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Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium

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A B S T R A C T

A predicted rise in anthropogenic greenhouse gas emissions and associated effects on the Earth's climate system likely imply more frequent and severe weather extremes with alternations in hydroclimatic parameters expected to be most critical for ecosystem functioning, agricultural yield, and human health. Evaluating the return period and amplitude of modern climatic extremes in light of pre-industrial natural changes is, however, limited by generally too short instrumental meteorological observations. Here we introduce and analyze 11,873 annually resolved and absolutely dated ring width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany, and the Czech Republic, which continuously span the AD 962–2007 period. Even though a dominant climatic driver of European fir growth was not found, ring width extremes were evidently triggered by anomalous variations in Central European April–June precipitation. Wet conditions were associated with dynamic low-pressure cells, whereas continental-scale droughts coincided with persistent high-pressure between 35 and 55°N. Documentary evidence independently confirms many of the dendro signals over the past millennium, and further provides insight on causes and consequences of ambient weather conditions related to the reconstructed extremes. A fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming may question the common believe that frequency and severity of such events closely relates to climate mean stages. This joint dendro-documentary approach not only allows extreme climate conditions of the industrial era to be placed against the backdrop of natural variations, but also probably helps to constrain climate model simulations over exceptional long timescales.

1. Introduction

Anthropogenically-induced climate change is projected to rise Central European temperatures by around 2–5 °C over the 21st century (IPCC, 2007), to increase the frequency, severity and probability of extremes (Fischer and Schär, 2009), and therefore to affect biological, ecological and even societal systems among various spatiotemporal scales (Hegerl et al., 2011). An associated increase in evaporation and amplification of the hydrological cycle will likely occur during the next decades (Min et al., 2011), yielding subtropical drying but augmented precipitation at more northern latitudes (Zhang et al., 2007). Hydrological regime shifts have already been simulated by climate models (Wentz et al., 2007), and were placed in a long-term context of natural climate variability by means of proxy records (Esper et al., 2007).

Quantification of the expected hydroclimatic changes, however, appears to be particularly challenging at the continental-scale and across the mid latitudes (Stott et al., 2010), where prediction of frequency, severity and probability of future climatic extremes still

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remains puzzling (O'Gorman and Schneider, 2009). Instrumental station measurements that systematically cover the last 100–150 years hinder any proper assessment of the statistical likelihood of return period, duration and magnitude of climatic extremes prior to the anthropogenic era of approximately the past 150 years, equal to the industrialization across Europe (Auer et al., 2007; Büntgen et al., 2010a). A palaeoclimatic perspective is therefore indispensable to place modern trends and events in a pre-industrial context (Battipaglia et al., 2010), to disentangle effects of human greenhouse gas emission from natural forcing and internal oscillation (Hegerl et al., 2011), and to constrain climate model simulations and feedbacks of the global carbon cycle back in time (Frank et al., 2010).

More frequent and severe heat waves (Schär et al., 2004; Fischer and Schär, 2009; Barriopedro et al., 2011), together with an increase in the rate and magnitude of flood and/or drought events (Pall et al., 2011) is expected to be most critical for environmental sustainability, forest vitality and agricultural productivity, as well as for economic capacity, public vulnerability and even political stability (Büntgen et al., 2011c). The most recent and certainly most dramatic example emerges from the catastrophic 2011 drought at the Horn of Africa (United Nations Report, 2011). Enhanced monitoring efforts and proxy archives, in tandem with advanced timeseries analyses and complex modeling experiments are thus mandatory to disentangle return period and magnitude of extremes from shifts in mean stages, and to quantify their effects on ecological thresholds, tipping points, and collapses (Ims et al., 2008), particularly because single climatic events may be strong enough to trigger long-term ecosystem changes (Jentsch and Beierkuhnlein, 2008).

European tree-ring chronologies, together with documentary evidence, successfully demonstrated the ability to reconstruct climatic variations for different regions and over several centuries (Brázdil et al., 2002; Battipaglia et al., 2010; Büntgen et al., 2011a). Understanding spatiotemporal fluctuations in frequency and severity of climatic extremes over the past millennium and most of the continent is though limited. It further remains unclear if long-term changes in climatic mean stages such as those associated with the Medieval Climate Anomaly (AD ~900–1300), the Little Ice Age (AD ~1300–1850), and the Recent Global Warming (AD ~1850–present), affected the probability of extremes (IPCC, 2007). Comprehensive detection and attribution studies must therefore be improved to analyze ambient climate patterns that are conductive to extreme events (Hegerl et al., 2011).

