Influence of atmospheric circulation patterns on the oxygen isotope ratio of tree rings in the Alpine region

Matthias Saurer,1 Anne Kress,1,2 Markus Leuenberger,3,4 Katja T. Rinne,1 Kerstin S. Treydte,5 and Rolf T. W. Siegwolf1

Received 12 September 2011; revised 13 January 2012; accepted 13 January 2012; published 9 March 2012.

1The oxygen isotope ratio of precipitation and tree rings is a complex function of climate variables and atmospheric dynamics, which often makes the interpretation of δ18O for palaeoclimate research challenging. Here we analyzed monthly precipitation δ18O series for 1973–2004 and annually resolved tree ring δ18O chronologies for 1945–2004 for three sites in Switzerland: one north of the Alps, one at high-elevation within the Alps, and one south of the Alps. The goal of the study was to improve the understanding of the tree ring archive by a systematic analysis of nonlocal parameters related to atmospheric circulation, in particular, geopotential height field anomalies and the frequency of synoptic weather situations, in addition to the usual local climate parameters like temperature, sunshine duration, and relative humidity. We observed that on average high-pressure situations during summer were associated with relatively high δ18O and low-pressure situations were associated with relatively low δ18O, for both the isotope ratio in precipitation and tree rings. However, correlations to the frequency of weather types were not higher than simple correlations to local temperature. Accordingly, we constructed a combined index from temperature and air pressure that proved to be a good predictor of δ18O in precipitation and used this as the source water term in a tree ring isotope fractionation model. This enabled us to use the model beyond the period where isotope values for precipitation are available, opening new perspectives in the interpretation of long tree ring δ18O chronologies.


1. Introduction

[2] Oxygen isotope variations in cellulose of tree rings have been frequently studied with the goal to extract climate variables, but correlations with local variables such as temperature are often rather low [McCarroll and Loader, 2004; Treydte et al., 2007] or not very stable over time [Hilasvuori et al., 2009; Reynolds-Henne et al., 2007]. It has been known for a long time that δ18O in precipitation and subsequently in tree rings is not a simple measure of one single climate variable. The whole chain of fractionation processes, from the evaporation over the oceans to rain out from clouds over the continents, is important for understanding δ18O of precipitation. The Raleigh fractionation describing the removal of vapor from clouds is the main temperature-driven process, while the source region and the path of moisture governed by atmospheric circulation also play significant roles [Froehlich et al., 2008; Gat, 1980; Jouzel et al., 2003; Rozanski et al., 1992]. While the “amount effect” is significant mainly in the tropics, the oxygen isotope ratio of precipitation in most continental regions can be regarded as a mixed proxy for dynamics and temperature [Frankenberg et al., 2009], but disentangling these influences for palaeoclimate studies remains challenging [Masson-Delmotte et al., 2005].

[3] When interpreting tree ring oxygen isotope signals, it is not only the precipitation signal that needs to be considered, but also the 18O/16O isotope fractionation steps occurring within the tree, mainly leaf water enrichment and biochemical fractionations. This complicates the use of δ18O in tree rings for climate reconstruction further, although the different processes can be quantitatively assessed by isotope fractionation models [Roden et al., 2000; Sternberg, 2009]. Nevertheless, often high correlations between δ18O of summer precipitation and tree rings have been reported. This could be due to a dampening of the leaf water enrichment after the transport
of sucrose to the stem and isotopic re-exchange with xylem water during subsequent biochemical reactions [Stemberg, 2009]. Therefore the isotopic signal of soil water is clearly a dominating factor for \( ^{18}O \) in the tree rings [Edwards and Fritz, 1986; Robertson et al., 2001; Roden et al., 2000; Saurer et al., 2002]. Understanding the isotope signal in precipitation—not only in terms of temperature, but considering also atmospheric circulation—is crucial in extracting information from the isotope signal in tree rings.

[4] Isotopes in the hydrological cycle can be adequately modeled by general circulation models (GCMs) supplemented with an isotope module [Hoffmann et al., 2000; Lee et al., 2007]. Such models have been successfully applied in paleoclimate studies to interpret past oxygen isotope variability [Jouzel et al., 2000]. From a practical perspective, however, the use of GCM models in climate reconstruction studies has some limitations. In a usual calibration procedure, a proxy such as \( ^{18}O \) of tree rings is related to a measured (not modeled) climate variable for the time when instrumental data are available [Fritts, 1976]. This is probably the most reliable, statistically testable method for assessing the climatic content of a proxy and its stability over time. Such calibrations are easy to carry out with parameters abundantly available like temperature, but more difficult with variables related to atmospheric circulation. Accordingly, studies that interpret isotopic records in terms of changes of atmospheric circulation sometimes are descriptive rather than quantitative [Rozanski et al., 1997].

[5] One way to overcome such limitations could be the analysis of weather types. Atmospheric circulation patterns can be described by definition of large-scale weather types that are based on measurable quantities such as temperature, wind and pressure fields. For Europe, Hess and Brezowsky [1977] defined a classification scheme, while a similar system was introduced for the smaller domain of the Alps by Schüepp [1979] who suggested a classification of weather situations on a daily basis. The Alpine record, which starts in 1945 [Schüepp, 1979], was used in our analysis. While originally developed for weather forecasting, the Schüepp classification scheme has proven useful in climate change research [Bárdossy and Caspary, 1990]. It has been shown, for instance, that the observed increase of the winter North Atlantic Oscillation (NAO) index in recent decades, which is related to a shift of westerlies to more northern latitudes, results in an increase in the frequency of winter high-pressure conditions in Central Europe [Stefanicki et al., 1998].

