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A 400-year reconstruction of July relative air humidity for the Vienna region (eastern Austria) based on carbon and oxygen stable isotope ratios in tree-ring latewood cellulose of oaks (*Quercus petraea* Matt. Liebl.)

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Abstract Stable isotope chronologies of carbon and oxygen for the period from 1600 to 2003 and of non-exchangeable hydrogen for the last century were constructed base upon tree-ring latewood cellulose from oaks (*Quercus petraea* Matt. Liebl.) grown in the Vienna region (Austria). The stable isotope ratios reflect highly significantly the summer climate conditions. For the reconstruction of temperature and relative air humidity, verifiable bivariate linear regression models were calculated. Hydrogen isotope values clearly enhanced the model verification. The reconstruction of July relative air humidity in the region Vienna (Austria) for the last 400 years was carried out with carbon and oxygen stable isotope ratios. During this period the humidity oscillated around a mean of $74.7 \pm 4.4\%$ with wet and dry periods in a cycle of approximately 130 years. Predominant wet conditions were reconstructed for the periods 1690–1710, 1765–1820 and 1900–1960, predominant dry periods for 1715 to 1730, 1830 to 1870 and from approximately 1960 to present. Extreme wet months of July were identified in the years 1663, 1795, 1816, 1906, 1915 and 1926, exceptionally dry were inferred for 1616, 1636, 1637, 1751, 1822, 1857, 1863, 1990, 1992 and 2001.

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1 Introduction

Knowledge of past variations in regional climate, registered in natural climate archives, contributes to a better understanding of current global climate change. Trees are one of the best climate archives as their growth conditions are recorded in tree-ring width, density as well as by stable isotope composition of wood constituents with annual and even seasonal resolution. For the purpose of climate proxy, the ring width or density are mainly sensitive in ecological border areas, as at northern latitudes, at high altitudes or at extremely dry sites, where the tree growth is limited by climate (e.g. Fritts 1976; Briffa et al. 2002). In contrast the stable isotope ratios of carbon, oxygen and hydrogen in tree rings are also sensitive to climate in more temperate regions (Rebetez et al. 2003; Treydte et al. 2007).

Carbon from atmospheric carbon dioxide,oxygen and hydrogen from source water (e.g. precipitation, soil water, ground water, air water vapour) are the elements assimilated by plants during photosynthesis and ultimately stored in wood cellulose.

The basic model equation of Farquhar et al. (1982) describes the stable carbon isotope ratio in leaf tissue as result of a two step fractionation during CO_2 diffusion and carboxylation, which are both affected from environmental and plant physiological conditions (Farquhar et al. 1989). In particular, air temperature and humidity influence the stomata conductance and hence these fractionation processes. Furthermore plant physiology, for example leaf morphology and anatomy can also affect the isotope fractionation in leaf tissue (Schleser et al. 1989, 1999).

The oxygen and hydrogen isotope ratios in tree-ring cellulose are determined mainly by the isotopic composition of source water, by leaf water enrichment caused by leaf transpiration and by biochemical fractionation processes also described by basic model equations (Craig and Gordon 1965; Dongmann and Nürnberg 1974; Anderson et al. 2002). The applicability of oxygen and hydrogen stable isotope ratios as proxies for climate reconstructions is based on the assumption, that the isotopic composition of rainfall is strongly correlated to temperature, precipitation amounts and relative humidity at the investigated site (Dansgaard 1964; Edwards and Fritz 1986; White et al. 1994). On the other hand geographic particulars like altitude and topography, which are also related to temperature and water availability, influence the isotope composition of the source water too (Siegenthaler and Oeschger 1980; Feng and Epstein 1995). During the transport of photosynthetic assimilates from the leaves to the stem and during cellulose formation other isotope fractionation processes occur like exchange with xylem sap water (Roden et al. 2000; Waterhouse et al. 2002).

Temperature and humidity as covariant climate factors affect the stomata conductance and therefore the equilibrium between transpiration and assimilation rate and consequently the isotope composition of tree-ring cellulose (McCarroll and Loader 2004; Shu et al. 2005). The isotopic enrichment in leaf water, caused for example by decreased relative air humidity (as well as by increased air temperature), leads to simultaneously increased isotope ratios of carbon, oxygen and hydrogen in stem cellulose and offers the potential for multi-proxy approaches (Saurer et al. 1997; McCarroll and Loader 2004; Danis et al. 2006).

Climate reconstructions for Central Europe mostly based on tree-ring width or maximum density chronologies and have been recently established as well for the Alpine region (Schweingruber et al. 1988; van der Schrier et al. 2007) as for

Table 1 Correlation coefficients (r; r^2) between stable isotope ratios measured in oak latewood cellulose and climate factors from this study and selected European sites; Latin numbers I through XII represent the 12 months of the year, italic numbers the months of previous year; n.a. not available

Reference	Site	Isotope ratio	Climate factor	r	r^2	Calculation period	Significance level (p-value)
This study *Quercus petraea* Matt. Liebl. latewood	Lainzer Tiergarten (Vienna, Austria) dry	$\delta^{13}C_{lw}$	RH_{VII}	−0.66	0.44	1900–2003	<0.001
			T_{IV-X}	0.55	0.30	1900–2003	<0.001
			P_{VI-VII}	−0.47	0.22	1900–2003	<0.001
			$P_{\mathit{IX}-VIII}$	−0.47	0.22	1900–2003	<0.001
		$\delta^{18}O_{lw}$	RH_{VI-VII}	−0.62	0.38	1900–2003	<0.001
			$RH_{VI-VIII}$	−0.62	0.38	1900–2003	<0.001
			$T_{\mathit{IX}-VIII}$	0.45	0.20	1900–2003	<0.001
			$P_{\mathit{IX}-VIII}$	−0.36	0.13	1900–2003	<0.001
		$\delta^{2}H_{lw}$	$RH_{VI-VIII}$	−0.62	0.38	1900–2003	<0.001
			$T_{VI-VIII}$	0.49	0.24	1900–2003	<0.001
			P_{VI-VII}	−0.23	0.05	1900–2003	<0.05
Robertson et al. (2001) *Quercus robur* L. latewood	Sandringham Park (eastern England) dry, free draining	$\delta^{18}O_{lw}$	$T_{VII-VIII}$	0.34		1895–1994	<0.01
			$P_{VII-VIII}$	−0.37		1904–1994	<0.01
			$RH_{VII-VIII}$	−0.48		1920–1994	<0.01
			$\delta^{18}O_{prec-I}$	0.56		1982–1994	<0.05
			$\delta^{18}O_{prec-III}$	0.68		1982–1994	<0.05
			$\delta^{18}O_{prec-X}$	−0.56		1982–1994	<0.05
	Babingley (eastern England) wet, poorly drained	$\delta^{18}O_{lw}$	$T_{VII-VIII}$	0.38		1895–1994	<0.01
			$P_{VII-VIII}$	−0.41		1904–1994	<0.01
			$RH_{VII-VIII}$	−0.50		1920–1994	<0.01
			$\delta^{18}O_{prec-I}$	0.71		1982–1994	<0.01
			$\delta^{18}O_{prec-\mathit{XII}}$	0.69		1982–1994	<0.01

