TO WHAT EXTENT CAN OXYGEN ISOTOPES IN TREE RINGS AND PRECIPITATION BE USED TO RECONSTRUCT PAST ATMOSPHERIC TEMPERATURE? A CASE STUDY

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Abstract. We analyzed the relationship between air temperature and oxygen isotopes measured in tree rings of silver fir (*Abies alba* Mill.) from a long-term forest ecosystem research plot in the Swiss Jura mountains (LWF project). The oxygen isotope data were compared with a century-long meteorological series of air temperature data. Measurements of oxygen isotope ratios in precipitation were also used for comparison. Results show that the late-wood tree-ring series is significantly correlated with May to August temperatures. Correlations were higher for maximum (daytime) air temperature and even better for air temperature measured on rainy days only. We stress that trends in maximum temperature series for this time of the year, like trends in oxygen isotope ratios series from tree rings, are completely different from trends in yearly mean temperature. Indeed, maximum temperature trends during the vegetation period slightly decreased during the 20th century, whereas yearly means increased strongly.

1. Introduction

Temperatures have warmed by 0.6 °C globally during the last century (IPCC, 2001) and by 1.5 °C, more than twice the global value, in Switzerland (Rebetez, 1999, 2001). Within this context, great efforts have been made to reconstruct past climate in an attempt to discern whether such an increase is unprecedented (e.g., Mann et al., 1999; Briffa and Osborn, 2002; Esper et al., 2002). Although it is now well-known that the diurnal temperature range has changed significantly during the same period, both globally (IPCC, 2001; Karl et al., 1993; Easterling et al., 1997) and in Switzerland (Rebetez and Beniston, 1998; Rebetez, 2001), it is still standard practice to reconstruct mean temperature conditions without referring to the relationship between the proxy and maximum or minimum temperatures. It is also widely recognized that the winter season is warming more rapidly, at least in the Northern hemisphere (IPCC, 2001; Jones et al., 2001), and in Switzerland in particular (Rebetez, 2001). We suspect that tree-growth and oxygen isotopes in rainfall may be more highly correlated with maximum than with minimum temperature. We also logically suspect that oxygen isotopes in tree rings are more

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highly correlated with the temperatures during the vegetation period than with temperatures during the rest of the year.

Tree-ring data (i.e., ring-width and density) are powerful tools for reconstructing climatic conditions where temperature or precipitation are limiting factors, namely at mid-to-high-elevation or high-latitude sites (density), and at low-elevation or mid-latitudes (ring width). At mesic sites, low correlations between ring-width or density and climatic data are found.

Oxygen isotopes in rainfall are correlated with atmospheric temperature (e.g., Dansgaard, 1964; Siegenthaler and Oeschger, 1980; Jouzel et al., 1997). Although other parameters such as the continentality or the atmospheric circulation pattern also play a role in the oxygen isotope ratio (δ^{18}O) (Rozanski et al., 1993; Jouzel et al., 1997), temperature at the location of the precipitation is widely recognized to be the most important parameter determining the respective proportions of ^{18}O and ^{16}O in precipitation at middle and high latitudes (Rozanski et al., 1993; Jouzel et al., 1997). The possibility of using oxygen isotopes trapped in natural archives such as sea or lake sediments, ice cores or tree rings to reconstruct past climates has held promise for some time (Gonfiantini et al., 1965; Hoefs, 1987; McKenzie and Hollander, 1993; Lipp et al., 1996; Anderson et al., 1998; Saurer et al., 2000). The basic processes governing the isotope fractionation in clouds are well understood (Rayleigh condensation model; see Siegenthaler and Matter, 1983), although it is still difficult to establish a quantitative relationship between oxygen isotope variations in rainfall and temperature due to interfering factors such as the admixture of moisture with different air path histories (Jouzel, 1997; Rozanski et al., 1993).