[6] In this study, we analyzed time series of \( ^{18}O \) from precipitation and tree rings for three sites in Switzerland with respect to large-scale pressure fields (geopotential height fields) and the frequency of synoptic weather situations. We used monthly precipitation \( ^{18}O \) data for 1973–2004 and annually resolved tree ring \( ^{18}O \) data for 1945–2004 for three regions in Switzerland: one north of the Alps, one at high-elevation within the Alps, and one south of the Alps [Kress et al., 2009; Saurer et al., 2008]. The \( ^{18}O \) values in the tree rings were additionally compared to an isotope fractionation model with \( ^{18}O \) of precipitation as the input variable. We hypothesized that large-scale atmospheric circulation features would correlate better with \( ^{18}O \) in tree rings than local climate variables.

[7] With this set-up our goal was (1) to determine to what degree atmospheric circulation patterns (geopotential height fields) govern the oxygen isotope variations of tree rings in the Alpine region, (2) to determine whether the frequency of synoptic weather situations according to Schüepp [1979] is a useful parameter for interpreting the oxygen isotope variability in precipitation and tree rings, and (3) to improve an isotope fractionation model of \( ^{18}O \) in tree rings by including information on atmospheric circulation.

2. Materials and Methods

2.1. Tree Ring Isotope Chronologies

[8] The tree ring isotope chronologies are all from sites in Switzerland, Central Europe. The “North” chronology (1945–1997) refers to a combined chronology with annual resolution from north of the Alps in the Swiss Central Plateau (1100–1200 m a.s.l.). It is the average of three chronologies, described in detail by Saurer et al. [2008], comprising the species Abies alba, Picea abies and Fagus sylvatica. This analysis showed that averaging the chronologies results in an improved climate signal. The climate for the northern sites of the Alps is temperate-moist with an annual precipitation sum of about 1100 mm and an annual average temperature of about 9°C. The “Alpine” chronology (1945–2004) is based on a high-altitude (1800–2000 m a.s.l.) Larix decidua data set, which contains a very strong climate signal in both carbon and oxygen isotopes [Kress et al., 2009]. The climate at this altitude is characterized by a high annual precipitation sum (>1500 mm) and low annual average temperature (ca. 0°C). The “South” chronology (1945–2001) is built as an average of a Quercus petraea and a Pinus sylvestris series. These sites located south of the Alps (900–1400 m a.s.l.) were studied in detail by Reynolds-Hemme et al. [2007]. The climate in southern Switzerland has a moderate Mediterranean influence with higher annual temperature (12°C) than north of the Alps. The yearly precipitation sums are in the same range (1150 mm), but with differing seasonal distribution (summer maximum in the north versus winter/spring maximum in the south). Because the three chronologies differ in length, some statistical analyses were conducted for the common period 1945–1997 only. Whole-wood was analyzed for the North chronology, while cellulose was extracted for the Alpine and South chronologies. Whole-wood and cellulose isotope chronologies were shown to contain similar climatic information [Borella et al., 1999; Saurer et al., 2008] and were compared to each other in this study after normalization of \( ^{18}O \) to a mean of zero. Cellulose extraction and isotope analysis were done according to standard protocols [Boettger et al., 2007]. The \( ^{18}O \) values were determined by pyrolysis and subsequent isotope-ratio mass spectrometry and are given as per mil deviations from VSMOW with an analytical uncertainty of less than 0.3%.

2.2. Isotope Data of Precipitation

[9] Monthly \( ^{18}O \) of precipitation was obtained from the Global Network of Isotopes in Precipitation (GNIP) for 1973 to 1993 and from the Federal Office of Water and Geology (FOWG) for 1994 to 2004 for the stations Bern (541 m a.s.l.), Grimsel (1950 m a.s.l.) and Locarno (379 m a.s.l.) (Figure 1). All stations have been in operation since 1973 and provide unique long records. The data were measured by the Climate and Environmental Physics Department of the Physics
2.3. Climate Data

[10] The 0.5° × 0.5° monthly gridded meteorological data set CRU TS 3.0 [Mitchell and Jones, 2005] was used for the investigated period of 1945–2004, where grid cells covered both the tree ring and GNIP sites. Air pressure and sunshine duration data and the occurrence of the weather types according to Schüepp’s classification were provided by the Federal Office of Meteorology and Climatology, MeteoSwiss. In Schüepp’s classification scheme a region of 444 km in diameter in the central part of the Alps is considered. The relevant parameters for determining such a synoptic weather type are the distribution of surface pressure, the geostrophic wind direction which follows from the surface pressure distribution, the upper-level wind speed and direction and the height of the 500 hPa surface. Schüepp’s weather types are determined on the basis of observed data by strict rules, but manually, and therefore the classification is called semi-objective (as explained in detail by Wanner et al. [1998]). The synoptic weather types have been classified by the MeteoSwiss back to January 1st 1945 and were continuously provided until December 31, 2010. This classification has recently been replaced by a fully automatic circulation type classification [Schiemann and Frei, 2010]. The Schüepp system is based on 40 Alpine synoptic weather conditions, which can be divided into three main classes: the convective, the advective and the mixed weather type. The convective weather type consists of three subclasses describing high, flat and low 500 hPa pressure distribution, corresponding to anticyclonic, indifferent and cyclonic conditions. The advective weather type consists of four sub-classes describing westerly, northerly, southerly and easterly winds (at 500 hPa). In this study, we considered 6 of the 7 subclasses (all except the indifferent subclass). The classification is semi-quantitative, but the data set was checked carefully for heterogeneities [Wanner et al., 1998]. Pressure fields over Europe have been investigated with the NOAA/NCEP reanalysis data based on the reference period 1971–2000 [Kalnay et al., 1996]. The statistical significance of correlations between climate parameters and δ18O was assessed by the F test. For the correlation analysis with tree ring isotope chronologies, a reduced degree of freedom due to lag-1 autocorrelation was applied [Saurer et al., 2008].