Table 1 (continued)

Reference	Site	Isotope ratio	Climate factor	r	r^2	Calculation period	Significance level (p-value)
Waterhouse et al. (2002)	Norfolk (United Kingdom)	$\delta^{18}O_{lw}$	$T_{VII-VIII}$	0.34		1895–1994	<0.001
Quercus robur L. latewood	well-drained		$RH_{VII-VIII}$	−0.48		1920–1994	<0.001
		$\delta^{2}H_{lw}$	$T_{VII-VIII}$	0.37		1895–1994	<0.01
			$RH_{VII-VIII}$	−0.46		1920–1994	<0.001
Raffalli-Delerce et al. (2004)	Brittany (western France)	$\delta^{18}O_{lw}$	$RH_{VI-VIII}$		0.41	1951–1996	n.a.
Quercus robur latewood	coastal		T_{VII}		0.43	1951–1996	n.a.
		$\Delta^{13}C_{lw}$	$RH_{VI-VIII}$		0.17	1951–1996	n.a.
			T_{VII}		0.18	1951–1996	n.a.
Danis et al. (2006)	Bout-du-Lac (south-east France)	$\delta^{18}O_{lw}$	$\delta^{18}O_{prec-VI}$		0.33	1971–2001	<0.01
Quercus R. latewood	flood plain of river Ire		RH_{VI-IX}		0.30	1971–2001	<0.05
	La Serraz (south-east France)	$\delta^{18}O_{lw}$	$\delta^{18}O_{prec-VI-VII}$		0.40	1971–2001	<0.01
	85 m about lake level		RH_{VI-IX}		0.38	1971–2001	<0.01

temperate regions in northern Italy (Serre-Bachet 1994) or in England (Briffa et al. 1999). For the Viennese region, Strumia (1999) reconstructed the summer (June to August) and spring/summer (April to August) precipitation amounts for the period from 1400 to 2000 based on pine tree-ring widths.

Previous studies have examined sensitivity of isotope values in tree-ring cellulose to climate. Table 1 summarized selected correlation and sensitivity coefficients of carbon, oxygen and hydrogen isotope ratios in latewood cellulose of oaks from temperate European regions. These are mostly related to summer climate conditions. Reconstructions of summer temperature and precipitation variability during the last four centuries were done by Masson-Delmotte et al. (2005) for western France. Recently Etien et al. (2008) reconstructed the maximum growing season temperature (April to September) in northern France for the period from 1596 to 2000.

For Lainzer Tiergarten (Vienna, Austria), the high sensitivity of carbon and oxygen isotopes ratios in oak latewood cellulose to summer climate was first reported by Treydte et al. (2007). Furthermore Weigl et al. (2008b) described a strong response of oak latewood width to summer temperature for a regional chronology of five different sites surrounding Vienna.

The goal of this study is a detailed correlation and sensitivity analysis of stable isotope ratios of carbon, oxygen and of non-exchangeable hydrogen in latewood cellulose from oak (*Quercus petraea* Matt. Liebl.) grown in Lainzer Tiergarten (Vienna, Austria) to instrumental climate data for the calibration period 1900–2003. We want to evaluate the potential of hydrogen for climate reconstructions in comparison to oxygen. The final aim is the reconstruction of climate variability during the last 400 years on the base of these calibration/verification studies.

2 Material and methods

2.1 Study area and sample set

The Vienna region (Austria) is located at the eastern edge of the Alps (Fig. 1a) on the border between the alpine region and the Pannonic plain. Consequently the Viennese climate is influenced from both, the alpine climate in the east and the more continental climate to the south and west of the town (Strumia 1999). The sampling locations are closed to the Viennese meteorological station Hohe Warte (48°15′00″ N, 16°21′04″ E, 202 m a.s.l.) belonging to the Zentralanstalt für Meteorologie und Geodynamik (ZAMG). Homogenized monthly mean data are provided for surface temperatures (T) since 1775, relative air humidity (RH) since 1862, monthly precipitation amounts (P) since 1841, oxygen isotope ratios ($\delta^{18}O_{prec}$) and hydrogen isotope ratios ($\delta^{2}H_{prec}$) in precipitation as monthly means weighted by precipitation amount since 1961.

The whole sample set was composed from living trees and historical wood of oaks from different locations in the Vienna region (Fig. 1a, b). Living sessile oaks (*Quercus petraea* Matt. Liebl.) sampled in 1998 and 2004 (120–180 rings, last ring 1997, 2003 respectively) grew in the Viennese municipal forest Lainzer Tiergarten (48°11′28″ N, 16°12′26″ E, 300 m a.s.l.). The site, described in detail by Liebert (1996), Geihofer et al. (2005) and Weigl et al. (2007, 2008a, b), is characterized by a low slope of about 0° to 10° and a flat and shallow ground of brown soil