Individual tree-ring width (TRW) measurement series from European fir (*Abies alba* Mill.) stands north of the Alps correlate positively with TRW data from southern Europe, namely Italy, making fir the only tree species that can be accurately cross-dated diagonally over the Alpine arc. This exceptionally strong common signal is likely triggered by continent-wide atmospheric circulation patterns during the onset of ring formation around April–June (Battipaglia et al., 2010), when the amount of soil moisture availability is most important (Büntgen et al., 2011a). Even though European fir was spatially much more abundant over most of the Holocene (Pearman et al., 2008) and frequently used as construction timber (Strassburger and Tegel, 2009), it has so far barely been considered for dendroclimatological studies (Brázdil et al., 2002; Wilson and Elling, 2004; Carrer et al., 2010; Büntgen et al., 2011a). Fir TRW compilations developed from well-replicated datasets among several regions and for the past 1000 years are, however, still missing (Büntgen and Tegel, 2011).

Here we introduce the largest TRW collection of living and historical European fir, reconstruct hydroclimatic springtime extremes over the past millennium, use independent documentary evidence for comparison, and discuss strengths and weaknesses associated with this study. Conclusive remarks may appear stimulating not only for (palaeo-)climatologists but also for other scientists within the interdisciplinary arena of global environmental change research, because the herein obtained annually resolved and absolutely dated record of Central European hydroclimatic extremes represents a proxy benchmark to placed climate and environmental conditions of the industrial era against the backdrop of natural variations, to improve the absolute dating of lower resolution proxy archives, and to further help constraining climate model simulations over the past millennium.

2. Materials and methods

Annually resolved and absolutely dated TRW measurement series of 11,873 living and historical firs were compiled from low- to mid-elevation forests (<900 m asl) in France, Switzerland, Germany, and the Czech Republic (Fig. 1). This compilation likely represents the largest TRW collection ever used for dendroclimatological investigations in Europe, and allowed three regional subsets (West, Mid, East) of even sample distribution over the past millennium to be independently developed (Fig. 2). Data from France, Switzerland and Germany were included in the 'West' subset, data from Germany entered the 'Mid' subset, and data from Germany and the Czech Republic were aggregated in the 'East' subset (Fig. 1). Only core or disc samples with more than 50 rings were considered to avoid possible dating errors of the historical material, and to further reduce the relative proportion of juvenile wood within the chronologies (Esper et al., 2008).

The original TRW measurement series (mm/year) were gap-filled and power-transformed prior to their standardization (Cook and Peters, 1997). Residuals were used for index calculation between the power-transformed measurement series and their corresponding cubic smoothing splines with 50% frequency-response cutoff at 20 years (Cook and Peters, 1981). Chronologies were derived from bi-weight robust means, and temporal variance changes were stabilized (Frank et al., 2007b). The three regional chronologies (West, Mid, East) were normalized to means of zero and standard deviations (STDEV) of one over their common period AD 1010–1996. Running 31-year STDEV values of the regional z-scores were computed and deviated to further mitigate temporal biases in year-to-year variance (Battipaglia et al., 2010). Regional extremes were assigned for years in which two out of three chronologies exceeded the 1.5 STDEV threshold, whereas more severe network extremes were reflected from simultaneous values >1.5 STDEV among all three regional chronologies (Büntgen et al., 2011c).

Long, homogenized and spatially averaged instrumental temperature and precipitation measurement series from the Greater Alpine Region were employed for growth–climate response analyses back to AD 1800 (HISTALP; Auer et al., 2007). Composite analyses were performed for the 20 strongest positive and 20 strongest negative fir growth anomalies back to AD 1659 (Büntgen et al., 2010b), using monthly resolved and gridded mid-tropospheric 500 hPa geopotential height estimates (Z500) of the 30–70°N and 30°W–40°E Atlantic/European sector (Luterbacher et al., 2002). Gridded 2.5 × 2.5° field indices of monthly resolved Z500 available back to 1659 are represented by a combination of instrumental station temperature, precipitation, and pressure series, as well as documentary proxy evidence, which were statistically evaluated by various calibration/verification exercises and industrial/pre-industrial transfer functions (Luterbacher et al., 2002). Methodological details related to the field reconstruction, together with the predictor sources, and associate uncertainties are outlined in Luterbacher et al. (2002).