2.4. Isotope Fractionation Model

[11] The major input signal for the isotope ratio in tree rings, δ18O_{TR}, is the δ18O of source or soil water, δ18O_S, which is derived from δ18O of precipitation (modified by averaging over several rain events and by a possible lag in the soil, depending on rooting depth). The water taken up by the roots gets isotopically enriched in the leaves of the trees (δ18O_L), thus δ18O_L > δ18O_S. The enrichment is often described with the “big-Delta”:

\[ \Delta^{18}O_L = \delta^{18}O_L - \delta^{18}O_S \] (1)

Models of different complexity have been developed to describe Δ^{18}O_L as a function of environmental parameters (e.g., relative humidity, temperature) and leaf physiological properties (e.g., transpiration rate, Péclet number) [Farquhar and Lloyd, 1993]. For tree ring research with long chronologies, based on averages of several trees and several species and with limited knowledge about past environmental conditions, the most simple model by Dongmann et al. [1974] might be appropriate:

\[ \Delta^{18}O_L = \varepsilon_k + \varepsilon_v + (\delta^{18}O_v - \delta^{18}O_S - \varepsilon_k)\frac{e_v}{e_l} \] (2)

where ε_k is the kinetic fractionation due to diffusion of vapor into unsaturated air, ε_v is the equilibrium fractionation due to the change of phase from liquid water to vapor, δ^{18}O_S is the isotopic composition of atmospheric water vapor, and ε_v/ε_l the ratio of internal to external water vapor pressures which can often be approximated by the relative humidity (assuming that leaf temperature equals that of air). The isotopic composition in the tree ring cellulose, δ^{18}O_{TR}, is related to that of leaf water by the following expression [Barbour, 2007; Roden et al., 2000]:

\[ \Delta^{18}O_{TR} = \delta^{18}O_{TR} - \delta^{18}O_S = \Delta^{18}O_L(1 - p_{ex}p_x) + \varepsilon \] (3)

where p_{ex} is the proportion of exchangeable oxygen during cellulose synthesis (atoms that become part of a carbonyl group and exchange with local water in the tree trunk), p_x the proportion of source (soil) water in the developing cell in the trunk, and ε the “biological fractionation,” i.e., the fractionation factor between carbonyl oxygen and water (27‰). The oxygen isotope exchange during cellulose...
formation results in a partial removal of the leaf enrichment signal. Assuming $p_{ex_p}$ in the range 0.3–0.5 [Barbour, 2007], then the leaf water enrichment is reduced by 30–50%, whereby the variability in $\delta^{18}O$ of the source water becomes relatively more important for determining the tree ring isotopic composition. By defining a dampening factor

$$f = (1 - p_{ex_p})$$

we obtain $\Delta^{18}O_{TR} = f\Delta^{18}O_L + \epsilon$. Using $\Delta^{18}O_{TR} = \delta^{18}O_{TR} - \delta^{18}O_S$ and inserting equation (2) on the right-hand side, we obtain

$$\delta^{18}O_{TR} = \delta^{18}O_S + f(\epsilon_k + \epsilon_v + (\delta^{18}O_v - \delta^{18}O_S - \epsilon_k)\epsilon_o/\epsilon_v) + \epsilon,$$

an equation originally presented by Saurer et al. [1997], which is equivalent to equation (3).

## 3. Results

### 3.1. The $\delta^{18}O$ of Precipitation and Weather Patterns

The oxygen isotope values of precipitation for Bern, Grimsel and Locarno show the usual large seasonal cycle with lowest values in winter and highest values in summer months (see Figure S1 in the auxiliary material). In Figure 2, we show the average May to August values in view of the later comparison with tree ring values that reflect mainly uptake of summer precipitation. The year-to-year variability (range) of these summer values is between 1 and 4%. In comparison, the seasonal amplitude range is much larger. The average absolute summer values differ between the three locations, reflecting altitude, circulation and temperature differences between the sites. The average summer temperature is highest in Locarno (19.4°C), the site south of the Alps, intermediate in Bern (16.0°C), the site north of the Alps, and lowest at Grimsel (6.4°C), the high-elevation site. The maximum $\delta^{18}O$ is observed in the dry-warm summer 2003 for all three sites. The inter-annual variability of the summer averages is very similar between Bern and Grimsel ($r = 0.85$; $p < 0.01$) and Grimsel and Locarno ($r = 0.84$; $p < 0.01$), and slightly more different between the most distant locations Bern and Locarno ($r = 0.74$; $p < 0.01$), which are separated by the main chain of the Alps.

