

Signal strength and climate calibration of a European tree-ring isotope network

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[1] We present the first European network of tree ring $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, containing 23 sites from Finland to Morocco. Common climate signals are found over broad climatic-ecological ranges. In temperate regions we find positive correlations with summer maximum temperatures and negative correlations with summer precipitation and Palmer Drought Severity Indices (PDSI) with no obvious species-specific differences. Regional $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chronologies share high common variance in year-to-year variations. Long-term variations, however, exhibit differences that may reflect spatial variability in environmental forcings, age trends and/or plant physiological responses to increasing atmospheric CO_2 concentration. Rotated principal component analysis (RPCA) and climate field correlations enable the identification of four sub-regions in the $\delta^{18}\text{O}$ network - northern and eastern Central Europe, Scandinavia and the western Mediterranean. Regional patterns in the $\delta^{13}\text{C}$ network are less clear and are timescale dependent. Our results indicate that future reconstruction efforts should concentrate on $\delta^{18}\text{O}$ data in the identified European regions. **Citation:** Treydte, K., et al. (2007), Signal strength and climate calibration of a European tree-ring isotope network, *Geophys. Res. Lett.*, 34, L24302, doi:10.1029/2007GL031106.

1. Introduction

[2] 21st century global warming and its potential impact on the hydrological cycle [Allen and Ingram, 2002;

Trenberth and Shea, 2005; Treydte et al., 2006] strengthen the need to quantify climate changes particularly in regions with large human populations. Europe represents a region where significant progress has been made in assessing past climate variations due to the availability of long instrumental records, documentary archives, and natural proxies. Temperature and precipitation fields have been reconstructed over the whole European region based primarily on long instrumental records and documentary data [Luterbacher et al., 2004; Pauling et al., 2006; Xoplaki et al., 2005]. Many long-term high-resolution proxy reconstructions are, however, restricted to temperature variations at high latitudes or altitudes [Esper et al., 2002; Büntgen et al., 2006; Frank and Esper, 2005] or to local/regional precipitation or drought variability [e.g., Casty et al., 2005; Masson-Delmotte et al., 2005; Wilson et al., 2005]. This is because the climatic signal in the most prominent proxies - tree ring width and maximum latewood density - is strongest at ecological boundary conditions. Hence, additional proxy records are required, which enable the expansion of climate reconstructions into temperate regions. Local analyses of tree ring stable isotopes have demonstrated potential in providing environmental information from such sites [e.g., Masson-Delmotte et al., 2005; Rafalli-Delerce et al., 2004; Saurer et al., 1997] and therefore could help to overcome some limitations in dendroclimatology [Esper et al., 2005].

[3] Here we present 20th century carbon and oxygen isotope data ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) from a network of 23 sites