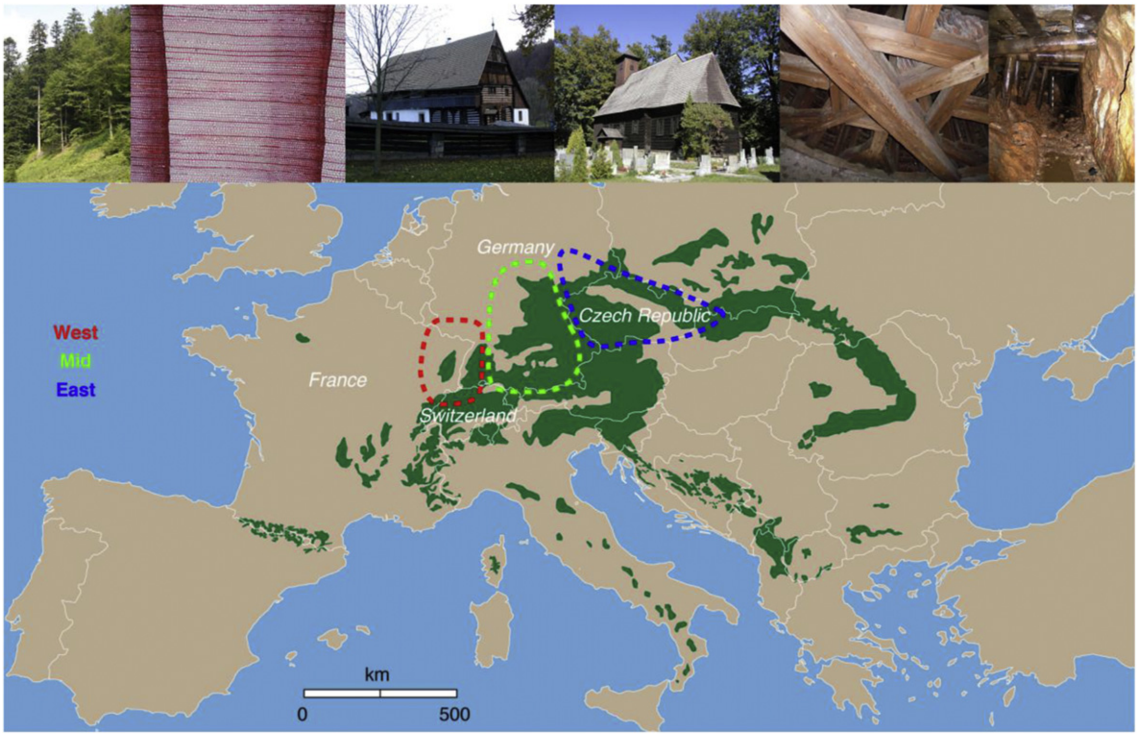

Fig. 1. Examples of living and historical sampling sites, as well as a high-resolution (40× amplified) micro-section superimposed on a European fir (*Abies alba*) distribution map that indicates location of the three regional (West, Mid, East) fir subsets (red, green, blue) including a total of 11,873 individual TRW samples. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Documentary index series back to AD 1500 were selected for Switzerland (Pfister, 1999), Germany (Glaser, 2008; http://www.hisklid.de), and the Czech Lands (Historical–climatological database). Both, temperature and precipitation patterns of the individual months were classified into an ordinal seven-degree scale: −3 extremely cold (extremely dry), −2 very cold (very dry), −1 cold (dry), 0 normal, +1 warm (wet), +2 very warm (very wet), +3 extremely warm (extremely wet). Seasonal indices were obtained by summing the corresponding monthly values, and TRW extremes were related to spring (March–May, MAM) and summer (June–August, JJA) weather indices between −9 and 9, as well as against March–June indices between −12 and 12, and May indices between −3 and 3.