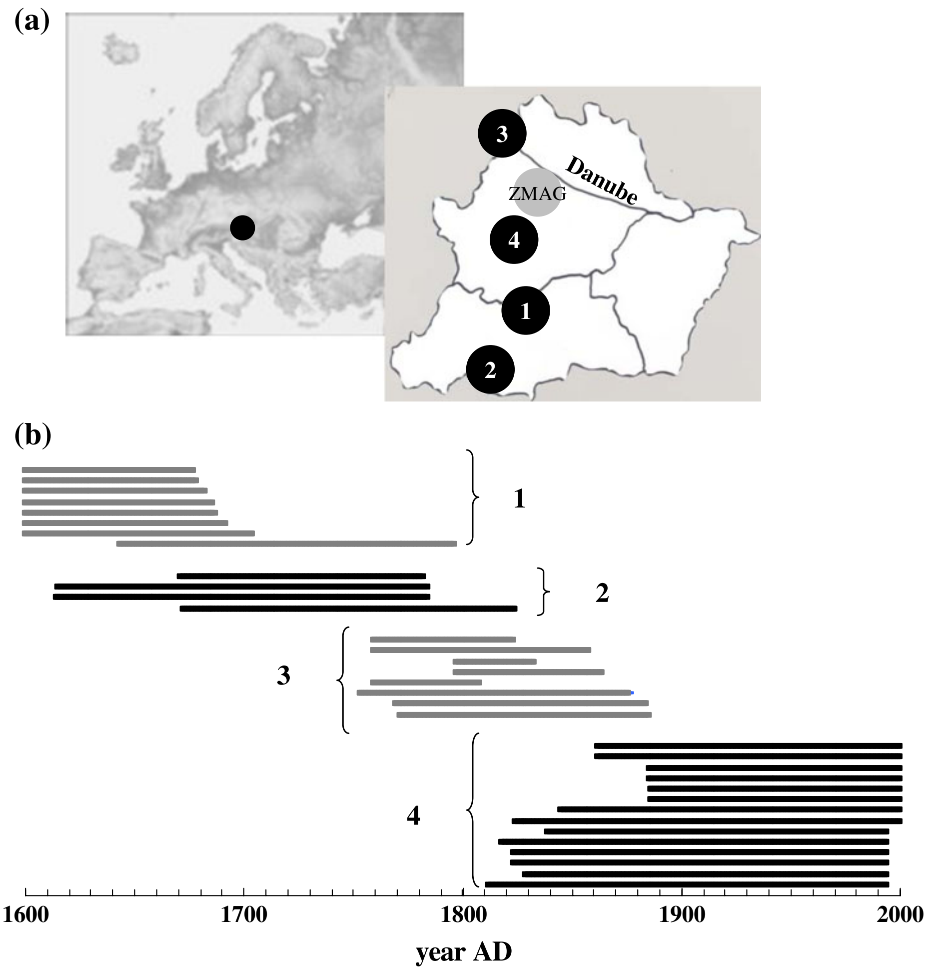

Fig. 1 Locations of sampling sites and of the meteorological station in the Vienna region (**a**), trees sampled for isotope analyses covering the period from 1600 to 2003 (**b**); *1* Perchtoldsdorf (historical wood), *2* Gaaden (historical wood), *3* Klosterneuburg (historical wood), *4* Lainzer Tiergarten, Vienna (living trees), ZMAG meteorological station Hohe Warte

built up on flysch. The forest shows an open structure with partial gaps. The roots have no contact to water reservoirs like lakes or rivers. Besides different oak species (*Quercus petraea* Matt. Liebl., *Quercus robur* L.), beech (*Fagus sylvatica* L.), hornbeam (*Carpinus betulus* L.) and ash (*Fraxinus excelsior* L.) predominantly form the forest canopy (Weigl 2006). The investigated site is dry and has therefore a great potential for reconstruction of moisture conditions. Isotope analyses were carried out with pooled samples out of seven individual living trees (two cores per tree). Historical wood samples (*Quercus petraea* Matt. Liebl., 1600–1885) were collected from three historical buildings surrounding Vienna: for the period 1753–1885 from the belfry in Klosterneuburg Monastery (48°18′27″ N, 16°19′38″ E), for the period 1614–1824 from an interior beam construction of the church “St. Jakobus der Ältere” in Gaaden (48°03′14″ N, 16°12′01″ E) and for the period 1600–1769 from the peel roof construction in Perchtoldsdorf (48°07′12″ N, 16°15′59″ E).). The sample set for isotope analyses was performed on two beams from Gaaden (two cores per beam, in total four cores), eight beams of Perchtoldsdorf (one core per beam) and five beams from Klosterneuburg (two cores per beam in three cases and one core per beam in two cases, in total eight cores) like shown in Fig. 1b. The clear provenience of the oak timber wood is unknown, but however, there is the evidence from archives, that local trees were used generally.

2.2 Methods

2.2.1 Data acquisition

Latewood preparation and pooling The recent (1812–2003) and the ancient (1600–1883) sample set (Fig. 1b) were prepared separately. The best representative wood samples for isotope analyses were carefully selected from the whole sample sets after cross-dating against the Eastern Austrian oak chronology (Geihofer et al. 2005). Pooling was necessary because of very narrow rings from most of the trees with regard to get enough material for cellulose extraction and preparation of cellulose nitrate. So the latewood (lw) of the individual tree rings was separated manually using razorblades and equal homogenized latewood portions of corresponding calendar years were pooled from selected trees.

Cellulose extraction α-Cellulose was extracted from pooled latewood samples using a multistage procedure including organic solvent extraction, bleaching and separation steps. For the analyses of non-exchangeable hydrogen α-cellulose was processed to cellulose nitrate (Boettger et al. 2007).

Mass spectrometric analysis The isotope ratios of carbon ($\delta^{13}C_{lw}$), oxygen ($\delta^{18}O_{lw}$) and of non-exchangeable hydrogen ($\delta^{2}H_{lw}$) in oak latewood cellulose were analyzed at least in duplicates. The results were calculated according to Knöller et al. (2005, 2007) and Boettger et al. (2007). The results are presented as δ values using conventional notation[1] with respect to VPDB (for carbon) and VSMOW (for oxygen and hydrogen) standards (STD). The overall precisions of the methods were ±0.2‰ for $\delta^{13}C_{lw}$, ±0.3‰ for $\delta^{18}O_{lw}$ and ±3‰ for $\delta^{2}H_{lw}$.

2.2.2 Data treatment and statistics

Stable isotope chronologies The $\delta^{2}H_{lw}$ raw data of oak latewood cellulose were measured for the last 100 years and used without any data treatment.

The $\delta^{13}C_{lw}$ raw data series were corrected for anthropogenic changes in the atmospheric CO_2 according to Leuenberger (2007). In order to construct the 400 year long carbon and oxygen isotope time series we assembled $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ of the historical sample set from 1600 only up to 1811 and the whole recent sample set (1812–2003). In this way we got two segments with nearly equal statistical attributes. The historical part of whole Vienna isotope chronology consists of 212 annual

[1] $\delta = \left(R_{Sample} - R_{STD}\right)/R_{STD} \times 1000‰ \left(R = {}^{13}C/{}^{12}C;\ {}^{18}O/{}^{16}O;\ {}^{2}H/{}^{1}H\right)$.

latewood samples with means of $-24.54 \pm 0.60‰$ and $27.40 \pm 0.89‰$ for $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ values, respectively. The recent part was covered by 192 annual samples with means of $-24.60 \pm 0.69‰$ ($\delta^{13}C_{lw}$) and $27.46 \pm 0.98‰$ ($\delta^{18}O_{lw}$).

The building of simple mean series in the overlapping period from 1812 to 1883 (71 years) would be difficult, as the correlation between the historical and the recent chronology is only highly significant for oxygen ($r = 0.71$; $p < 0.001$; $n = 71$) but not for carbon. This fact will not influence our calibration/verification study (1900–2003), as only the recent chronology of both isotopes is being used for this purpose. For climate reconstructions the influence of using the recent as well as the historical part of the isotope chronologies for this period (1812–1883) is discussed in Section 3.5.

Seasonal climate data The response of stable isotope ratios in oak latewood cellulose to climate was checked for the available monthly data (I–XII) and for seasons defined as: spring (March to May, III–V), summer (June to July, VI–VII; July to August, VII–VIII; June to August, VI–VIII), autumn (September to November, IX–XI), winter (December of the previous year to February of the current year, XII–II), growing season (April to October, IV–X) and the annual mean (September of the previous year to August of the current year, IX–VIII).