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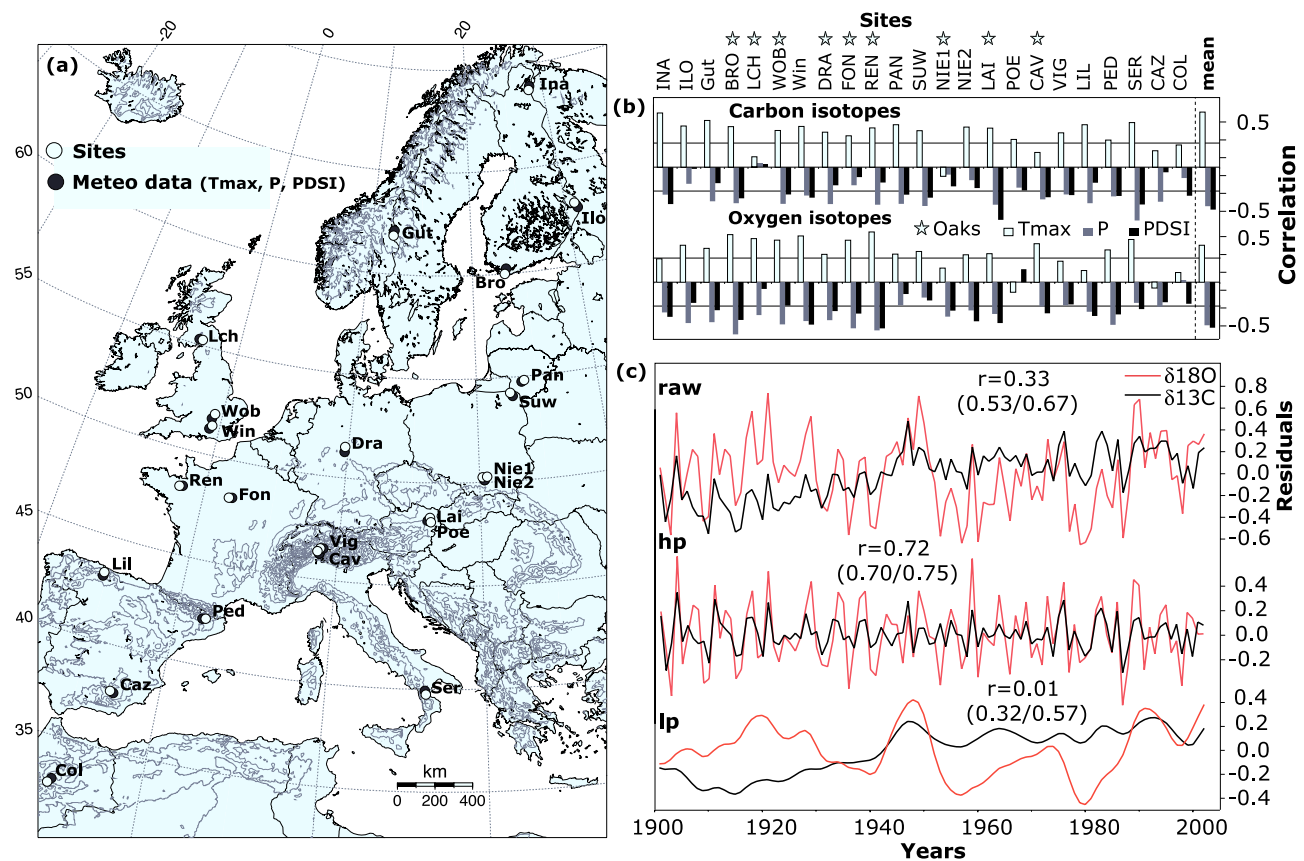


Figure 1. (a) Tree sites and corresponding meteorological grid cells for the 20th century with codes indicating site names. (b) Site dependent June–August climate correlations of ‘raw’ carbon and oxygen isotope chronologies, with sites being latitudinally arranged (for detailed site information, see Table S1); stars indicate oak sites; ‘mean’ are correlations between mean isotope records averaged over all sites and mean meteorological data averaged over corresponding grid cells; and lines are $p < 0.01$ significance levels. (c) ‘European’ carbon and oxygen isotope chronologies (each calculated by averaging site chronologies); ‘raw’ = residuals from 1901–1998 means, hp = high pass filtered data; lp = low pass filtered data; r = Pearson’s correlation coefficient; and numbers in brackets are r -values for the early AD 1901–1951 and the recent AD 1952–2002 period, respectively.

ranging from Fennoscandia to the Mediterranean region. We discuss results from (i) signal strength analyses within the networks, (ii) climate calibration of isotopic parameters to summer conditions, and (iii) spatial network analyses. We detail common variance within European sub-regions and emphasise the reconstruction potential of annually resolved $\delta^{18}O$ from tree rings.

2. Material and Methods

[4] Twenty-three sites ranging from northern Finland to Morocco with $\delta^{13}C$ and $\delta^{18}O$ chronologies from three genera (*Quercus*, *Pinus*, *Cedrus*) were included in the analysis (Figure 1a and Table S1). The sampling design considered not only ecologically extreme sites, with a single climatic factor dominating tree growth, but also temperate sites where mixed climate signals are recorded in tree ring width and maximum latewood density. All chronologies cover the 1901–1998 period, with 20 sites extending to 2002. Ring widths were measured and tree rings cross-dated following standard procedures [Fritts, 1976]. At least four dominant trees per site (two cores per tree) were selected for isotope analysis, a number proven to be satisfactory to

develop a (population-) representative isotope site record [Leavitt and Long, 1984; McCarroll and Loader, 2004; Gagen et al., 2004; Treydte et al., 2001, 2006].