Documentary index series are based on the combined interpretation of direct and indirect data. Direct data are narratives describing the course of weather and climate per se, often including

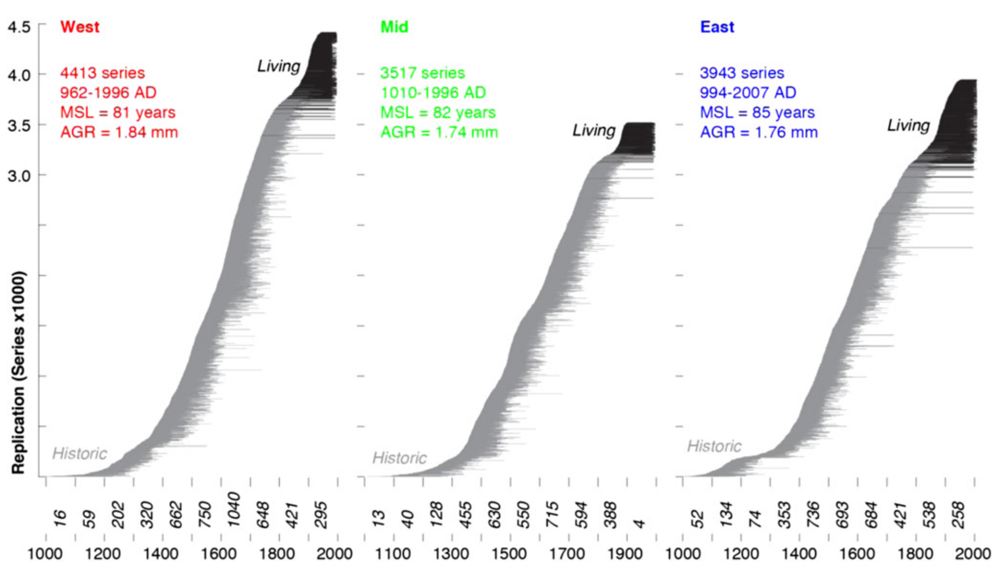

Fig. 2. Temporal distribution of the 11,873 individual Central European fir TRW samples sorted by region (West, Mid, East), their subset characteristics (MSL = mean segment length, AGR = average growth rate), and regional replication sums per century (vertical values).

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accounts of the societal impacts of extreme events and their perception by individuals, local communities, and authorities. Indirect data, in contrast, refer to physically based phenomena associated with weather and climate such as plant and animal life cycles or ice and snow seasonality (Brázdil et al., 2010), and therefore generally appear to be more robust and direct climate proxy archives (Frank et al., 2007a). With respect to source generation, Pfister et al. (2009) draw an important distinction between sources produced by individuals (e.g., chronicles, weather diaries, travel diaries, pictorial evidence) on the one hand shaped by the social background, the motivations and the preferences of their authors and centuries-long quantitative and relatively homogeneous series of institutional data (e.g., grape and grain harvest dates) produced by governments or other bodies such as the church, for which procedures of calibration and verification could be applied (Chuine et al., 2004; Brázdil et al., 2010; Možný et al., 2011). It should be noted that documentary data were so far successfully employed to assess Central European monthly temperatures (Dobrovolný et al., 2010b), extreme winters and summers in the Czech Lands (Dobrovolný et al., 2010a), as well as for high-frequency comparison with regional to continental-scale fir TRW extremes (see Battipaglia et al., 2010 for details), over the past centuries.

To compare dendro-extremes with documentary data, box-plots (mean, upper and lower quartile, highest and lowest values) of Swiss, German and Czech temperature and precipitation indices from AD 1500 onwards were calculated for different groups of positive and negative fir extremes, but were only shown for those groups of extreme years, in which the number of cases was sufficient, i.e., not <10. Statistical significance of the individual mean indices was tested by F-tests for differences in variance and by *t*-tests for differences in mean ($p = 0.05$).

Documentary data prior to AD 1500 are generally much more scarce, however, sporadic evidence may be drawn from Alexandre (1987), Brázdil and Kotyza (1995) or Glaser (2008). Glaser and Riemann (2009), for instance, used an incomplete archive for developing seasonal indices in Germany but only in the -1, 0 and $+1$ scale (for this data see http://www.hisklid.de). We herein, for the first time, utilized documentary evidence from Western and Central Europe of (preliminary) seasonal temperature and precipitation indices in a seven-degree scale (from -3 to $+3$), compared these data with TRW extremes, and expressed their statistical relationships via box-plots.