May–August pressure patterns over Europe are related to $\delta^{18}O$ of precipitation for the investigated period 1973–2004 as shown in Figure 3. For this analysis, $\delta^{18}O$ of May–August precipitation was averaged over the three sites because of their high similarity, anomalies from the mean of the whole period were calculated and then the years were grouped into 4 classes: (1) years with very high $\delta^{18}O$ of precipitation ($>1\%$) consisting of the years 1989, 1990, 1993, 1994, 1999, 2000, 2001, 2003 (n = 8); (2) years with high $\delta^{18}O$ ($0\% < \delta^{18}O < 1\%$) including 1974, 1976, 1979, 1983, 1986, 1988, 1998 (n = 7); (3) years with low $\delta^{18}O$ ($-1\% < \delta^{18}O < 0\%$) including 1973, 1977, 1982, 1985, 1987, 1991, 1995, 1996, 1997, 2004 (n = 10); and (4) years with very low $\delta^{18}O$ ($<-1\%$) including 1975, 1978, 1980, 1981, 1984, 1992, 2002 (n = 7). For each class, the average geopotential height field anomaly at 500 mbar was calculated with a tool provided by the NOAA/NCEP Reanalysis website (http://www.esrl.noaa.gov/psd/) representing the summer pressure anomaly over Europe when a specific group of years is combined (Figure 3). There is a clear relationship between pressure patterns and $\delta^{18}O$ of precipitation, when the classes of years with large deviations of $\delta^{18}O$ are considered (either >1% or <1%; Figures 3a and 3d). In contrast, grouping of years with only moderately positive or negative $\delta^{18}O$ are more difficult to interpret, because the pressure anomalies are not centered over Central Europe and the pressure gradients are small. The same graphs as in Figure 3 were also done for all single years instead of classes of years, but then the relationship between pressure maps and corresponding $\delta^{18}O$ is much more ambiguous.

![Figure 2](image1.png)  
**Figure 2.** May to August averages of $\delta^{18}O$ of precipitation for the site north of the Alps (Bern), within the Alps (Grimsel), and south of the Alps (Locarno).

![Figure 3](image2.png)  
**Figure 3.** Composite anomalies of geopotential height fields at 500 mbar during May–August for groups of years with different $\delta^{18}O$ of precipitation: (a) very high ($>1\%$), (b) high (0%–1%), (c) low (−1%–0%), and (d) very low (<1%). Data covering the years 1973–2004 were used. The color code indicates the geopotential height field anomaly in meters.

---

**Auxiliary materials are available in the HTML. doi:10.1029/2011JD016861.**
While for extreme cases like 2003, it holds that relatively high $\delta^{18}O$ is accompanied by a high-pressure situation, there are also quite a number of years where this is not the case.

In a quantitative time series analysis, we investigated the relationship between the frequency of weather patterns according to Schüepp and the $\delta^{18}O$ of precipitation (frequency = number of days per calendar month). This analysis was done for monthly values of precipitation and monthly frequencies of six weather types (Figure 4). As an example, one series consisted of the frequency of cyclonic conditions in January 1973, January 1974, ..., January 2004 ($n = 32$). We compared the six weather types with 14 time series of $\delta^{18}O$, consisting of 12 individual months and two different summer averages, i.e., July–August (= JA) and May–August (MJJA), resulting in a total of 84 investigated relationships for each of the three locations (Bern, Grimsel, and Locarno). As the results did not differ strongly between the sites, only results for Bern are shown in Figure 4. The relationship between weather types and $\delta^{18}O$ of precipitation varied considerably between months. The influence of anticyclonic and cyclonic conditions was relatively consistent compared to the other weather types, but was still only highly significant ($p < 0.01$) for a few months, including the MJJA-average. For the advective weather types, significant relationships at $p < 0.01$ were found for westerlies in May, northerlies and southerlies in November and for easterlies in August.

### 3.2. The $\delta^{18}O$ of Tree Rings and Weather Patterns

The tree ring $\delta^{18}O$ anomalies for the three investigated chronologies are shown in Figure 5. Because one chronology (North) is based on whole-wood and the other two on cellulose, anomalies were used to facilitate comparison. The variability, expressed as standard deviation, was higher for the Alpine (0.95‰) than for the North (0.65‰) and South (0.67‰) chronologies. The North and the Alpine chronology show good correspondence to each other ($r = 0.66$ for the common period 1945–1997, $p < 0.01$), while the South chronology has a weaker correlation to the other.

![Figure 4. Correlation coefficients $r$ between monthly $\delta^{18}O$ of precipitation in Bern and monthly frequency of weather situations for 1973–2004 (JA = July/August average, and MJJA = May–August average). Levels of significance (based on the $F$ test) are indicated with dashed lines ($p < 0.05$) and dotted lines ($p < 0.01$).](image-url)
chronologies ($r = 0.34$ and $0.26$ to Alpine and North, respectively, both at $p < 0.05$). The South chronology further shows a significantly increasing trend of $0.017\%$/yr over time ($p < 0.05$), which is not the case for the two other series. A comparison between tree ring $\delta^{18}O$ and precipitation $\delta^{18}O$ over the common period (1973–1997) yielded linear regression coefficients $r = 0.63$ (North versus Bern), $r = 0.58$ (Alpine versus Grimsel) and $r = 0.51$ (South versus Locarno) (all significant at $p < 0.01$).