[5] Pine and cedar tree rings were separated year-by-year, whilst for oak latewood was analysed (except CAV, where no separation in early and latewood was possible owing to the extreme narrowness of the latewood). At most sites, all tree rings from the same year were pooled prior to cellulose extraction to provide enough matter for isotopic analysis [Leavitt and Long, 1984; Treydte et al., 2001]. Alpha-cellulose was extracted following standardized procedures [Boettger et al., 2007] and combusted to CO_2 or pyrolysed to CO, prior to mass spectrometer analysis. $\delta^{18}O$ values are expressed as deviations from the VSMOW and $\delta^{13}C$ values as deviations from the VPDB standards. $\delta^{13}C$ records were corrected for the atmospheric $\delta^{13}C$ decrease due to fossil fuel burning since the beginning of industrialisation [McCarroll and Loader, 2004]. Initially all isotope series were screened for missing values and gaps filled using information from adjacent chronologies [Pederson et al., 2004]. Signal strength analyses were conducted on high pass (hp) and low pass (lp) filtered data using cubic smoothing splines

with 50% frequency-response cut-off at 10 years [Cook and Peters, 1981] for frequency decomposition.

[6] Climate calibration was performed using an updated version of the $0.5^\circ \times 0.5^\circ$ monthly gridded meteorological data set CRU TS 2.1 [Mitchell and Jones, 2005]. Analyses considered mean, minimum and maximum temperatures, precipitation, wet day frequencies and vapour pressure. Here we focus on the highest correlations observed for maximum temperatures ($T_{\max}$) and precipitation (P). Additionally, a newly developed European $0.5^\circ \times 0.5^\circ$ grid of monthly resolved Palmer Drought Severity Index data (PDSI) is used for calibration [van der Schrier et al., 2006; Wells et al., 2004] as well as a $2.5^\circ \times 2.5^\circ$ grid of PDSI data [Dai et al., 2004], accessed via the KMNI climate explorer (<http://climexp.knmi.nl>).

3. Results

[7] 20th century mean values of the individual $\delta^{13}\text{C}$ site chronologies span 5.1 ‰ with lowest values recorded at the Polish site ‘Nie2’ and highest values in Morocco (‘Col’). Lowest $\delta^{18}\text{O}$ means are found at the Finnish site ‘Bro’ and highest values at the Spanish site ‘Caz’ and again at the Moroccan site ‘Col’ differing by 7.9 ‰ (Table S1). Mean inter-site correlations for the residual as well as for the hp and lp records indicate little common variance in the overall isotope networks, although correlations are slightly higher for $\delta^{18}\text{O}$ (records and values shown in Figure S1¹). This result is not surprising, considering the large region covered, yet the question remains whether different climate sensitivity at individual sites or regional differences in climate variability are responsible for the low inter-site correlations.

[8] On a site basis, the strongest responses of both isotope parameters are found with climate variables for the year of tree ring formation, displaying highest correlations with the summer months. Calculations based on different seasonal windows indicate that the number of significantly correlating sites varies depending on the climatic variable and isotopic parameter (Figure S2). Nevertheless, correlation signs of combined June–August (JJA) maximum temperature (positive), precipitation (negative) and PDSI (negative), respectively, are common at the majority of sites, despite the broad climatic and ecological range (Figure 1b). Interestingly, the moisture signal (particularly $\delta^{13}\text{C}$) of the dry sites (Switzerland, Mediterranean) is generally weaker than was expected from some earlier analyses [Warren et al., 2001]. Signals are not only robust between sites but also between isotope parameters. Temperature sensitivity in the $\delta^{18}\text{O}$ network is particularly strong at northern latitudes and at sites influenced by North Atlantic air masses. It has to be noted, that on the ‘site’ as well as on the ‘European’ scale, high correlations to several climate variables are partly based on systematic associations between the target variables themselves, particularly during summer. All European JJA records are significantly ($p < 0.001$) correlated with each other: $T_{\max} - P$ at $r = -0.41$, $T_{\max} - \text{PDSI}$ at $r = -0.39$ and $P - \text{PDSI}$ at $r = 0.50$.