3. Results

3.1. Growth trends, variations, and responses

Replication of the three regional datasets ranges from 3517 to 4413 samples, and the common period is AD 1010–1996 (Fig. 2). A similar age structure of 81–85 years among the regions yields an even temporal sample distribution, and average growth rates (AGR) only slightly vary between 1.74 and 1.84 mm (Fig. 2). The three independent regional chronologies share a significant ($p < 0.001$) fraction ($r_{1133-1996} = 0.73$) of common inter-annual to multi-centennial growth variability (Fig. 3). Running 31-year correlation coefficients describe less agreement during the records' early portions before the mid-13th century and again during the 20th century (Fig. 3A). Below-mean growth rates were found in all three chronologies prior to ~1250, from ~1670–1725, ~1775–1845, and in the 1970s (Fig. 3B), whereas positive growth anomalies were most obvious in the 14th century, ~1490, and from ~1880–1950. The three detrended chronologies correlate at 0.81 over the common period 1133–1996 (Fig. 3C). These records evidently demonstrate that most of the coherency is related to the high-frequency domain. The herein observed extraordinary growth similarity at the sub-continental-scale reinforced data polling, as well as the development of one single Central European fir chronology. This combined record counts 11,873 TRW samples and spans the AD 962–2007 period. Mean segment length (MSL) and average growth rate (AGR) of the individual raw measurement series is 83 years and 1.78 mm, respectively. First order autocorrelation of this timeseries is 0.78. The mean Expressed Population Signal (EPS; computed over 30-year windows lagged by 15 years) is 0.98 over the past millennium and thus clearly ranges above the frequently applied quality threshold of 0.85 (Wigley et al., 1984) – replication matters.

In contrast to the considerable amount of detected common inter-annual to multi-centennial growth variability within and between the three regional TRW subsets were relationships between fir growth and climate variation found to be fairly weak (Fig. 4). The majority of correlation coefficients computed between the detrended Central European fir chronology and monthly precipitation and temperature variability (HISTALP) from previous year March to October of the current year averaged over three different geographical regions within the Greater Alpine Region and back to AD 1800, remained non-significant. Significant positive (negative) correlations ($p < 0.05$) were found with previous year

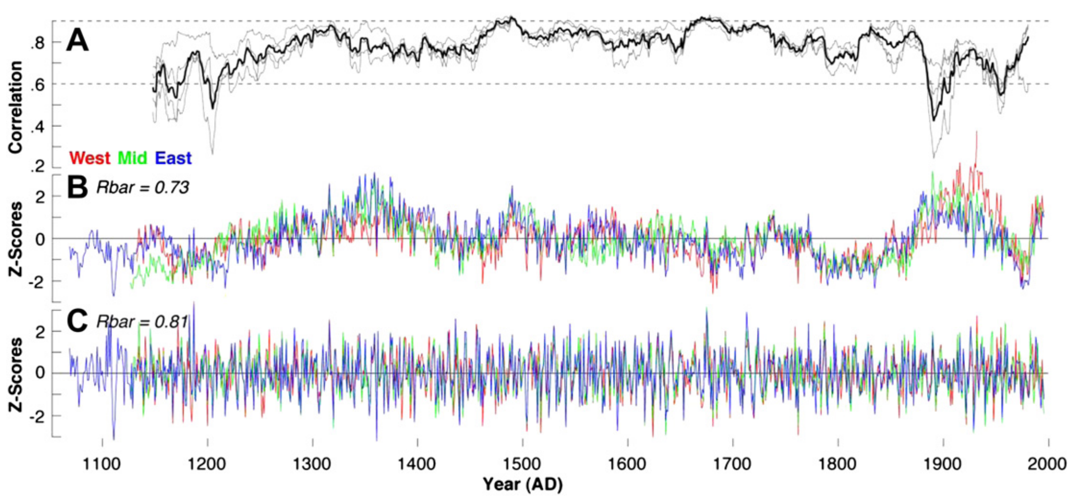

Fig. 3. (A) Moving 31-year correlation coefficients (gray) between the three regional (West, Mid, East) chronologies based on (B) raw and (C) detrended series (truncated <20 samples), and their grand mean correlation (black). Inter-series correlations (Rbar) were computed over the common period AD 1133–1996 (>20 series per region).