The analysis of oxygen isotopes in tree rings clearly constitutes a potential source of proxy data for reconstructing the atmospheric temperature of past centuries and even millennia (Libby et al., 1976; Burk and Stuiver, 1981; Saurer et al., 1997). Spatial δ^{18}O correlations with temperature are generally high and quite well understood (e.g., the continentality effect), but temporal correlations are weaker and more difficult to understand. One reason is that series of ^{18}O in precipitation are still short (shorter than 30 years), which makes calibration difficult. In tree rings, oxygen isotopes have been shown to be related to the isotopic composition of the water taken up by the roots (Roden et al., 2000), but until now we have been uncertain as to exactly how far oxygen isotopes can really be considered to represent the atmospheric temperature and in particular what part of the yearly temperature they correspond to in middle latitudes. In this respect, we still lack calibration studies during the instrumental period (Jones et al., 1993).

In this paper we compare a series of tree-ring oxygen isotope data measured in Bettlachstock, Switzerland, a forest observation site (Saurer et al., 2000), with temperature data measured by the Swiss Meteorological Service (MeteoSwiss). At this site no significant correlation between ring-width and climatic parameters was found (Saurer et al., 2000). We also compare the temperature data with a series of rainfall δ^{18}O (measured by the Physics Institute of the University of Bern). Our purpose was to determine to what extent oxygen isotopes measured in tree rings

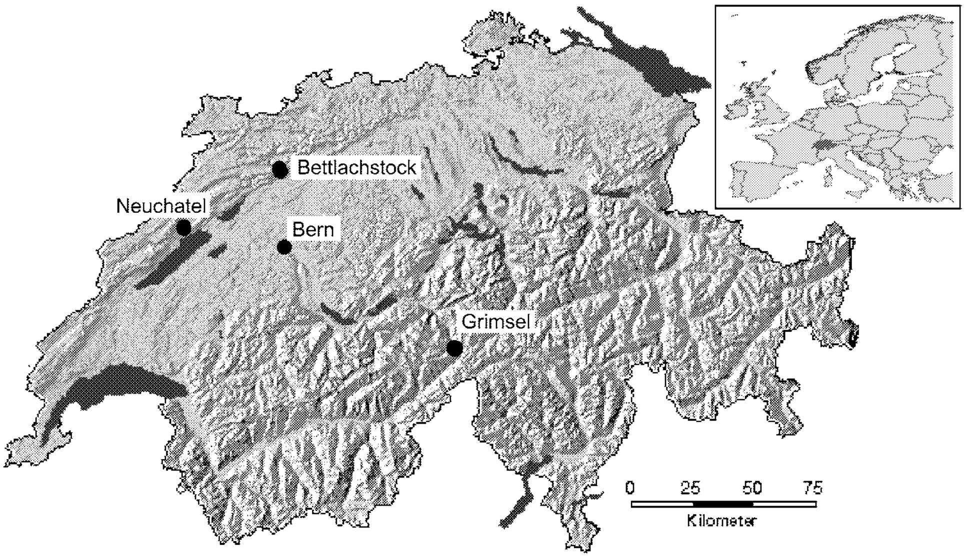

Figure 1. Location of sampling sites.

can be correlated with atmospheric temperature, with three subsidiary questions: (1) to what extent can oxygen isotopes measured in rainfall be correlated with atmospheric temperature? (2) what part of the yearly atmospheric temperature can be inferred from oxygen isotopes measured in the late wood of tree rings? (3) to what extent can this part of the yearly temperature be used to represent long-term climate change?

2. Data

The location of the measuring sites is presented in Figure 1. A $^{18}O/^{16}O$ ratio ($\delta^{18}O$) chronology was determined for *Abies alba* Mill. (silver fir) at the long-term monitoring plot of Bettlachstock, located on a southern slope of the Jura Mountains, at an altitude of 1150 m (Saurer et al., 2000). We took one core at 1.3 m from four trees (*Abies alba*), using an increment borer (diameter 0.5 cm). Each tree ring of the cores was dated, and the latewood and earlywood were separated using a razor under a stereomicroscope. Only the latewood of each tree ring was then analysed, pooling together the latewood of tree rings of the four cores formed in the same calendar year. The mean chronology was determined by pooling the individual rings of 4 trees prior to the analysis. The isotope ratio was determined with an on-line pyrolysis system (Saurer et al., 1998). Based on the results by Borella et al. (1999), we did not extract the cellulose of late wood but measured the whole wood. Measurements covered the period 1840–1997.