Statistical parameters The correlations between the raw data series of tree-ring isotope ratios and instrumental climate data were estimated as Pearson's correlation coefficients (r) for the calibration period from 1900 to 2003 ($n = 104$) in which the isotope data of carbon, oxygen and hydrogen were available. The climate sensitivity (slope between isotope ratios and climate factors) and the transfer functions for climate reconstructions were calculated according to common linear regression models. No indexed raw data series were used to present the absolute variability of reconstructed climate signals. The reconstruction errors were calculated on the basis of estimated model uncertainties (±). The postulated models were verified by sharing the whole calibration period into two sub-periods ($n = 52$) and alternating them for calibration and verification statistics between instrumental and predicted data. The squared correlation (r^2), the mean squared errors (MSE), the reduction of error statistic (RE) and the coefficient of efficiency (CE) were estimated according to Briffa and Jones (1992).

3 Results and discussion

3.1 Climate regime

The climate regime in Vienna was discussed in detail by numerous authors (e.g. Rozanski et al. 1993; Strumia 1999; Böhm et al. 2001; Weigl 2006). Patterns in summer (June to August) mean temperature, mean relative air humidity and total precipitation amount for the full instrumental periods are shown in Fig. 2a–c. The summer (VI–VIII) temperature (Fig. 2a) declined up to 1910 and afterwards increased up to now, whereas this trend is twice as large (0.04°C/year; $p < 0.001$) for the last 50 years in the twentieth century than for the first 50 years (0.02°C/year; $p < 0.001$).

The summer (VI–VIII) total precipitation amounts (Fig. 2b) did not show any significant trend over the full instrumental period from 1842 up to now. In contrast,

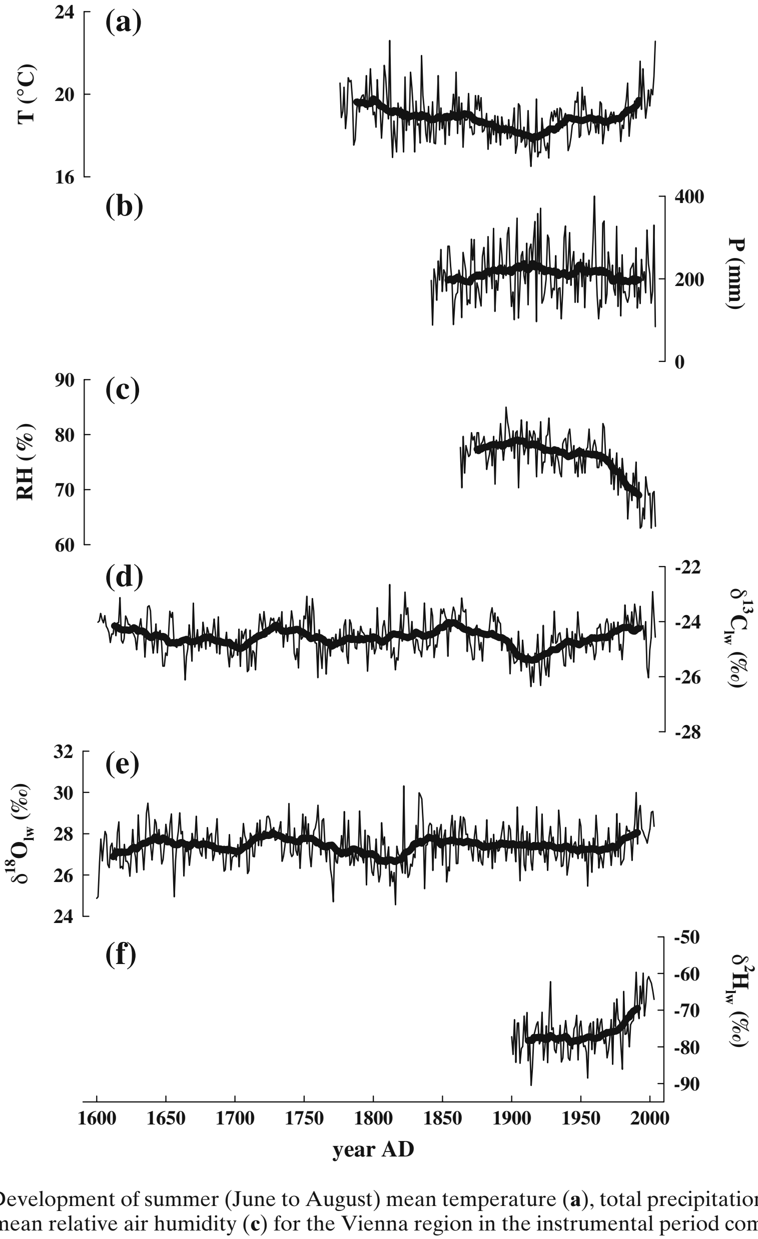

Fig. 2 Development of summer (June to August) mean temperature (**a**), total precipitation amount (**b**) and mean relative air humidity (**c**) for the Vienna region in the instrumental period compared to the stable isotope chronologies for oak latewood cellulose from 1600 to 2003 for carbon (**d**), oxygen (**e**) and from 1900 to 2003 for non-exchangeable hydrogen (**f**); 25-year running mean (*bold black line*)

the summer (VI–VIII) relative air humidity (Fig. 2c) increased very slightly from the beginning of the instrumental period up to 1900 followed by a significant downward trend (−0.06%/year; $p < 0.001$) up to 1950. The last five decades of the twentieth century are marked by a dramatic enhancement of this trend (−0.26%/year; $p < 0.001$), more than four times larger than for the period 1900–1950.

3.2 Tree-ring stable isotope chronologies

Stable isotope chronologies of carbon and oxygen in oak latewood cellulose cover 400 years (1600–2003) and non-exchangeable hydrogen isotope chronology spans the last century from 1900 to 2003. The $\delta^{13}C_{lw}$ values vary around a mean of −24.6 ± 0.6‰ between −26.4‰ and −22.7‰ in this time span (Fig. 2d), the $\delta^{18}O_{lw}$ values are between 24.6‰ and 30.3‰ with a mean value of 27.4 ± 0.9‰ (Fig. 2e). The $\delta^{2}H_{lw}$ values show variations around −75.5 ± 6.5‰ between −90.5‰ and −59.7‰ (Fig. 2f). All latewood raw data series of isotope ratios are GAUSSIAN distributed and significantly autocorrelated (fifth order for carbon, seventh for oxygen and sixth for hydrogen). This indicates memory effects from up to seven previous years similar to Monserud and Marshall (2001) and Boettger and Friedrich (2009).