In Figure 5, we present an analogous analysis for $\delta^{18}O$ of tree rings as was done in Figure 3 for $\delta^{18}O$ of precipitation. $\delta^{18}O$ anomalies of the three tree ring sites were averaged and classes of years with very high ($\delta^{18}O > 1$; $n = 16$), high ($0 < \delta^{18}O < 1$; $n = 13$), low ($-1 < \delta^{18}O < 0$; $n = 16$) and very low $\delta^{18}O$ ($\delta^{18}O < -1$; $n = 15$) determined considering the period 1945–2004. The classes were similar to the ones derived for $\delta^{18}O$ of precipitation (described above) in the overlapping period 1973–2004. For the class of years with very high $\delta^{18}O$, for instance, the years 1989, 1990, 1993, 1994, 2000, 2001, 2003 were the same for tree rings and precipitation, while 1991 was additionally found for tree rings only, and 1999 for precipitation only. Corresponding average geopotential height field anomalies at 500 mbar are shown in Figure 6. The derived patterns are also rather similar to the ones derived for $\delta^{18}O$ of precipitation (Figure 3). Classes of years with very high/very low $\delta^{18}O$ of tree rings are associated with a high/low pressure situation over Central Europe. The years with moderately high $\delta^{18}O$ reflect a situation with high pressure in Southern Europe and low pressure in Northern Europe, similar as observed for $\delta^{18}O$ of precipitation. In contrast, moderately low $\delta^{18}O$ of tree rings is not related to a specific pressure pattern, but rather to a very flat pressure distribution. This does not necessarily mean that such a pressure pattern existed, but could also be the result of averaging out slightly positive and negative anomalies.

The tree ring $\delta^{18}O$ chronologies were correlated to the July–August (JA) and May–August (MJJA) averages of the weather types according to Schüepp (Figure 7). Similar to the results for $\delta^{18}O$ of precipitation, the convective conditions generally correlate better than the advective ones. We found a consistent influence of both the frequency of cyclonic and anticyclonic conditions on $\delta^{18}O$ of tree rings, which was highly significant for all sites (except for the relationship between cyclonic and South). The correlation coefficients were, however, not very high (on the order of 0.4). While we focus our attention in this study on the average chronologies, we would also like to indicate the results for individual species correlations: We observed that the strongest relationship exists for beech (North), followed by larch (Alps), oak (South), pine (South), spruce (North), and fir (North), thus not indicating a clear ranking regarding coniferous versus broadleaved species. Westerlies and Southerlies were only important to explain variability for the South chronology, the frequency of easterlies correlated (marginally significant) for the North chronology, while no influence of northerlies could be detected. Further analysis will be based on MJJA-averages only, because results for JA were similar.

3.3. Climate Correlations

May–August values of $\delta^{18}O$ of precipitation as well as $\delta^{18}O$ of tree rings were related to a range of climate parameters by regression analysis in addition to the ones discussed so far (Tables 1 and 2). Regarding $\delta^{18}O$ of summer precipitation, highly significant correlations were observed to several May–August climate parameters, including temperature, frequency of anticyclonic conditions and sunshine duration, while the correlations to precipitation amount (except Alpine) and relative humidity were weaker or non-significant. Correlations to the tree ring series also showed many significant relationships. The strength of the relationships is moderate and does not vary much between the climate parameters, which makes it difficult to point out a dominant factor. E.g. for the North chronology $r$ is in a narrow range from 0.43 to 0.48 for correlations to temperature, air pressure, frequency of anticyclonic conditions and sunshine duration. As expected based on theoretical grounds (leaf water enrichment), the relationship with relative humidity was negative, but significant only for the North and Alpine chronologies.
We further investigated if the combination of temperature and a circulation type parameter in a multilinear regression model would result in a better description of $\delta^{18}O$ in precipitation and tree rings. To explore this, we tested linear relationships of temperature ($T$) and frequency of cyclonic conditions ($C$), frequency of anticyclonic conditions ($AC$) and air pressure ($p$). Considering all months, the most consistent results and improvement of $r$ over simple correlations to temperature were obtained for the combination of $T$ and $p$, while smaller improvements of $r$ were found for $T-C$ and $T-AC$. This is not the case, for instance, when combining $T$ and precipitation, which does not improve $r$ over simple correlations to $T$. The regression analysis indicated that a similar weight of $T$ and $p$ is optimal for the linear combination. It is therefore possible to calculate a temperature-air correlation.

Figure 7. Correlation between $\delta^{18}O$ of tree rings (anomalies) and frequency of July–August (JA) and May–August (MJJA) synoptic weather situations (for the common period 1945–1997). Levels of significance are indicated with dashed lines ($p < 0.05$) and dotted lines ($p < 0.01$).