The Physics Institute, Bern, Switzerland, measured the $^{18}O/^{16}O$ ratio in precipitation. Data were available for 28 years, from 1972 to 1999 for 2 sites in

Switzerland, namely Bern, on the Swiss Plateau, at a lower elevation (565 m), and Grimsel, a high elevation (1980 m) site in the Alps. Data were provided by IAEA Vienna and by the Swiss Federal Office for Water and Geology, Bern.

Temperature data used in this paper originated from the Swiss national database maintained by MeteoSwiss. Series are available for Bern and Grimsel for the period 1972–99 for comparison with the series of data for $^{18}O/^{16}O$ ratio in precipitation. Neuchatel (487 m), with an uninterrupted series of data of remarkably good quality (Rebetez, 2001) for all the meteorological parameters since 1901 has been used for comparisons with the nearby (40 km) tree-ring series of Bettlachstock.

3. Results

We compared the monthly $^{18}O/^{16}O$ ratio measured in precipitation at Bern and Grimsel with monthly temperature data. Three temperature series were analyzed: mean monthly temperature, minimum monthly temperature and maximum monthly temperature. Correlations were highly significant ($p > 0.001$) in the three cases and at both sites (see Table I), although they were in all cases higher at Bern. At Grimsel, there were only very slight differences between the $\delta^{18}O$ correlations with mean, minimum and maximum temperature data. This contrasts with Bern, where the correlation with minimum temperature was clearly lower than for the others. Maximum temperature produced the highest correlations.

As long periods of drought may influence monthly temperatures but not the $^{18}O/^{16}O$ ratio measured in precipitation, we also analyzed the correlation between $\delta^{18}O$ and temperature, taking only rainy days into account. We defined a rainy day as a day with at least 1 mm of precipitation so as to exclude foggy days. The results are also presented in Table I. The correlation coefficients on rainy days were always better than when all days were included.

The relationship between oxygen isotopes in tree rings and atmospheric temperature is presented in Table II. For temperature, we analyzed several periods rather than series starting at the beginning or at the end of a calendar month. We also tested series starting every 5th calendar day in order to detect the most appropriate vegetation period. Correlations were much higher with maximum temperature ($p < 0.01$) than with minimum or mean temperature. The correlations were even higher with maximum temperature during the vegetation period, between May and August. These correlations were highly significant ($p < 0.001$). Correlations with minimum temperature were not significant, even when restricting the analysis to the vegetation period. Compared to the correlations between oxygen isotopes and maximum temperatures of the vegetation period, correlations were slightly higher when considering only the temperature of rainy days (days with precipitation reaching at least 1 mm) of the vegetation period. The best correlation we obtained was for the maximum temperature of rainy days during the period from the 15th of May until the 5th of August: $r = 0.453$, which is highly significant ($p < 0.001$).

Table I

Correlation coefficients between air temperature and oxygen isotope ratios in precipitation (monthly data, 1972–1999)

	r	Temperature coeff. (slope) [‰/°C]
BERN		
Minimum temperature	0.7471 [a]	0.4
Mean temperature	0.7714 [a]	0.358
Maximum temperature	0.7801 [a]	0.315
Minimum temperature on rainy days	0.7841 [a]	0.449
Mean temperature on rainy days	0.8073 [a]	0.43
Maximum temperature on rainy days	0.8158 [a]	0.378
GRIMSEL		
Minimum temperature	0.6912 [a]	0.465
Mean temperature	0.6924 [a]	0.459
Maximum temperature	0.6769 [a]	0.409
Minimum temperature on rainy days	0.7028 [a]	0.474
Mean temperature on rainy days	0.7103 [a]	0.481
Maximum temperature on rainy days	0.7147 [a]	0.444

[a] $p < 0.001$.

To ensure that the higher correlation between the temperature of the vegetation period and oxygen isotope ratios from tree-rings was a direct relationship rather than being caused by stronger correlations between temperature and precipitation oxygen isotopes during this period, we used the data from Bern to examine the correlation between air temperature and oxygen isotopes in precipitation during the vegetation period (Table III). As the data only exist on a monthly basis for oxygen isotopes in precipitation, this analysis was made for three different periods stretching from May to August and not for the precise vegetation period as used in the earlier analysis. Comparison with Table I reveals that the correlation between air temperature and precipitation oxygen isotopes is not stronger during the vegetation period than it is for the whole year. The reverse is the case: it is lower, particularly when a shorter time period is taken into account, such as June to July.

