## SUPPLEMENTARY MATERIAL

## Covariance and climate signals among state-of-the-art tree-ring proxies

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**Table S1.** Summary statistics of the sub-seasonal radial lumen diameter ( $D_{rad}$ ) and cell wall thickness (CWT<sub>rad</sub> and CWT<sub>tan</sub>) chronologies.

Sec	D <sub>rad</sub>			CWT <sub>rad</sub>			CWT <sub>tan</sub>		
	Mean ± 1σ	AC1	Rbar	Mean ± 1σ	AC1	Rbar	Mean ± 1σ	AC1	Rbar
Ι	30.3 ± 4.2	0.35	0.27	3.7 ± 0.4	0.63	0.17	3.2 ± 0.3	0.62	0.21
П	29.3 ± 3.9	0.40	0.25	3.7 ± 0.4	0.67	0.12	3.2 ± 0.3	0.59	0.22
Ш	28.1 ± 3.8	0.44	0.27	3.7 ± 0.4	0.65	0.11	3.3 ± 0.4	0.60	0.23
IV	26.7 ± 3.8	0.43	0.29	3.8 ± 0.4	0.63	0.13	3.3 ± 0.4	0.58	0.22
V	24.8 ± 3.7	0.40	0.31	3.9 ± 0.5	0.58	0.15	3.4 ± 0.4	0.53	0.21
VI	22.2 ± 4.0	0.31	0.35	4.1 ± 0.5	0.51	0.20	3.5 ± 0.4	0.48	0.22
VII	18.4 ± 4.0	0.24	0.38	4.4 ± 0.6	0.44	0.24	3.7 ± 0.5	0.45	0.23
VIII	14.0 ± 3.3	0.23	0.40	4.8 ± 0.6	0.44	0.25	3.8 ± 0.5	0.48	0.22
IX	10.2 ± 2.4	0.31	0.39	5.1 ± 0.5	0.46	0.28	3.7 ± 0.5	0.56	0.21
X	6.7 ± 1.5	0.29	0.30	5.0 ± 0.5	0.43	0.29	$3.3 \pm 0.4$	0.58	0.20

**Sec:** sector. **Mean ± 1** $\sigma$ : arithmetic mean [µm] ± 1 standard deviation (1 $\sigma$ ) calculated over all rings between 1861–2020 CE. **AC1:** first-order autocorrelation of the raw chronologies. **Rbar:** average inter-series correlation between the 30SP-detrended series. All statistics are calculated for the period 1861–2020 CE.

**Table S2.** Results of the principal component analysis (PCA) applied on the annually resolved TRW, MXD,  $\delta^{13}C_c$ ,  $\delta^{13}C_m$ ,  $\delta^{18}O_c$ ,  $\delta^{2}H_m$ , and the 30  $D_{rad}$ , CWT<sub>rad</sub> and CWT<sub>tan</sub> sector chronologies.

Principal component	Eigenvalue	Explained variance [%]	Cumulative percent- age of variance [%]	P value of randomization
1	12.27	34.09	34.09	< 0.001
2	8.99	24.97	59.06	< 0.001
3	3.54	9.83	68.89	< 0.001
4	2.04	5.66	74.55	< 0.001
5	1.65	4.59	79.14	> 0.05

Note that according to the Random-Lambda rule, PC4 is the last useful axis.



**Fig. S1.** Tree-ring width (TRW) chronology of this study (black curves) compared to the well-replicated (n = 872 series) TRW chronology of Esper et al. (2021; grey curves) after detrending with **(a)** 30-year and **(b)** 100-year cubic smoothing splines (left panels). Boxplots (right panels) show the distribution of TRW indices over the 1861–2016 CE common period. Maximum latewood density (MXD) chronology of this study (black curves) compared to the well-replicated (n = 192 series) MXD chronology of Esper et al. (2020; grey curves) after detrending with **(c)** 30-year and **(d)** 100-year cubic smoothing splines. Boxplots show the distribution of MXD indices over the 1861–2017 CE common period. R values indicate correlations between the TRW and MXD chronologies calculated from 1861 to 2016 (TRW) and 2017 CE (MXD), respectively. All correlations are significant at p < 0.001.



**Fig. S2.** Carbon isotope corrections. Raw mean chronologies of the **(a)** cellulose ( $\delta^{13}C_c$ ) and **(b)** methoxy ( $\delta^{13}C_m$ ) stable carbon isotopes. Grey curves are the raw chronologies ( $\delta^{13}C_{raw}$ ), black solid curves are the Suess-effect-corrected chronologies ( $\delta^{13}C_{atm}$ ), and black dashed curves are the pin-corrected chronologies ( $\delta^{13}C_{pin}$ ).



**Fig. S3.** Cambial ages of the individual series (grey lines) and their arithmetic mean (black lines) over the 1861–2020 CE period for (a) the TRW, TRSI and QWA data, and (b) MXD data.



**Fig. S4.** Individual series (grey lines) and mean chronologies (black lines) of raw  $CWT_{rad}$  and  $CWT_{tan}$ . Values (right top) are the arithmetic mean ± 1 standard deviation calculated over all tree rings between 1861–2020 CE. The mean chronologies of  $CWT_{rad}$  and  $CWT_{tan}$  correlate at r = 0.77 (p < 0.001) over the 1861–2020 CE common period.