With focus on the last 100 years the $\delta^{13}C_{lw}$ values show a similar development like summer temperature, a declining trend up to 1910 and a strictly increasing trend afterwards. This upward trend of 0.01‰/year ($p < 0.001$) is constant over the whole twentieth century. The very weak downward trend of $\delta^{18}O_{lw}$ values is replaced in 1980 by a significant upward trend (0.03‰/year; $p < 0.001$). This corresponds well to the results of Danis et al. (2006), who described increasing values during the last 30 years for two $\delta^{18}O_{lw}$ series (*Quercus* R.) from south-east France. The possibility of multiproxy-approaches was described by Saurer et al. (1997), who found simultaneous variations of carbon and oxygen isotope ratios in coniferous and broad-leaved trees from Switzerland to changes in humidity. In our case the applicability of bivariate linear regression models using carbon and oxygen isotope ratios as independent variables seems to be limited by their different trends. On the other hand the $\delta^{2}H_{lw}$ values show this potential better than $\delta^{18}O_{lw}$ with a strong upward trend started approximately in 1960 (0.31‰/year; $p < 0.001$) corresponding very well to the starting time point of drastic decrease in relative air humidity.

3.3 Climate response of stable isotope ratios in oak latewood cellulose

Significant correlations between stable isotope ratios in latewood cellulose of oaks from the Vienna region and meteorological data are shown in Fig. 3. Table 1 summarizes the highest correlation coefficients of our study in comparison with published data from other investigated European oak sites.

Generally the isotope values in oak latewood cellulose correspond very well to summer climate conditions, mostly to relative air humidity followed by temperature and precipitation amounts. The highest correlation coefficients were found between $\delta^{13}C_{lw}$ and RH_{VII} ($r = -0.66$; $p < 0.001$), between $\delta^{18}O_{lw}$ and RH_{VI-VII} respectively $RH_{VI-VIII}$ ($r = 0.62$; $p < 0.001$) and between $\delta^{2}H_{lw}$ and $RH_{VI-VIII}$ ($r = -0.62$; $p < 0.001$). In the case of temperatures, strongest correlations were found between growing season mean and $\delta^{13}C_{lw}$ ($r = 0.55$; $p < 0.001$), annual mean and $\delta^{18}O_{lw}$ ($r = 0.45$; $p < 0.001$), as well as between $T_{VI-VIII}$ and $\delta^{2}H_{lw}$ ($r = 0.49$; $p < 0.001$). The relations between isotope ratios and precipitation amounts are largest between $\delta^{13}C_{lw}$ and P_{VI-VII} respectively total annual sum ($r = -0.47$; $p < 0.001$), between $\delta^{18}O_{lw}$ values and total annual sum ($r = -0.36$; $p < 0.001$) and

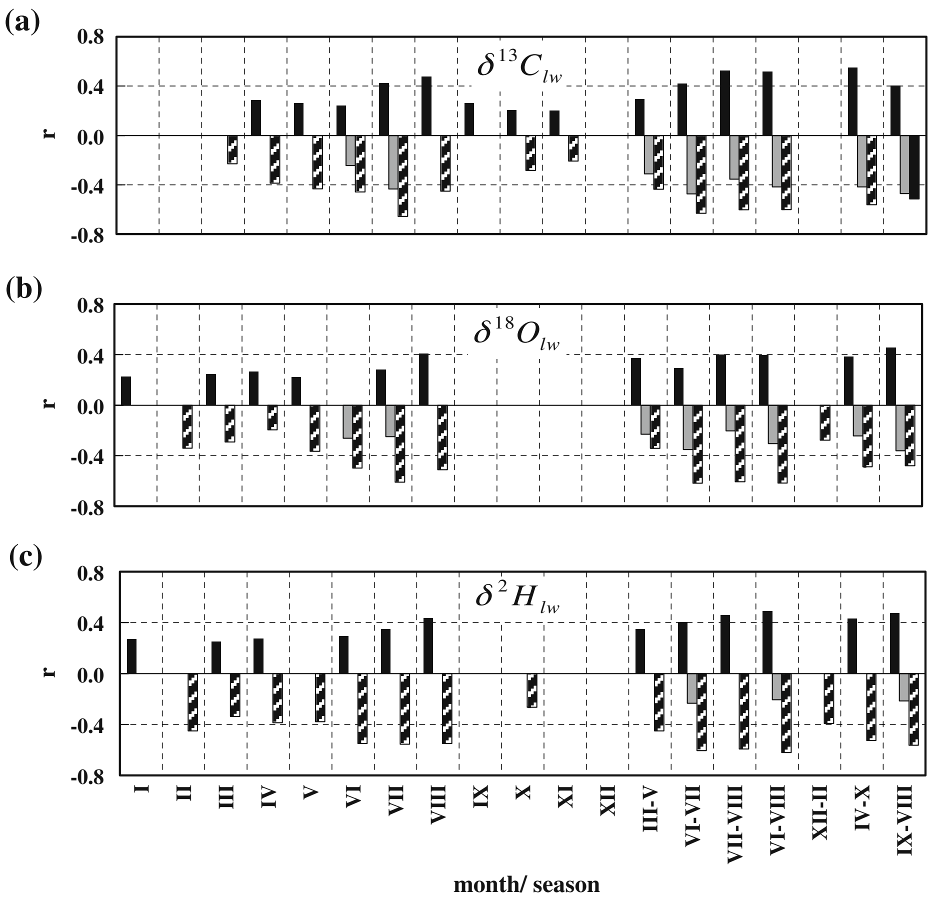

Fig. 3 Significant correlations ($p < 0.05$) between carbon (**a**), oxygen (**b**) and hydrogen (**c**) isotope ratios in oak latewood cellulose and mean temperature (*black bars*), total precipitation amount (*gray bars*) and mean relative air humidity (*black and white brindled bars*) calculated for the calibration period 1900–2003; *I* through *XII* represent the months January to December; *X–II* winter (December previous year to February of the ring year); *III–V* spring (March to May); summer *VI–VII* (June/July), *VII–VIII* (July/August), *VI–VIII* (June to August); *IV–X* growing season (April to October); *IX–VIII* annual mean/sum (September previous year to August of the ring year)

between $\delta^2 H_{lw}$ and P_{VI-VII} ($r = -0.23$; $p < 0.05$). Nevertheless, we excluded the precipitation amounts from further consideration due to its low variation during the last 150 years in contrast to humidity (Fig. 2b, c).

In comparison to other European oak sites (Table 1) the correlation coefficients between $\delta^{13}C_{lw}$ and summer temperature as well as relative air humidity are higher than in Brittany (western France) and comparable for $\delta^{18}O_{lw}$. The two sites in south France (Danis et al. 2006) show correlation coefficients between $\delta^{18}O_{lw}$ and RH_{VI-IX} similar to these from Vienna region.

The $\delta^{18}O_{lw}$ response to summer temperature in Vienna is similar to those from British sites (Robertson et al. 2001; Waterhouse et al. 2002) but lower than for the

Rennes site in France (Raffalli-Delerce et al. 2004). The relation of $\delta^{18}O_{lw}$ to relative humidity is much higher than for the British sites and comparable to the French sites.

The correlations of $\delta^2 H_{lw}$ with summer (June to August) temperature and relative humidity are higher than those from Norfolk, UK (Waterhouse et al. 2002).