[9] Previous year conditions do not have a strong effect on either carbon or oxygen isotope values (Figure S2). This finding was somewhat expected for the latewood cellulose from oak, but interestingly also holds for pine (whole ring cellulose) and, thus, does not indicate substantial carry-over effects in conifers due to remobilized reserves from previous summer [Kagawa et al., 2006; Helle and Schleser, 2004].

[10] A grand mean over all site records and comparison with corresponding instrumental data provides an indication of the common climatic variance emphasised by combining numerous sites. (Figure 1b). Particularly the temperature signal in the $\delta^{13}\text{C}$ network ($r = 0.61$) and the PDSI signal in the $\delta^{18}\text{O}$ network ($r = -0.51$) are higher than most individual site correlations, with the latter even increasing when based on hp data ($r = -0.66$; Figure S3). Comparisons of the ‘European’ $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ chronologies indicate strong and temporally robust coherence in the higher frequency domain. Discrepancies, however, can be found in the longer-term trends with increasing $\delta^{13}\text{C}$, particularly in the first half of the 20th century, and more decadal variation in $\delta^{18}\text{O}$ (Figure 1c).

[11] To analyse spatial coherence within the isotope networks, principal component analysis (PCA) was applied. The first five PCs containing 56% of the variance in the $\delta^{13}\text{C}$ and 57% of the variance in the $\delta^{18}\text{O}$ network were retained and subjected to Varimax Rotation [Richman, 1986]. The rotated principal components (RPC) of the $\delta^{18}\text{O}$ network seem to be largely independent of species and allow the identification of regional subsets using the highest loadings on the first four axes: The first rotated factor (RPC1) explains 18% of the variance with highest loadings of the northern Central European sites in the UK and France (mean loading = 0.71) and moderately high loadings of the oaks from the Swiss Alps (0.47, ‘Cav’) and Austria (0.58, ‘Lai’). Loadings on RPC2 (12% variance explained) are highest at the four eastern Central European sites and the Austrian pine site ‘Poe’ (mean loading = 0.62) and moderately high at the German (0.49, ‘Dra’) and Italian sites (0.50, ‘Ser’). RPC3 (11%) shows highest loadings at all Scandinavian sites (mean loading = 0.63) with the northernmost site ‘Ina’ contributing less (0.48). Finally, loadings on RPC4 (8%) are highest in the western Mediterranean region (mean loading = 0.61) and at the Swiss pine site ‘Vig’ (0.60) and moderately high at the southernmost Spanish site ‘Caz’ (0.53). As only ‘Col’ from Morocco loads most strongly on RPC5 (7%), this component is not further detailed here. Interestingly the identified sub-groups are identical for the RPCs derived from high pass filtered $\delta^{18}\text{O}$ records, and hence are robust over different frequencies. In contrast, RPC patterns of the $\delta^{13}\text{C}$ chronologies are much more diffuse and timescale dependent (not shown), a result that we attribute to more site-specific variance and/or complex long-term behaviour of this parameter.

[12] Comparison of the most relevant principal components with European climate field data (Figure 2) revealed strongest influences of all climate variables during JJA on RPC1 and 3 and slightly shifted maximum temperature response seasons for RPC2 (JAS) and 4 (MJJ). Generally, the spatial distribution of the highest loading sites nicely corresponds with the climate correlation patterns (see the colours in Figure 2). This holds particularly for RPC1,

¹Auxiliary materials are available in the HTML. doi:10.1029/2007GL031106.

