintain their water regime, the spruce trees which exhibit a shallow root system have to counterbalance enhanced transpiration by narrowing their stomata earlier than at NNW exposure sites. This results in lower discrimination rates and leads to more positive δ^{13}C values of the organic matter produced. However, exposure does not conspicuously influence the climatic signal of the carbon isotope records. With regard to the extreme sites, it should also be noted that the instrumental records used for correlations may not be fully representative of the exact conditions experienced by the trees.

Finally, the interpretation of single extreme events in the δ^{13}C records emphasises the significance of dry–warm summer conditions in relation to cool–humid ones and identifies the trees' response to such events as being both more sensitive and uniform at all sites. When reconstructing past environmental conditions from isotope records, the interpretation of positive anomalies provides more reliable information than the negative ones. Indeed lately it has been shown that positive and negative pointer years derived on the basis of tree ring widths alone also have to be interpreted in a different sense (Meyer, 2000).

6. Conclusion

δ^{13}C chronologies from subalpine spruces (latewood cellulose) in six ecologically different settings (elevation, exposure, soil moisture) of the central alpine valley Lötschental in the Swiss Alps were established. All records are strongly related to temperature, precipitation and relative air humidity of the summer months. The effects of site conditions on the climate sensitivity are less important for the isotopes as they are known for ring width and density. The anthropogenic effect of increasing atmospheric carbon dioxide concentration and its $\delta^{13}C_{CO_2}$ change has been identified in the records and corrected for with published data.

With these results we deem the application of δ^{13}C tree ring studies in high mountain areas (upper timber line) to be a powerful tool for climate reconstruction including humidity, which is presently restricted to temperature only. The combination of carbon isotopes, which record temperature and humidity information with other tree ring parameters such as oxygen and hydrogen isotopes, tree ring width and density should in future permit an integral approach for reconstructing past temperature and humidity variability. However, only the detailed knowledge of both exogenous and endogenous processes will ultimately lead to the development of the transfer functions required to account for the remaining unexplained statistical variance contained in tree ring records.

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