We also computed the correlation between the oxygen isotope ratio from rainfall at Bern and the oxygen isotope ratio in tree rings (Table IV). The results, computed for both the precipitation data for the whole year and for the vegetation period only (May to August and June to July), indicate that the correlation coefficients

Table II

Correlation coefficients between temperature and oxygen isotope ratios in tree-rings (annual data 1901–1997)

Bettlachstock/Neuchatel	r	Temperature coeff. (slope) [‰/°C]
Annual minimum temperature	0.0004	
Annual mean temperature	0.166	
Annual maximum temperature	0.301 [a]	0.327
Minimum temperature in July and August	0.028	
Mean temperature in July and August	0.189	
Maximum temperature in July and August	0.281 [a]	0.127
Minimum temperature on rainy days in July and August	0.101	
Mean temperature on rainy days in July and August	0.242	
Maximum temperature on rainy days in July and August	0.318 [a]	0.138
Maximum temperature in June and July	0.37 [b]	0.193
Maximum temperature May–June–July	0.392 [b]	0.201
Maximum temperature May–June–July–August	0.405 [b]	0.268
Maximum temperature May 15–August 5	0.428 [b]	0.255
Maximum temperature May 15–July 31	0.431 [b]	0.253
Maximum temperature May 10–July 31	0.447 [b]	0.262
Maximum temperature on rainy days in June and July	0.415 [b]	0.181
Maximum temperature on rainy days in May–June–July	0.436 [b]	0.265
Maximum temperature on rainy days May 10–July 31	0.451 [b]	0.211
Maximum temperature on rainy days May 15–July 31	0.452 [b]	0.213
Maximum temperature on rainy days May 15–August 5	**0.453** [b]	0.218

[a] $p < 0.01$.
[b] $p < 0.001$.

are positive in all cases, higher during the vegetation period, but highly significant only with the June to July period.

4. Discussion

The stronger relationship between temperature and $\delta^{18}O$ measured in precipitation at Bern than at Grimsel can be explained by the year-round, lower temperatures at Grimsel. A weaker correlation when temperatures are low has been observed by Siegenthaler and Matter (1983). Rozanski et al. (1993) have shown that this can be partly explained by the relation being non-linear and showing a steeper slope in

Table III

Correlation coefficients between air temperature and oxygen isotope ratios in precipitation (monthly data, 1972–1999)

Bern	*r*	Temperature coeff. (slope) [‰/°C]
in May–June–July–August		
Mean temperature	0.7 [a]	0.517
Maximum temperature	0.717 [a]	0.4674
in May–June–July		
Mean temperature	0.685 [a]	0.484
Maximum temperature	0.704 [a]	0.44
in June–July		
Mean temperature	0.522 [a]	0.45
Maximum temperature	0.557 [a]	0.395

[a] $p < 0.001$.

Table IV

Correlation coefficients between oxygen isotopes ratios in precipitation and in tree-rings (monthly data, 1972–1997)

Bern	*r*	O18 coeff. (slope) [‰]
June–July	0.58 [a]	0.79
May–August	0.332	0.324
January–December	0.208	0.269

[a] $p < 0.001$.

the lower temperature range. The relationship between monthly mean temperature and the δ^{18}O in Bern precipitation is weaker for lower temperatures, mainly for those below 5 to 10 °C (Figure 2). At Grimsel, all monthly minimum temperature values, half of the monthly mean temperature values and one third of the monthly maximum temperature values are below zero. Even for maximum temperatures, 75% of the values are lower than 10 °C.

The difference in the correlation between the δ^{18}O measured in precipitation and minimum temperature compared to maximum temperature at Bern can be explained by the impact of night cooling on the Plateau, which happens mainly during clear nights and lowers temperature without affecting precipitation. This