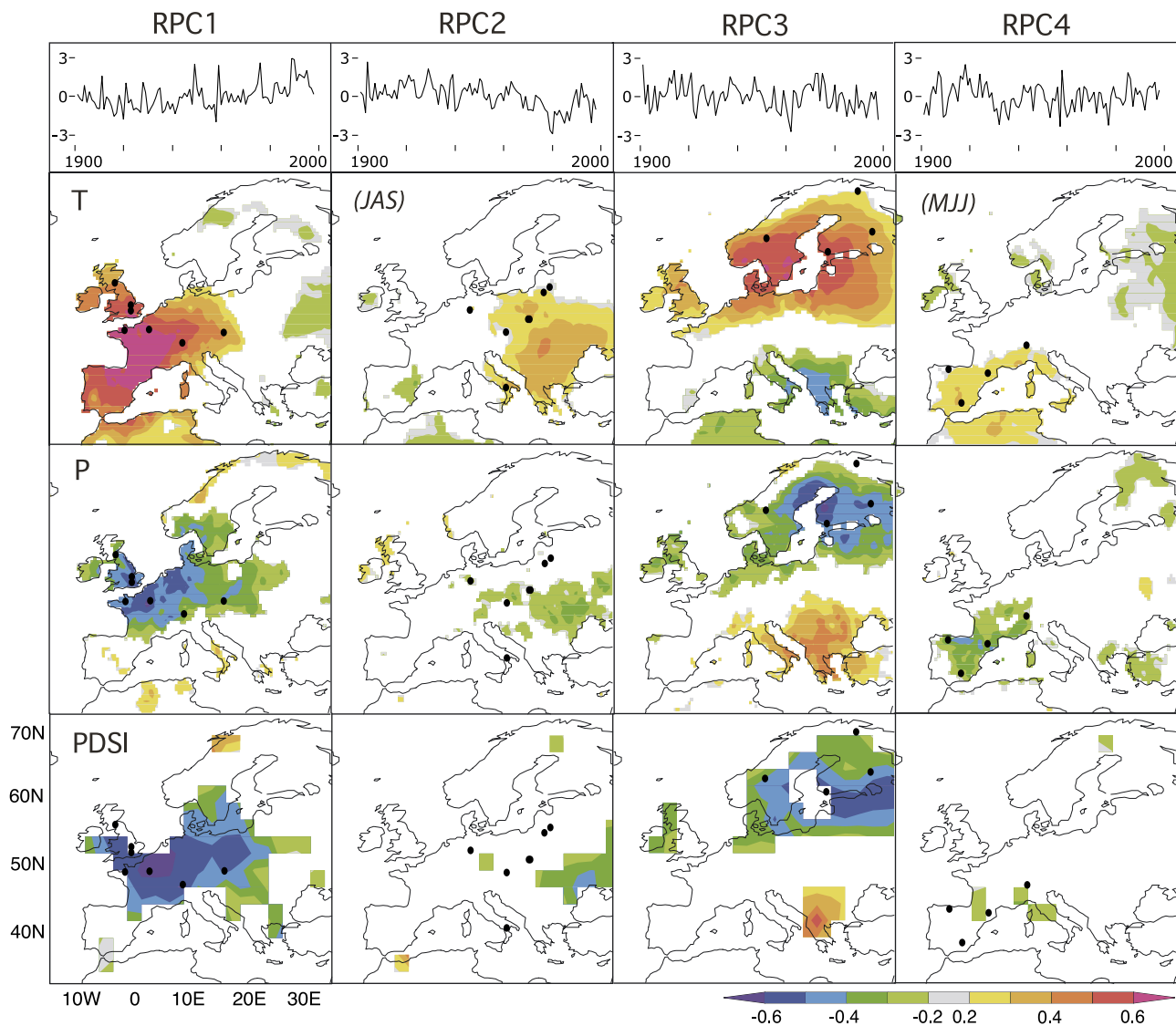


Figure 2. Maps of loadings of site chronologies on varimax-rotated principal components, for the first four of five retained $\delta^{18}\text{O}$ chronology factors (RPC1–4) and corresponding spatial correlation fields for temperature (T), precipitation (P), and PDSI. Dots are sites participating with highest loadings at the corresponding RPCs (time series shown top). Correlations were calculated with seasonal means of June–August (JJA), if not noted differently (*JAS* = July to September, *MJJ* = May to June). All calculations are based on the 1901–1998 common period.

representing Northern and Central European conditions and RPC3, correlating closely with a broad area in North-eastern Europe. RPC4 matches JJA temperature and precipitation over the western Mediterranean Region, whereas RPC2 – with contributing tree sites weighted towards a central European transition zone – shows only weak correlations with the instrumental variables tested.