Table 1. Correlation Coefficients ($r$) Between Average May–August $\delta^{18}O$ of Precipitation (Bern, Grimsel, Locarno) and Climatic Parameters (Also for Averages of May–August) Calculated for the Period 1973–2004$^a$

<table>
<thead>
<tr>
<th></th>
<th>Bern</th>
<th>Grimsel</th>
<th>Locarno</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.69</td>
<td>0.69</td>
<td>0.62</td>
</tr>
<tr>
<td>Air pressure</td>
<td>0.56</td>
<td>0.68</td>
<td>0.47</td>
</tr>
<tr>
<td>Frequency of cyclonic conditions</td>
<td>$-0.62$</td>
<td>$-0.61$</td>
<td>$-0.56$</td>
</tr>
<tr>
<td>Frequency of anticyclonic conditions</td>
<td>0.52</td>
<td>0.55</td>
<td>0.45</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>0.70</td>
<td>0.47</td>
<td>0.48</td>
</tr>
<tr>
<td>Precipitation amount</td>
<td>$-0.63$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>$-0.45$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature-pressure index$^b$</td>
<td>0.72</td>
<td>0.75</td>
<td>0.61</td>
</tr>
</tbody>
</table>

$^a$Numbers are indicated only when significant at $p < 0.01$.
$^b$See section 3.3 for definition.

Table 2. Correlation Coefficients ($r$) Between Average $\delta^{18}O$ of Tree Rings (North, Alpine, and South Chronologies) and Various Climatic Parameters (Averages of May–August) Calculated for the Period 1945–1997$^a$

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>Alpine</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>0.48</td>
<td>0.44</td>
<td>0.50</td>
</tr>
<tr>
<td>Air pressure</td>
<td>0.47</td>
<td>0.44</td>
<td>0.34</td>
</tr>
<tr>
<td>Frequency of cyclonic conditions</td>
<td>$-0.35$</td>
<td>$-0.37$</td>
<td></td>
</tr>
<tr>
<td>Frequency of anticyclonic conditions</td>
<td>0.43</td>
<td>0.39</td>
<td>0.41</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>0.46</td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>Precipitation amount</td>
<td>$-0.53$</td>
<td>$-0.53$</td>
<td>$-0.42$</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>$-0.43$</td>
<td>$-0.47$</td>
<td></td>
</tr>
<tr>
<td>Temperature-pressure index$^b$</td>
<td>0.57</td>
<td>0.53</td>
<td>0.47</td>
</tr>
<tr>
<td>Tree ring model$^b$</td>
<td>0.62</td>
<td>0.64</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$^a$Numbers are indicated only when significant at $p < 0.01$.
$^b$See sections 3.3 and 3.4 for definition.
pressure index $i$ by the sum of standardized values according to the following equation:

$$i = \frac{(T - T_{mean})}{\sigma_T} + \frac{(p - p_{mean})}{\sigma_p}$$  \hspace{1cm} (6)

This index $i$ is then correlated to $\delta^{18}O$ values of precipitation:

$$\delta^{18}O_{\text{precip}} = a + bi$$  \hspace{1cm} (7)

where $a$ and $b$ are the coefficients of the experimentally determined linear relationship. This equation may be considered as an estimation of $\delta^{18}O$ from $T$ and $p$, which could be useful in an isotope fractionation model (see also Figure 8 and section 3.4).

### 3.4. Modeling of $\delta^{18}O$ of Tree Rings

The parameters of equation (7) are determined over the period where precipitation isotope data are available using an average of several (summer) months to account for...
mixing in the soil. The relationship can be used for a longer period to estimate \( \delta^{18}O_{\text{precip}} \) (where T and p data are available) and used as an input for the tree ring model (equation (5), Figure 8). Monthly data needed are temperature, air pressure, relative humidity, while constant parameters are \( f, e_k, e_e, \) and \( \varepsilon_c. \) A further assumption is isotopic equilibrium between soil water and water vapor, such that \( \delta^{18}O_V = \delta^{18}O_S - e_e. \) This assumption is not necessary for the model, but used here due to the lack of data for \( \delta^{18}O_V \) in the past and because some studies suggested equilibrium to be the case under relatively humid conditions [Angert et al., 2008]. The modeled tree ring \( \delta^{18}O \) calculated accordingly agrees fairly well with measured tree ring series for the North and the Alpine chronology \( (r \sim 0.62-0.64, \text{Figure 9}) \) and moderately for the South chronology \( (r = 0.48). \) The model explained more variance of \( \delta^{18}O_{\text{TR}} \) than simple correlations to a climate parameter for the North and Alpine sites (see Table 2). The dampening factor \( f \) was adjusted such to yield the highest possible \( r \) and was 0.35–0.4 for the North and the Alpine, but only 0.05 for the South chronology (corresponding to strong dampening or almost a complete loss of the leaf water signal). The influence of variable \( f \) on \( r \) was investigated in a sensitivity study (Figure 10). The analysis shows that the dependence of \( r \) from \( f \) is not very strong for the North and the Alpine sites. For South, removal of the temporally increasing trend in \( \delta^{18}O \) (Figure 5) resulted in higher \( r \) and a dependence of \( r \) from \( f \) in a similar way as for the other sites.