We found only a very weak correlation ($r = 0.35$; $p < 0.1$) between $\delta^{18}O_{lw}$ and the annual mean of oxygen isotope ratios in precipitation ($\delta^{18}O_{prec}$) and no seasonal influence of $\delta^{18}O_{prec}$ to $\delta^{18}O_{lw}$ in contrast to other European oak sites, where high correlations were found between the oxygen isotope ratios in tree-ring cellulose and in precipitation water (Table 1). Furthermore, no significant affect of hydrogen isotope ratios in precipitation ($\delta^2 H_{prec}$) on $\delta^2 H_{lw}$ could be estimated. This corresponds to the results reported by Pendall (2000) for southern USA. In contrast, Tang et al. (2000) described a slope of nearly one in the relation between hydrogen isotope ratio in source water and in tree rings of Douglas fir (*Pseudotsuga menziesil*) and subalpine fir (*Abies lasiocarpa*) among different sites. They suggested decreased air humidity when the estimated slope is lower than one. In this context our results are not surprising, because on the investigated site the humidity conditions changed drastically during the last 50 years of twentieth century (Fig. 2c). On the other hand the Lainzer Tiergarten is situated on hills, and the trees no seem to have contact to other sources beside precipitation. Probably the deep roots of oaks still reach ground water or use water of different seasons mixed in the soil column (Waterhouse et al. 2002; Shu et al. 2005).

Summarizing, it seems possible to find multivariate models for the reconstruction of summer relative air humidity and mean temperature, due to the high response of all isotope signals to these climate factors (Fig. 3).

3.4 Calibration/verification study

The relationships with significant correlation coefficients (Table 1) were expressed with linear regressions models for the calibration period (1900 to 2003) generally using the single application of one isotope signal and combining $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ or $\delta^{13}C_{lw}$ and $\delta^2 H_{lw}$ as multi-proxy approach. We found only three verifiable bivariate models summarized in Table 2, two for the reconstruction of July relative air humidity (RH_{VII}) (Eqs. 1 and 2) and one for the summer (July to August) temperature ($T_{VI-VIII}$) (Eq. 3).

$$RH_{VII} = (-4.3 \pm 0.7) * \delta^{13}C_{lw} + (-2.8 \pm 0.5) * \delta^{18}O_{lw} + 44 \quad (1)$$

$$RH_{VII} = (-4.7 \pm 0.7) * \delta^{13}C_{lw} + (-0.35 \pm 0.07) * \delta^2 H_{lw} - 68 \quad (2)$$

$$T_{VI-VIII} = (0.57 \pm 0.13) * \delta^{13}C_{lw} + (0.05 \pm 0.01) * \delta^2 H_{lw} + 37 \quad (3)$$

The linear regression models expressed by Eqs. 1, 2 and 3 show the highest correlations ($r^2_{\max}$) and the lowest deviations ($MSE_{\min}$) between measured and predicted values of RH_{VII} and $T_{VI-VIII}$, respectively.

For the calibration period from 1900 to 2003 we evaluated the model adaption by the slope (b) between instrumental and predicted climate data (Fig. 4). In the case of RH_{VII} both valid models show a similar fitting, visible in values of $b = 0.56$ ($p < 0.001$) for $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ (Fig. 4a) and $b = 0.54$ ($p < 0.001$) using $\delta^{13}C_{lw}$ and $\delta^2 H_{lw}$ (Fig. 4c). The model validation (Table 2) is much better using of $\delta^2 H_{lw}$

Table 2 Calibration/verification statistics for the verifiable bivariate models ($Y = b_1X_1 + b_2X_2 + a$) as transfer functions for reconstruction of July relative air humidity and summer (June to August) temperatures from isotope ratios in oak latewood cellulose; r^2 squared correlation, MSE mean squared error, RE reduction of error statistic, CE coefficient of efficiency

Model parameter			Model fitting				
Y	X		Whole period	Sub periods			
			1900–2003 $n = 104$	Calibration 1900–1951 $n = 52$	Verification 1952–2003 $n = 52$	Calibration 1952–2003 $n = 52$	Verification 1900–1951 $n = 52$
RH_{VII}	X_1: $\delta^{13}C_{lw}$	r^2	0.56	0.48	0.50	0.51	0.47
	X_2: $\delta^{18}O_{lw}$	MSE	17.66	13.05	29.78	17.77	23.09
		RE	0.56	0.48	0.59	0.51	0.63
		CE			0.18		0.08
	X_1: $\delta^{13}C_{lw}$	r^2	0.54	0.41	0.44	0.45	0.40
	X_2: $\delta^{2}H_{lw}$	MSE	18.28	14.88	27.05	19.78	18.43
		RE	0.54	0.41	0.63	0.45	0.70
		CE			0.25		0.27
$T_{VI-VIII}$	X_1: $\delta^{13}C_{lw}$	r^2	0.37	0.32	0.13	0.25	0.25
	X_2: $\delta^{2}H_{lw}$	MSE	0.68	0.59	0.90	0.71	0.81
		RE	0.37	0.32	0.47	0.25	0.49
		CE			0.04		0.08

(CE = 0.25/0.27) instead of $\delta^{18}O_{lw}$ ($CE = 0.18/0.08$). The drastic decline of relative air humidity since 1960 is reflected more by the hydrogen isotope ratios than by oxygen (Fig. 2). For both models (Eqs. 1 and 2) the reconstructed air humidity is well adjusted to the course of instrumental data (Fig. 4b, d) and gives a sufficient description of the relation between isotope ratios and instrumental RH_{VII} despite the large differences in the slopes of trends in the two 50-year sub-periods.

The verifiable model for reconstruction of $T_{VI-VIII}$ using $\delta^{13}C_{lw}$ and $\delta^{2}H_{lw}$ (Eq. 3) shows lower agreement ($b = 0.37$; $p < 0.001$) between predicted and instrumental temperature data (Fig. 4e) and a flatter trend with low correspondence to measured data (Fig. 4f). Consequently, on this site, the direct reconstruction of summer temperatures using the investigated linear regression models does not seem advisable. So, only an indirect calculation with respect to temperature dependance of relative air humidity ($r = -0.59$; $p < 0.001$) about the instrumental period 1862–2003) would be possible.

Establishing robust models describing the climate development in Vienna has several limitations, despite the high significant correlations between the isotope ratios and temperature and humidity data (Table 1; Fig. 3). First, common linear transfer functions often oversimplify the complexity of relations. The stable isotope response to climate is also limited by biological inputs that are of non-linear nature (Schleser et al. 1999). Second, we used pooled material and neglected the fact that different trees could react in different ways to climate parameters (Shu et al. 2005). Third, the high-order autocorrelation in the isotope time series, possibly caused by plant physiological impacts (Monserud and Marshall 2001; Boettger and Friedrich 2009), can obscure the long term climate variations recorded in stable isotope ratios of tree-ring cellulose. Furthermore the enhancement in both warming and drying trends for the Vienna region in the second half of twentieth century, in contrast to the first half (Fig. 2a, c), is a real disadvantage for linear regression.