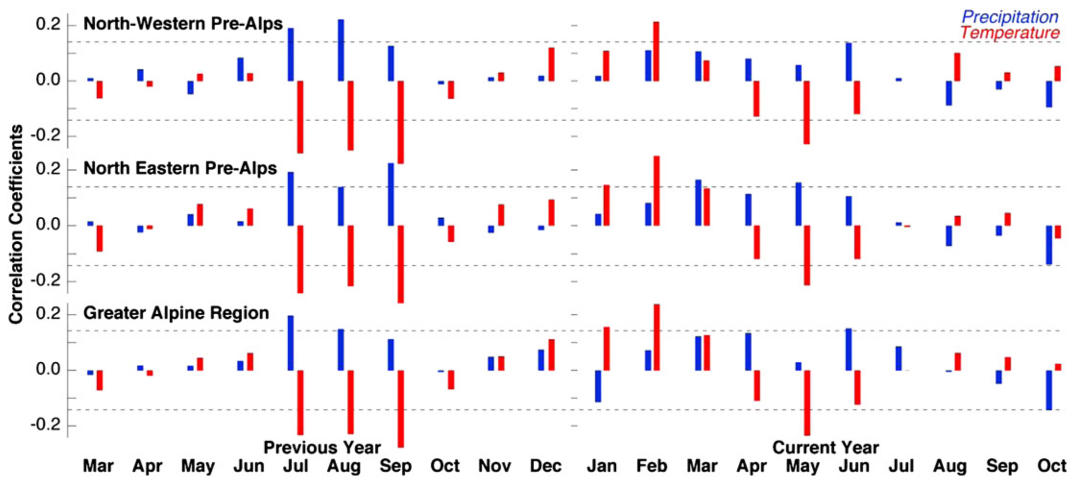

Fig. 4. Correlation coefficients between the detrended Central European fir TRW chronology and monthly precipitation totals (blue) and temperature means (red) from previous year March to current year October (1800–2007). Dashed lines correspond to 95% significance levels corrected for first order autocorrelation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

July, August and September precipitation (temperature). Significant positive correlations ($p < 0.05$) also exist with February temperature means, as well as March and June precipitation totals.

3.2. Growth extremes, pressure patterns, and documentary archives

Frequency and intensity of a total of 97 extreme departures in fir growth reveal spatiotemporal differences within and between the three regional TRW subsets and over the last 1000 years (Fig. 5A). Forty-three annual growth extremes occurred at the continental-scale, i.e., 15 positive and 28 negative extremes were simultaneously found in each of the three regions. While those sub-regions located next to each other shared most extreme years (19 and 27), were fewer extremes (8) common between the more separated subsets (West and East). The dominance of negative extremes at the network level somewhat diminished at the regional-scale. A total of 45 positive versus 52 negative departures describe an almost balanced picture. Nevertheless, remains some tendency towards an enhanced ability to capture negative rather than positive extremes, in line with common dendroclimatological observations (e.g., Frank et al., 2007a; Battipaglia et al., 2010). Maximum growth increases were reconstructed for AD 1052, 1187, 1316 and 1675, whereas most severe increment reductions occurred in 1167, 1361, 1397, 1504, 1762 and 1956. Century-resolved long-term changes in the return period suggest a dominance of positive extremes within the 11th, 15th and 18th centuries (Fig. 5B), whereas the 17th and 20th