[13] Altogether, temperatures yield the highest correlations and spatially the most homogenous patterns, which can be explained by the spatial homogeneity of this variable itself. Precipitation signals are patchier, but particularly for RPC1 correspond more closely to the region covered by the relevant tree sites. The PDSI patterns, especially for RPC1 and RPC3, cover the broadest areas, and appear relatively homogenous. This homogeneity is, however, affected by the coarser resolution of the PDSI grid and increased dependency of individual grid cells due to the inclusion of

temperature and soil type information [Dai *et al.*, 2004]. Strongest correlations to all climate variables over northern Central Europe (RPC1) are probably due to a concentration of sites in this region which additionally show rather strong climate signals on a site basis (Figure 1b).

4. Discussion

[14] Despite different sources and fractionation processes driving C and O isotope values in tree rings, surprisingly strong similarities in the response of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ networks to summer climate conditions are found. Tree ring $\delta^{13}\text{C}$ values depend on diffusion and biochemical processes during photosynthetic CO_2 assimilation, with fractionation effects occurring through the diffusion of CO_2 into the stomata and through enzymatic processes during carbon fixation by Rubisco [Farquhar *et al.*, 1982]. $\delta^{18}\text{O}$ values

largely depend on $\delta^{18}\text{O}$ of soil water, which itself is related to the isotope value of rain water, residence time in the soil, evaporation effects and leaf water enrichment due to transpiration at the stomata [Yakir and Sternberg, 2000]. Therefore, both isotope parameters are linked through effects at the leaf level, mediated through variation in stomatal conductance caused by the combined effect of varying temperature and precipitation conditions. Low stomatal conductance during dry/warm weather conditions causes high $\delta^{13}\text{C}$ values through reduced discrimination against ^{13}C . At the same time low relative humidity and high transpiration rates, due to a larger vapour pressure deficit, increase the leaf water enrichment and thus result in higher $\delta^{18}\text{O}$ values [Masson-Delmotte et al., 2005; Rafalli-Delerce et al., 2004; Roden et al., 2000; Saurer et al., 1997]. Hence, particularly under temperate conditions, both parameters are mainly related to summer moisture conditions. Altogether, these mechanisms drive the strong positive correlations to maximum temperature, which represents relevant daytime conditions slightly better than mean temperature (0.02 higher correlations to both isotope parameters than T_{mean} , averaged over all sites) and negative correlations to precipitation in our data. However, since particularly in Central Europe both variables are strongly inter-correlated during summer, the integrating PDSI might be the most appropriate parameter for reconstructing past climatic-ecological conditions, when including both isotope parameters in one model. A clearer focus on drought reconstructions using stable isotopes would also fill a current research gap in high-resolution palaeoclimatology, as such records are rare for temperate regions [Wilson et al., 2005]. Nevertheless, there is still the need to better disentangle mixed temperature and precipitation influences on isotopic discrimination.

[15] Using PCA we highlight the potential of the $\delta^{18}\text{O}$ network for climate reconstruction in four distinct European sub-regions. The retrieved west-east and north-south gradients and the close association of tree ring $\delta^{18}\text{O}$ with precipitation and temperature regimes support the theory of isotopic fractionation as functions of air mass sourcing (temperature of condensation) and air mass trajectory [Rozanski et al., 1993]. The less distinct regional patterns in the $\delta^{13}\text{C}$ network, which are also wavelength dependent, as well as the discrepancies between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records in the low frequency domain, are, however, not yet understood. It is possible that they are related to more local climatic and/or ecological conditions and trends, but could also result from long-term biases within the isotope records through individual age-related trends, site-dependent changes in the physiological response to increasing CO_2 , or currently unexplainable noise [Treydte et al., 2001, 2006]. Once the problem of differing long-term trends is solved, the approach of combining both isotopes may yield relationships that are less influenced by physiological disturbances [Loader et al., 2007], thereby further enhancing the climate signal (Text S1 and Figure S4).