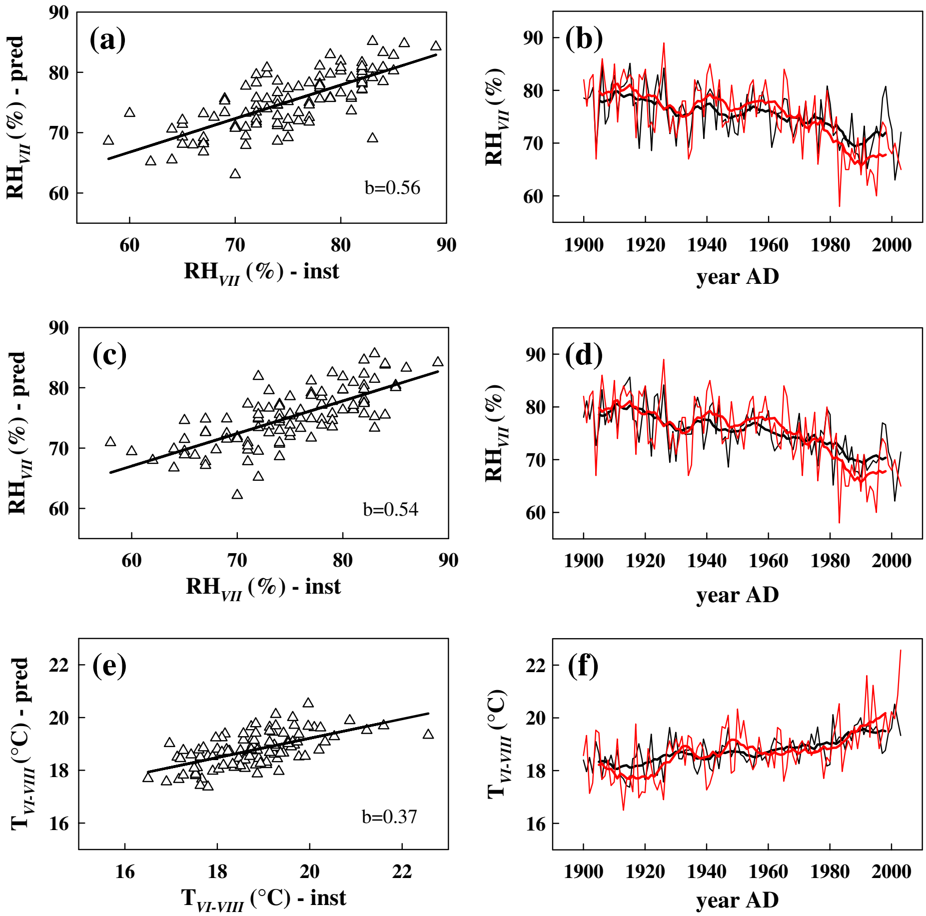

Fig. 4 Model fitting for the period 1900 to 2003: instrumental data versus predicted data for July humidity (RH_{VII}) from $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ (**a**, **b**), from $\delta^{13}C_{lw}$ and $\delta^{2}H_{lw}$ (**c**, **d**) and for June to August temperature ($T_{VI-VIII}$) from $\delta^{13}C_{lw}$ and $\delta^{2}H_{lw}$ (**e**, **f**); instrumental data (*red line*); predicted data (*black line*); 11-year running mean (*bold line*)

Additionally, the temporal stability of climate signals in the isotope ratios of tree ring cellulose in the investigated period is important. It is well known that the signal strength can change drastically in time (Aykroyd et al. 2001; Reynolds-Henne et al. 2007). Our analyses of the correlation between $\delta^{13}C_{lw}$ respectively $\delta^{18}O_{lw}$ and the full available climate data set (temperatures since 1775; relative air humidity since 1862) in a 25-year running mean window offers great oscillations and several periods of non-significant correlations (Fig. 5). The findings of Reynolds-Henne et al. (2007), who described the strongest climate signals in oak for the twentieth century, can be confirmed in our results for air humidity signals (Fig. 5a). In contrast, the summer temperature signal strength in $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ is extremely unstable in the whole period from 1775 to 2003 (Fig. 5b). This is possibly the main reason for the weak model adaption in the case of temperature reconstructions in Vienna.

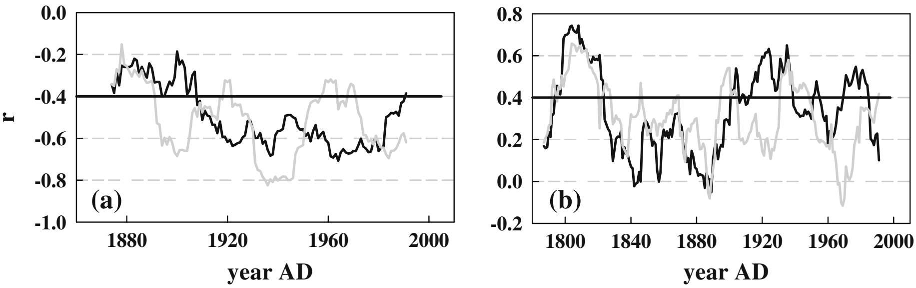

Fig. 5 Temporal stability of correlation between carbon (*black line*) and oxygen (*gray line*) isotope ratios in oak latewood cellulose and July relative air humidity (**a**) and June to August mean temperature (**b**) for the full instrumental period (25-year running mean); *straight black line* $p < 0.05$ significance level

3.5 Reconstruction of July air humidity for the Vienna region

The well fitted bivariate model combining $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ as independent variables (Eq. 1) was used as a transfer function to reconstruct July relative air humidity in the Vienna region back to the year 1600. The slope between instrumental and predicted RH_{VII} data is estimated with $b = 0.46$ ($p < 0.001$) now for the whole period of available humidity data (1862–2003). The humidity data, predicted using the stable isotope ratios of recent wood samples in the time span of overlapping historical and recent wood sample sets (1812–1883) are well correlated to those predicted using the data of historical wood ($r = 0.46$; $p < 0.001$). The reconstructed RH_{VIII} values varied in the last 400 years between 59.6% and 85.9% around a mean of $74.7 \pm 4.4\%$ (Fig. 6). The model error bars were calculated on the base of regression error (Eq. 1). The course of instrumental RH_{VII} data varies within these error limits with two exceptions. The first and highest deviation between predicted and instrumental data up to approximately 5% is visible in the last decades of the