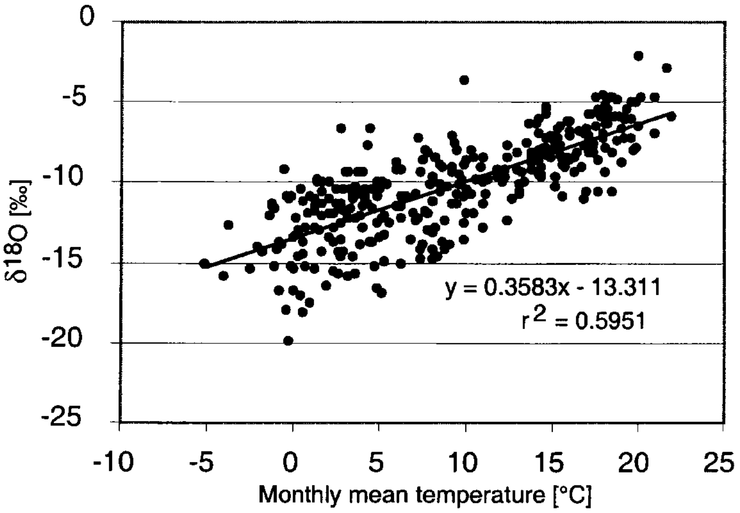

Figure 2. Correlation between monthly mean temperature and oxygen isotope ratio (δ^{18}O) in precipitation in Bern; 1972–1999, $N = 336$.

phenomenon does not happen at Grimsel, where the correlation between δ^{18}O and maximum temperature is not higher than with minimum temperature.

This absence of night cooling also explains in part the smaller difference in the correlation at Grimsel between δ^{18}O in precipitation and temperature on rainy days only compared to temperature on all days. Another factor also plays a role: Grimsel has more precipitation than Bern. There were on average 126 rainy days per year (i.e., with at least 1 mm of rain) at Bern during the study period (1972–1999) as well as for the whole century (1901–2000), whereas there were more than 160 rainy days at Grimsel, which is one of the wettest places in the Swiss Alps (161 precipitation days a year during the 1972–1999 period and 164 days a year in 1964–1999).

The relatively small difference observed in the correlations involving temperature on rainy days is probably attributable to both sites having frequent rain. At Bern, one day in three is a rainy day. Moreover, both Bern and Grimsel rarely experience drought periods. The difference between the temperature on rainy days and the other temperature values would probably be stronger in drier locations, such as Ticino, in southern Switzerland, where winter drought can be severe in spite of high annual sums (Rebetez, 1999), or in Valais where annual precipitation sums can be lower than 500 mm.

The correlations found between air temperature and oxygen isotopes in precipitation for these 28 year-long series suggest that temperature explains a substantial proportion of the seasonal isotope variation at Bern: from 56% (minimum temperature) to 67% (maximum temperature on rainy days) of the variance. This confirms the values found by Siegenthaler and Matter (1983) for continental stations (54 to

68%). Grimsel shows lower values (up to 51%). As discussed above, we suggest that this is at least in part due to the lower temperatures at this altitude. The temperature coefficient ranges from 0.32‰/°C to 0.45‰/°C at Bern, i.e., within the order of magnitude described by Siegenthaler and Matter (1983) and Rozanski et al. (1993). It is higher when taking only rainy days in consideration (Table I) and is also higher at the mountain site.

Correlations between oxygen isotopes in tree rings and atmospheric temperature are not significant with annual minimum or mean temperature, but they are significant with annual maximum temperature values. They are highly significant with maximum temperature data during the vegetation period (as also found by Anderson et al., 1998) and even more so with maximum temperature measured on rainy days only. This is probably because rain occurs frequently in May to August (11 rainy days per month on average in Neuchatel during the 20th century, 11 to 15 days at the elevation of Bettlachstock), and also because cooling during clear nights is not strong during this season.

Our analysis of the daily data suggests that $\delta^{18}O$ measured in tree rings in the late-wood part is best correlated with the temperature of a period going back as far as mid-May, and continuing only until August 5th. The highest correlation coefficient (r) between latewood $\delta^{18}O$ and temperature was 0.453, indicating that maximum temperature on rainy days from mid-May to the beginning of August explains 21% of the oxygen isotope ratio variance in these late-wood tree rings. This may seem low compared to the high correlation factors found between air temperature and $\delta^{18}O$ measured in precipitation. But when taking only the vegetation period into account, for $\delta^{18}O$ from precipitation, the explained variance is lower (31 to 51%) than for the whole year (56 to 71%). These results suggest that oxygen isotope ratios found in tree rings store about half of the temperature information found in precipitation.