[16] Our results demonstrate the utility of isotopes in tree rings as an additional proxy for climate reconstruction over Europe. While slightly higher correlations may be obtained for temperature, the physiological mechanisms responsible for isotopic discrimination, reflecting a mixture of temperature and moisture influences, point to the PDSI as a key parameter for climatic reconstruction.

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References

- Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrological cycle, *Nature*, **419**, 224–232.
- Boettger, T., et al. (2007), Wood cellulose preparation methods and mass spectrometric analyses of $\delta^{13}\text{C}$, $\delta^{18}\text{O}$ and non exchangeable $\delta^2\text{H}$ values in cellulose, sugar, and starch: An interlaboratory comparison, *Anal. Chem.*, **79**, 4603–4612.
- Büntgen, U., D. C. Frank, D. Nievergelt, and J. Esper (2006), Summer temperature variations in the European Alps, AD 755–2004, *J. Clim.*, **19**(21), 5606–5623.
- Casty, C., H. Wanner, J. Luterbacher, J. Esper, and R. Boehm (2005), Temperature and precipitation variability in the European Alps since 1500, *Int. J. Climatol.*, **25**, 1855–1880.
- Cook, E. R., and K. Peters (1981), The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, *Tree Ring Bull.*, **41**, 45–53.
- Dai, A., K. E. Trenberth, and T. Qian (2004), A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming, *J. Hydrometeorol.*, **5**, 1117–1130.
- Esper, J., E. R. Cook, and F. H. Schweingruber (2002), Low-frequency signals in long chronologies for reconstructing past temperature variability, *Science*, **295**, 2250–2253.
- Esper, J., R. J. S. Wilson, D. C. Frank, A. Moberg, H. Wanner, and J. Luterbacher (2005), Climate: Past ranges and future changes, *Quat. Sci. Rev.*, **24**, 2164–2166.
- Farquhar, G. D., M. H. O'Leary, and J. A. Berry (1982), On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves, *Aust. J. Plant Physiol.*, **9**, 121–137.
- Frank, D., and J. Esper (2005), Temperature reconstructions and comparisons with instrumental data from a tree-ring network for the European Alps, *Int. J. Climatol.*, **25**, 1437–1454.
- Fritts, H. C. (1976), *Tree Rings and Climate*, 567 pp., Academic, New York.
- Gagen, M., D. McCarroll, and J.-L. Edouard (2004), Latewood width, maximum density, and stable carbon isotope ratios of pine as climate indicators in a dry subalpine environment, French Alps, *Arct. Antarct. Alp. Res.*, **36**, 166–171.
- Helle, G., and G. H. Schleser (2004), Beyond CO_2 -fixation by Rubisco: An interpretation of $^{13}\text{C}/^{12}\text{C}$ variations in tree rings from novel intra-seasonal studies on broad-leaf trees, *Plant Cell Environ.*, **27**, 367–380.
- Kagawa, A., A. Sugimoto, and T. C. Maximov (2006), Seasonal course of translocation, storage, and remobilization of ^{13}C pulse-labeled photoassimilate in naturally growing *Larix gmelinii* saplings, *New Phytol.*, **171**, 793–804.
- Leavitt, S. W., and A. Long (1984), Sampling strategy for stable carbon isotope analysis of tree rings in pine, *Nature*, **311**, 145–147.
- Loader, N. J., P. M. Santillo, J. P. Woodman-Ralph, J. E. Rolfe, M. A. Hall, M. Gagen, I. Robertson, R. Wilson, C. A. Froyd, and D. McCarroll (2007), Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions, *Chem. Geol.*, in press.
- Luterbacher, J., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner (2004), European seasonal and annual temperature variability, trends, and extremes since 1500, *Science*, **303**, 1499–1503.
- Masson-Delmotte, V., et al. (2005), Changes in European precipitation seasonality and in drought frequencies revealed by a four-century-long tree-ring isotopic record from Brittany, France, *Clim. Dyn.*, **24**, 57–69.
- McCarroll, D., and N. J. Loader (2004), Stable isotopes in tree rings, *Quat. Sci. Rev.*, **23**, 771–801.
- Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Clim.*, **693**–712.
- Pauling, A., J. Luterbacher, C. Casty, and H. Wanner (2006), Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation, *Clim. Dyn.*, **26**, 387–405.
- Pederson, N., E. R. Cook, G. C. Jacoby, D. M. Peteet, and K. L. Griffin (2004), The influence of winter temperatures on the annual radial growth of six northern range margin tree species, *Dendrochronologia*, **22**, 7–29.