**Fig. S5.** Correlations between the 30SP-detrended proxy chronologies and diurnal temperature range for 1931–2020 CE. The  $\delta^{13}$ C data are corrected for the Suess-Effect. Horizontal dashed lines indicate the significance level of p < 0.01. Please note that the significance level for MXD is marginally higher due to the shorter calibration period (1931–2017 CE), but is not displayed for the sake of clarity.



**Fig. S6.** Correlations between the 30SP-detrended proxy chronologies and previous-year (**a**) mean air temperature ( $T_{mean}$ ), (**b**) precipitation, (**c**) the PDSI, and (**d**) cloud cover data calculated for 1931–2020 CE. The  $\delta^{13}$ C data are corrected for the Suess-Effect. Horizontal dashed lines indicate the significance level of p < 0.01. Please note that the significance level for MXD is marginally higher due to the shorter calibration period (1931–2017 CE), but is not displayed for the sake of clarity.



**Fig. S7.** Squared coherence (1931–2020 CE) between **(a-b)**  $\delta^{13}C_c$ , **(c-d)**  $\delta^{13}C_m$ , **(e-f)**  $\delta^{18}O_c$ , **(g-h)**  $D_{rad}$  and June-August temperature (top panels) and precipitation (bottom panels). Grey dashed lines are the 95% confidence intervals.



**Fig. S8.** Temperature ( $T_{mean}$ ) and precipitation (Prec) signals in the Suess-effect-corrected (*ATM*) and pin-corrected (*PIN*) (a)  $\delta^{13}C_c$  and (b)  $\delta^{13}C_m$  data. Vertical bars (left panels) show correlations between the HOM-detrended  $\delta^{13}C$  records and June-August  $T_{mean}$  (red colors) and precipitation (blue colors) for 1931–2020 CE. The curves in the right panels show the corresponding 31-year running correlations for the different detrendings.



**Fig. S9. (a)** Thirty-one-year running correlations between the detrended  $\delta^2 H_m$  chronologies and June-September mean temperature (JJAS T<sub>mean</sub>) and between the detrended CWT<sub>rad.LW</sub> chronologies (mean of sectors VIII-X) and JJAS T<sub>mean</sub>. Squared coherence between **(b)**  $\delta^2 H_m$  and JJAS T<sub>mean</sub> and between **(c)** CWT<sub>rad.LW</sub> and JJAS T<sub>mean</sub> for 1931–2020 CE. Grey dashed lines are the 95% confidence intervals.



**Fig. S10. (a)** Z-scores of the HOM-detrended (annual) D<sub>rad</sub> record (black lines), raw June-August (JJA) precipitation (blue line), and JJA cloud cover (orange line). R values indicate correlations between D<sub>rad</sub> and the climate records. **(b)** Corresponding 31-year running correlations between the HOM-detrended D<sub>rad</sub> chronology and JJA precipitation and cloud cover, respectively (same colors as in panel a).



**Fig. S11.** Correlations between the 30SP-detrended  $D_{rad}$  sector chronologies (I = left, X = right) and  $T_{mean}$  calculated for 1931–2020 CE. Horizontal dashed lines indicate the significance level of p < 0.01.



**Fig. S12.** Squared coherence between the **(a-f)** precipitation-sensitive (blue labels) and **(g-i)** temperature-sensitive proxies (red labels) calculated for 1861–2020 CE (MXD to 2017 CE). Grey dashed lines represent the 95% confidence intervals.



**Fig. S13.** Z-Scores of the **(a-b)** Suess-effect-corrected  $\delta^{13}C_{c_atm}$  (black lines) and  $\delta^{13}C_{m_atm}$  (grey lines) records and **(c-d)** pin-corrected  $\delta^{13}C_{c_pin}$  and Suess-effect-corrected  $\delta^{13}C_{m_atm}$  records. The thick lines are 50-year cubic smoothing splines. Scatterplots on the right show the relationship between the  $\delta^{13}C_{data}$ . The single points are colored according to their year. Dashed lines are the linear trends.



**Fig. S14.** Z-scores of the  $\delta^{18}O_c$  record (black lines) together with **(a-b)** annual and **(c-d)** summer precipitation  $\delta^{18}O$  (blue lines). The precipitation  $\delta^{18}O$  data are from Nelson et al. (2021) and were calculated for the Mt. Smolikas site (https://isotope.bot.unibas.ch/PisoAI). Scatterplots on the right show the relationships between  $\delta^{18}O_c$  and seasonal precipitation  $\delta^{18}O$  for 1950–2010 CE. Dashed lines are the linear trends.



**Fig. S15.** Seasonality of precipitation  $\delta^2$ H. The precipitation  $\delta^2$ H data are from Nelson et al. (2021) and were calculated for the Mt. Smolikas site (https://isotope.bot.unibas.ch/PisoAI). The thick black line is the arithmetic mean and the shaded area indicates ± 1 standard deviation for 1950–2010 CE.

## Supplementary references

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