4. Discussion

[21] Our results show clear relationships between the year-to-year variability in weather situations and atmospheric pressure patterns and the oxygen isotope ratios in precipitation and tree rings. Summers that are associated with a relatively high frequency of anticyclonic conditions and a positive anomaly of the geopotential height fields over Switzerland experience on average high \( \delta^{18}O \) values in the study area, while summers with low anticyclone frequency and a negative pressure anomaly are accompanied with low \( \delta^{18}O \) values (Figures 3, 4, 6, and 7). These results are most consistent for extreme years, such as the hot and dry summer 2003 (see Figure S2 in Text S1), or when averaging several years with similar \( \delta^{18}O \) anomalies. In line with this result is a study on Alpine larch tree rings that found sunshine duration to be a good predictor of \( \delta^{18}O \) [Kress et al., 2010]. This mainly reflects the link between the pressure conditions and sunshine duration, but also a direct effect of the sunshine duration on leaf water enrichment via higher leaf temperatures and higher leaf-to-air vapor pressure gradients. In contrast, we found that years with only a moderate \( \delta^{18}O \) anomaly cannot be unambiguously related to a certain local pressure situation (Figures 3b, 3c, 6b, and 6c). It was observed that moderately high \( \delta^{18}O \) anomalies are associated with a dipole-like structure with a high over the Mediterranean and a low in the Northern Europe. Similarly, the moderately low anomalies based on the \( \delta^{18}O \) values in precipitation indicate
an east-west gradient with a low pressure situation over the British Isles (Figure 3c), although such a gradient cannot be detected in the corresponding figure describing the $\delta^{18}O$ signal in the tree ring data (Figure 6c), possibly because this weak signal is overridden by fractionations in the trees.

[22] Non-local effects and hemisphere-wide teleconnections were also found to be important in a GCM study examining the drivers of precipitation $\delta^{18}O$ in Europe [Field, 2010]. The strength of the circulation over the Mediterranean (with the corresponding opposite pattern over the high North Atlantic) was found to be a strong predictor of Central European $\delta^{18}O$, similar in strength as the local temperature, reflecting the fact that circulation variability strongly captures transport pathways and the distillation distance. Furthermore, there are strong seasonal differences to be considered. The strength of circulation controls on $\delta^{18}O$ is much stronger in winter than in summer, although the weakening of the $\delta^{18}O$ control in summer may be less expressed in the Alps compared to other regions [Baldini et al., 2008]. The reduced temperature effect in summer is due to the effects of continental moisture recycling and to the weaker atmospheric circulation controls reflecting the weaker zonal temperature gradients in summer in comparison to winter. Winter climate is more strongly determined by large scale atmospheric circulations (i.e., by the sequence of high and low pressure systems progressing onto the continent), while summer climate is strongly affected by regional processes and vertical exchange between the surface and the atmosphere [Field, 2010]. This may be partly the reason for the difficulty in understanding $\delta^{18}O$ signals in proxies that capture a summer precipitation signal, such as tree rings.

[23] Our results thus indicate a potential for the reconstruction of pressure patterns based on $\delta^{18}O$ of tree rings, but mainly for large deviations. This could result in a reconstruction of extreme situations such as the dry-hot summer 2003. Correlation coefficients obtained between circulation parameters and $\delta^{18}O$, however, were not particularly high, questioning our initial hypothesis that large-scale circulation features are better in explaining $\delta^{18}O$ than local climate variables. Nevertheless, considering atmospheric circulation may have some advantages regarding the stability of the climate-isotope relationships. When studying running correlations between isotope ratios in tree rings and simple parameters like summer temperature, it has been often observed that correlations hold for some time, but break down for some periods [Kress et al., 2010; Reynolds-Henne et al., 2007; Seftigen et al., 2011]. This is because the relationships between the climate variables themselves can change in different circulation regimes thereby affecting the isotope fractionations. Studies conducted in France on oak latewood, for instance, indicated a strong link between the isotope and growing season temperature for the recent time, but the isotope signal could additionally be influenced by precipitation amount for climate conditions, which are associated with different weather regimes [Etien et al., 2008]. In a study using Pinus sylvestris in Norway, Young et al. [2010] observed that the relationship between carbon isotopes and temperature was weak in episodes, where temperature and sunshine decoupled, which reflected changes in the influence of the Arctic oscillation on the site. We suggest that it is probably more mechanistically correct to reconstruct some feature of the large-scale circulation with tree ring $\delta^{18}O$, as opposed to just one facet of the local surface climate. Thus, by considering circulation parameters explicitly, a reconstruction might become more stable over time [Li et al., 2011]. This should be done not just by a simple correlation approach between circulation and tree ring isotopes, which would ignore local factors, but rather by including circulation parameters in a tree isotope fractionation model as discussed below.

[24] Regional differences in $\delta^{18}O$ were small in our study regarding isotopes both in precipitation and tree rings, even though we examined a chronology north of the Alps, a high-elevation site within the Alps and a chronology south of the Alps, where the climate is known to have Mediterranean influence (Figures 2 and 5). The only notable difference was the significant influence of southerlies for the tree ring South chronology. A limitation of our analysis of monthly frequencies of weather patterns may be that it is not considered which weather types are actually associated with much rainfall and thus should have the biggest impact on $\delta^{18}O$. It was shown for Switzerland that low pressure situations and westerlies have the strongest positive relationship to cloudiness and precipitation, whereas highs and easterlies the strongest negative relationship (thus are least associated with precipitation) [Stefanicki et al., 1998]. However, regarding tree ring $\delta^{18}O$, indirect effects are also important, like higher leaf- or evaporative enrichment associated with high-pressure situations. The generally good agreement between the sites points to the importance of large-scale weather patterns. Differences between the $\delta^{18}O$ values of the North and the South chronologies did not show systematic trends that could be associated with the ambient pressure patterns.