- Rafalli-Delerce, G., V. Masson, J. L. Dupouey, M. Stievenard, M. Breda, and M. Moisselin (2004), Reconstruction of summer droughts using tree-ring cellulose isotopes: A calibration study with living oaks from Brittany (western France), *Tellus, Ser. B*, 56, 160–174.
- Richman, M. B. (1986), Rotation of principal components, *J. Clim.*, 6, 293–335.
- Roden, J. S., G. Lin, and J. R. Ehleringer (2000), A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose, *Geochim. Cosmochim. Acta*, 64, 21–35.
- Rozanski, K., L. Arguas-Arguas, and R. Gonfiantini (1993), Isotopic patterns in modern global precipitation, in *Climate Change in Continental Isotopic Records*, *Geophys. Monogr. Ser.*, vol. 78, edited by P. K. Swart et al., pp. 1–36, AGU, Washington, D. C.
- Saurer, M., K. Aellen, and R. Siegwolf (1997), Correlating $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in cellulose of trees, *Plant Cell Environ.*, 20, 1543–1550.
- Trenberth, K. E., and D. J. Shea (2005), Relationships between precipitation and surface temperature, *Geophys. Res. Lett.*, 32, L14703, doi:10.1029/2005GL022760.
- Treydte, K., G. H. Schleser, F. H. Schweingruber, and M. Winiger (2001), The climatic significance of $\delta^{13}\text{C}$ in subalpine spruce (Lötschental, Swiss Alps): A case study with respect to altitude, exposure and soil moisture, *Tellus, Ser. B*, 53, 593–611.
- Treydte, K., G. H. Schleser, G. Helle, D. Frank, M. Winiger, G. Haug, and J. Esper (2006), The 20th century was the wettest period in northern Pakistan over the past millennium, *Nature*, 440, 1179–1182.
- van der Schrier, G., K. R. Briffa, P. D. Jones, and T. J. Osborn (2006), Summer moisture variability across Europe, *J. Clim.*, 19, 2818–2834.
- Wells, N., S. Goddard, and M. J. Hayes (2004), A self-calibrating Palmer Drought Severity Index, *J. Clim.*, 17, 2335–2351.
- Wilson, R. J. S., B. H. Luckman, and J. Esper (2005), A 500-year dendroclimatic reconstruction of spring/summer precipitation from the lower Bavarian forest region, Germany, *Int. J. Climatol.*, 25, 611–630.
- Warren, C. R., J. F. McGrath, and M. A. Adams (2001), Water availability and carbon isotope discrimination in conifers, *Oecologia*, 127, 476–486.
- Xoplaki, E., J. Luterbacher, H. Paeth, D. Dietrich, N. Steiner, M. Grosjean, and H. Wanner (2005), European spring and autumn temperature variability and change of extremes over the last half millennium, *Geophys. Res. Lett.*, 32, L15713, doi:10.1029/2005GL023424.
- Yakir, D., and L. S. L. Sternberg (2000), The use of stable isotopes to study ecosystem gas exchange, *Oecologia*, 123, 297–311.
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