The difference between $\delta^{18}O$ measured in precipitation compared to oxygen isotope ratios measured in tree rings can be linked to environmental influences on plant physiology. Relative humidity is important because the leaf water is isotopically enriched due to transpiration. As production of sucrose in the leaf or needle is influenced by leaf water, this enrichment is transferred to the organic matter and ultimately to the tree ring, (see e.g., Edwards and Fritz, 1986). Higher enrichment in dry conditions is expected, such that a negative correlation exists between $\delta^{18}O$ and relative humidity. Such an effect might interfere with temperature reconstructions from $\delta^{18}O$ in tree rings, although results by Saurer et al. (2000) suggest that the influence of relative humidity may be dampened and not as strong as indicated by Edwards and Fritz (1986).

The correlation we obtained between late wood $\delta^{18}O$ and maximum temperature shows that the analysis of oxygen isotopes enables a reconstruction of daytime atmospheric temperatures during the vegetation period. This should be verified on other sites to more reliably see the potential for temperature reconstruction, possibly near a location where longer temperature records are available so that

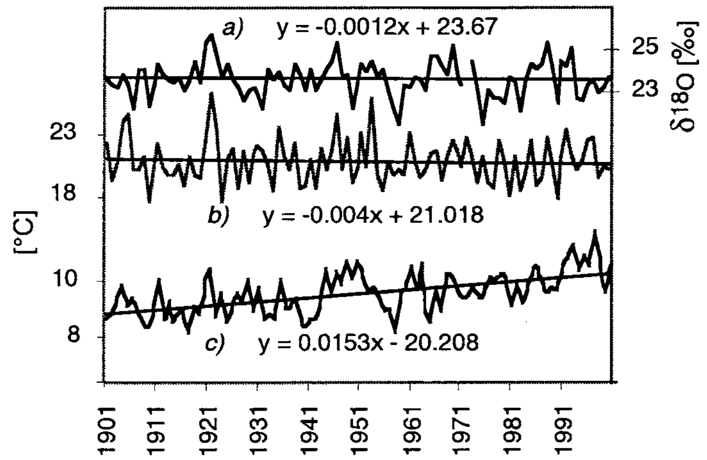

Figure 3. Trends in oxygen isotope ratio (δ^{18}O) from Bettlachstock tree rings (a), in maximum temperature on rainy days from May 10 to August 5 (b), and in yearly mean temperature (c).

both a calibration and verification period can be applied. This could be very useful for ecological studies and for a better understanding of impacts of past climate changes on vegetation.

Concerning temperature changes, it is important to stress here that maximum temperature data during the vegetation period do not exhibit the same trends as annual mean temperatures, at least during the 20th century. The monthly trends for mean temperatures in Neuchatel compared to trends in δ^{18}O and maximum temperature on rainy days from May 15 until August 5 (the best correlation between δ^{18}O in tree rings and air temperature) are shown in Figure 3. Other meteorological stations exhibit similar trends and the same reduction in diurnal temperature range in Switzerland (Rebetez and Beniston, 1998) and in the rest of the world (Karl et al., 1993; Easterling et al., 1997).

Maximum temperature on rainy days during the period May 15 to August 5 decreased during the 20th Century (–0.004 °C/100 years). This decrease is clear in the Bettlachstock δ^{18}O data (Figure 3). However, it does not correspond to the general increase in temperatures measured during this century (1.5 °C in Neuchatel and in Switzerland in general).

5. Conclusion

Our results show that the correlation between δ^{18}O measured in precipitation and atmospheric temperature is significant. This suggests that δ^{18}O values measured in precipitation can be used to reconstruct past air temperatures, provided that archives of this parameter can be found. Oxygen isotope ratios in precipitation provide an even better source of temperature information on rainy days, although in areas with frequent rain, the improvement amounts to less than 5%.

The analysis of oxygen isotope ratios in tree rings is a reasonable tool to reconstruct past temperature in temperate zones, where other tree-ring characteristics are usually of less value for climatic reconstructions. The potential reconstructed temperatures refer only to the period in which the wood is formed, i.e., corresponding roughly to the vegetation period. Oxygen isotope ratios in tree rings only vary in relation to a part of the yearly temperature cycle, but this portion is an important ecological information as it corresponds to the vegetation period.

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