[25] The results discussed above show many similarities between the drivers of $\delta^{18}O$ in precipitation and tree rings, indeed confirming that $\delta^{18}O$ of precipitation is a dominating influence on the tree ring isotopic composition. The direct comparison of the isotope signal in precipitation and tree rings also yield highly significant relationships ($r$ = 0.5–0.6). Nevertheless, the climate signal in the tree rings was weaker than in the $\delta^{18}O$ of precipitation (Table 1 versus Table 2). One confounding influence is that mixing processes and wet-lags in the soil may vary from year to year and thus disturb the tree ring signal, which is dependent on the water available to the roots during the growing season. However, it is also clear that for a more complete understanding of the tree ring isotope archive, the processes going beyond the source isotope signal need to be considered. A tree ring isotope fractionation model with a simple leaf enrichment term and a dampening factor was in the case of the North and the Alpine chronologies able to reproduce the observed isotope variability better than correlations to climate variables alone ($r = 0.62–0.64$), although a significant part of the $\delta^{18}O$ variability remained unexplained. The chosen values for the dampening factor, which was adjusted in the model to accommodate for the influence of relative humidity on the tree ring $\delta^{18}O$ values, are in a similar range as reported in previous studies [Anderson et al., 2002; Barbour, 2007; Roden et al., 2000]. Although the influence of relative humidity is dampened, it may introduce some uncertainty in the model. This is because relative humidity measurements tend to be difficult and variable in space and thus the meteorological data may not be representative for the site examined. Another uncertainty in the model is the isotope ratio of
We still conclude that it is useful to explicitly consider climate variables for predicting oxygen isotope variations. Large-scale circulation patterns are more important than local ones for Pinus uncinata in the Spanish Pyrenees [Esper et al., 2010] and for Douglas fir (Pseudotsuga menziesii) in the Rocky Mountains [Marshall and Monserud, 2006]. A recent study on Pinus sylvestris in Norway, however, did not find any evidence for age-related trends [Young et al., 2011]. Instead, the trend observed in our study could reflect a CO$_2$-induced physiological effect of lower stomatal conductance [McCarron and Loader, 2004]. Biological factors may be of relatively minor importance to explain the inter-annual variability in $\delta^{18}O$, as reflected in high degree of common variability across species and sites [Saurer et al., 2008], although post-photosynthetic reactions, namely biochemical effects during cellulose synthesis, introduce additional uncertainty and may diminish the climate signal [Sternberg, 2009].

Overall, plant isotope fractionation models are well established and tested in small-scale controlled experiments [Roden et al., 2000], but a common problem in their use is that they require the source isotope signal as input, which is only available for the recent four decades at most [Rozanski et al., 1997]. This seems to preclude their use for long chronologies. We suggest here a new approach based on an approximation of $\delta^{18}O$ of precipitation over a calibration period using instrumental climate variables available for a longer period, thus introducing a “circulation-temperature” index. For even longer chronologies spanning several centuries, parameters required to calculate this index could be obtained from other proxy records. Depending on the site conditions, temperature could be derived from ring width index or maximum density and relative humidity from $\delta^{13}C$ in tree rings. Independent long pressure field reconstructions are also increasingly becoming available [Casty et al., 2007; Philipp et al., 2007]. The ultimate goal will be to use a multiproxy approach in combination with an isotope fractionation model to provide a reliable and stable climate reconstruction.

**5. Conclusions**

We could not confirm our initial hypothesis that large-scale circulation patterns are more important than local climate variables for predicting oxygen isotope variations. We still conclude that it is useful to explicitly consider atmospheric circulation features in models explaining $\delta^{18}O$ of tree ring cellulose, because circulation both represents large-scale processes fundamental to the $\delta^{18}O$ signature of the tree’s source water, but also controls important additional influence on $\delta^{18}O$ in cellulose (namely, the extent of enrichment due to transpiration in the leaf). Here we suggest to use an index, which would take into account that $\delta^{18}O$ of precipitation is not a simple measure of temperature, thus enabling the application of isotope models over several centuries. However, improved functional relationships between $\delta^{18}O$ of precipitation and measured climate parameters would be important to have. Such relationships could then be used in plant fractionation models as an input. Thus, progress in tree ring isotope modeling and successful application in palaeoclimate research requires a better characterization of $\delta^{18}O$ source water changes in terms of climate variables rather than improvements in the leaf and biochemical fractionation models, which are already well established. We further conclude that the study of weather types to improve the understanding of $\delta^{18}O$ variability is promising. The recent introduction of fully automatic circulation type classifications [Schiemann and Frei, 2010], which clearly outperform descriptive classifications like the Schiepp weather types, may well stimulate further applications of this technique for isotopic investigations.

**Acknowledgments.** We gratefully acknowledge financial support by EU projects FP6-2004-GLOBAL-017009-2 (MILLENIUM), EVK2-CT-2002-00147 (ISONET) and SNF No. 200021_121838 and 200020_134864. We thank the Swiss Federal Office of Water and Geology for providing monthly data of $\delta^{18}O$ of precipitation.

**References**