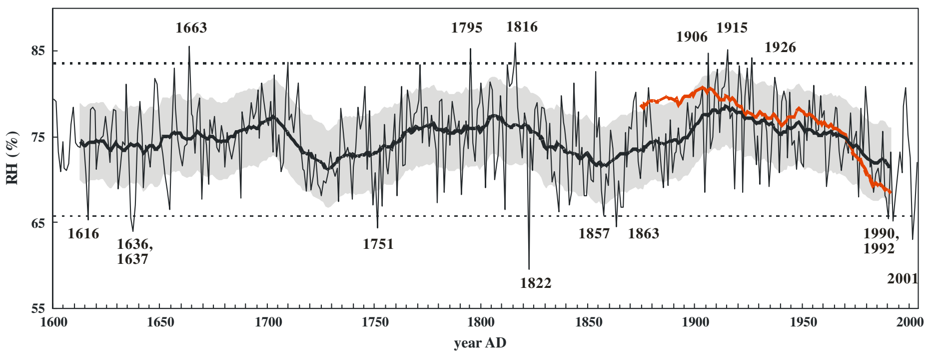

Fig. 6 Reconstruction of the Viennese July relative air humidity for the last 400 years based on $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$ (*black line*) compared to instrumental data (*red line*) with labelled extreme years; 25-year running mean (*bold lines*), $\pm\sigma$ (*gray shaded*), $\pm 2\sigma$ (*dashed lines*)

nineteenth century from 1860 to 1900. The second, appearing from 1980 to recent, is smaller (app. 1.5%) and closer to the regression error limit. It was possibly caused by the low temporal correlation between isotope signals and RH_{VII} in these periods. We found non-significant correlations for carbon before 1910 and additionally for oxygen before 1890 and rapidly diminishing correlations for carbon after 1982 (Fig. 5a). Furthermore another reason for the large difference at the end of the nineteenth century could be the uncertainty of humidity instrumental data in this period.

The chronology of RH_{VII} in the last 400 years seems to be periodic with wet and dry periods in a cycle of approximately 130 years. Reconstructed RH_{VII} values show a relatively stable period within the first approximately 80 years up to 1680 followed by a nearly 20-year period of increasing values. For the next 80 years two opposite trends are visible, a strongly decline to 1730 succeeded by a time span of steady increasing humidity up to ca. 1780. The following 40 years are characterized by relatively stable wet conditions. From 1820 to 1860 a new drying trend is visible followed by another wetting period, up to 1915. The instrumental data in this period show the maximum in RH_{VII} values somewhat earlier at ca. 1900. In the last century the July humidity in the Vienna region generally decreases. The characteristic downward trend, visible in the instrumental data since ca. 1960, is reflected by the model with an understated slope.

We found three wet and dry periods since 1600. Predominant wet conditions could be reconstructed for periods about 1690–1710, 1765–1820 and 1900–1960. The dry periods include 1715–1730, 1830–1870 and from 1960 to present with nearly similar amplitude. The results in general correspond to European Alpine moisture variability for the period 1800–2003 analysed on the basis of monthly self-calibrating Palmer Drought Severity Index maps reported by van der Schrier et al. (2007). These authors described wet summer conditions from 1800 to 1830 and more dry summers between 1830 and 1880 for the north-east of the Alpine region.

The reconstructed RH_{VII} anomalies (RH_{VII} differs more than 2σ from the mean) are shown in Fig. 6 in comparison to those of instrumental data.

Our results predicted extreme wet months of July for 1663, 1795, 1816, 1906, 1915 and 1926. This reconstruction is verified in the years 1906, 1915 and 1926 by instrumental data. Glaser (2001) also described a very wet summer in 1663 for Central Europe. Furthermore Casty et al. (2005) reported extremely high precipitation amounts for the summer in 1663 and an extreme cold summer for 1816 in the European Alps.

Exceptionally dry months of July were identified in 1616, 1636, 1637, 1751, 1822, 1857, 1863, 1990, 1992 and 2001. The instrumental humidity data affirm the reconstructed dry events in 1990 and 1992. July 1616 can be also verified as dry by Casty et al. (2005) who found extremely low rainfall amounts in the summer of this year. Glaser (2001) also reported the summer 1616 also as extreme hot and dry, and the summers of 1636 and 1637 as extremely dry.

Overall, reconstructed anomalies correspond well to instrumental data (Fig. 6). The humidity signals reconstructed from isotopes ratios in tree rings match well the wet (for example 1896–1926) and dry (1982 up to present) instrumental periods. Despite that, some deviations should be noted. Sometimes predicted data are smoothed in contrast to the measured values (e.g. 1965, 1976 and 2003). In other cases they show a stronger signal (e.g. 1863, 1865 and 2001). We even occasionally found inverse relations (e.g. 1891, 1977 and 1998). Such differences can be caused by complex adaptation processes of trees to other environmental changes despite humidity variation and/or possible memory effects of several years known for isotope signals in investigated oaks (see Section 3.2).

4 Conclusions

The stable isotope chronologies of carbon and oxygen for the period from 1600 to 2003 and of non-exchangeable hydrogen for the last 100 years (1900–2003) were constructed from tree-ring latewood cellulose of oaks (*Quercus petraea* Matt. Liebl.) grown in the region Vienna (Austria).

$\delta^{13}C_{lw}$, $\delta^{18}O_{lw}$ and $\delta^{2}H_{lw}$ values most sensitively reflect the summer climate conditions. The highest correlation coefficients for the calibration period from 1900 to 2003 could be estimated between $\delta^{13}C_{lw}$ and RH_{VII} (−0.66), between $\delta^{18}O_{lw}$ and RH_{VI-VII} (−0.61) and between $\delta^{2}H_{lw}$ and $RH_{VI-VIII}$(−0.56). In the case of temperatures we found highly significant correlations between growing season temperature and $\delta^{13}C_{lw}$ values (0.55), annual mean temperatures and $\delta^{18}O_{lw}$ ratios (0.45) and summer (June to August) mean temperatures and $\delta^{2}H_{lw}$ values (0.49).

For these relations linear regressions models were calculated as transfer functions for climate reconstructions. Three verifiable bivariate models were elaborated but only one, combining $\delta^{13}C_{lw}$ and $\delta^{18}O_{lw}$, was found as applicable to reconstruct RH_{VII} for the last 400 years.

Using $\delta^{2}H_{lw}$ for reconstruction of RH_{VII} instead of $\delta^{18}O_{lw}$would significantly enhance the model verification. Therefore, the potential of hydrogen isotope ratios in wood cellulose as climate proxy in future studies can be estimated as very high.

The reconstructed RH_{VII} values oscillate in the period from 1600 to 2003 around a mean of $74.7 \pm 4.4\%$. The course of RH_{VII} during this time seems to be periodic with wetting and drying periods in a cycle of approximately 130 years. Predominant wet conditions were reconstructed for the periods 1690–1710, 1765–1820 and 1900–1960, predominant dry periods for the periods from 1715 to 1730, from 1830 to 1870 and from approximately 1960 to present. These results correspond in general with the European Alpine moisture variability for the period 1800–2003 reported by van der Schrier et al. (2007).

Extreme wet months of July were reconstructed for 1663, 1795, 1816, 1906, 1915 and 1926, exceptionally dry were identified for 1616, 1636, 1637, 1751, 1822, 1857, 1863, 1990, 1992 and 2001. These results correspond to instrumental data and can be verified by independent reconstructions (Glaser 2001; Casty et al. 2005).

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