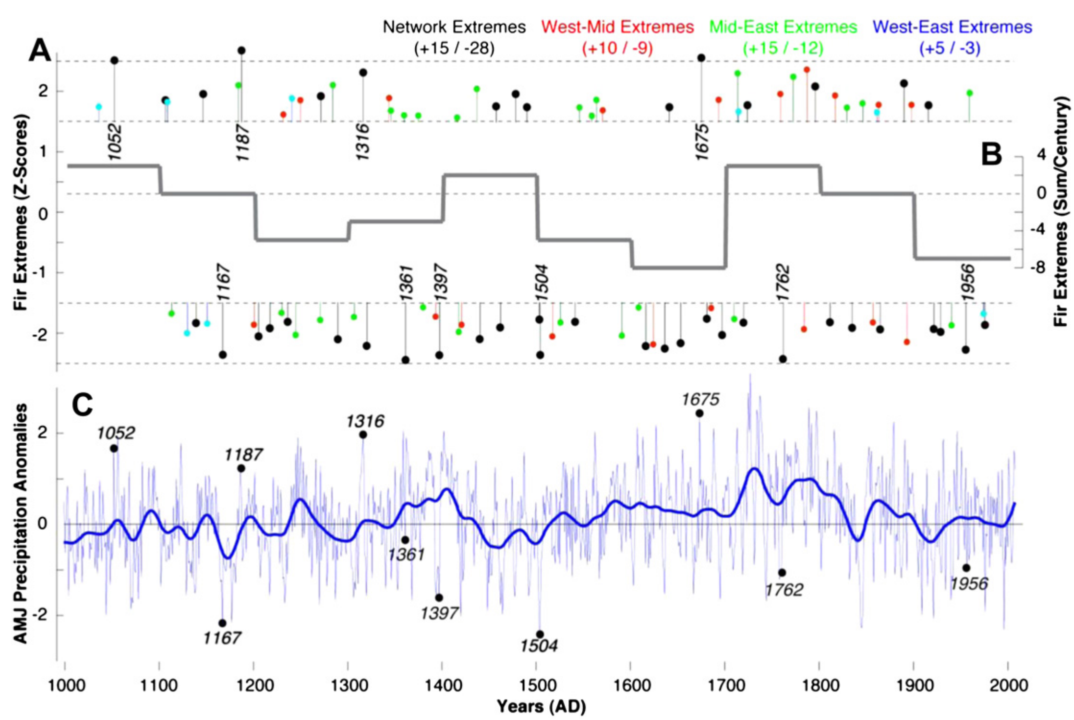

Fig. 5. (A) Central European and regional fir TRW extremes, and (B) their centennial changes over the past millennium (network extremes were double weighted), compared to (C) annual-resolve and 40-year low-passed Central European April–May precipitation variability.

centuries were subject to severe growth depressions. Comparison of the annual fir TRW extremes with reconstructed inter-annual to multi-centennial variations in Central European April–June precipitation totals (Büntgen et al., 2011c) shows synchronized high-frequency behavior (Fig. 5C), and further indicates a tendency of positive and negative fir extremes to parallel wetter and drier springtime conditions, respectively.

Below-mean mid-tropospheric (500 hPa) geopotential heights over Central to Eastern Europe between ~5–40°E and 35–55°N were characteristic for April climate during the 20 most positive fir growth extremes within the Central European fir TRW chronology and the AD 1659–1996 period (Fig. 6A). A negative pressure anomaly slightly extended and moved northwestwards during May, but already diminished during June (Fig. 6B–C). At the same time were positive pressure anomalies found over large parts of the North Atlantic and Scandinavia. Continental-scale growth depressions coincided with positive 500 hPa anomalies over Western Europe from April–June (Fig. 6D–F). A positive pressure anomaly during April was widespread over most of the continent and North Africa between 30–55°N and 10°W–30°E, but an extended latitudinal north–south belt of high- to mid-tropospheric pressure was characteristic for May. Above-mean pressure during June occurred over the Atlantic west of France between the British Isles and the Iberian Peninsula. The spatial anomaly patterns for the 20 most positive and the 20 most negative growth extremes are related to wet and dry springtime climate across the three regional fir subsets (West, Mid, East), respectively. Below-normal mid-tropospheric geopotential height anomalies over Central to Eastern Europe increase precipitation totals, whereas positive anomalies likely cause precipitation deficit.

High-resolution documentary evidence of Central European spring/summer climate variability provides a unique target to precisely dated and carefully interpreted temperature and precipitation indices, for instance (Fig. 7). Such data have been compared with the fir TRW extremes back to AD 1500, and subsequently not only supported independent validation of many dendro-based events but also provided detailed understanding of ambient weather conditions associated to these extremes. Negative TRW departures were most often related to warmer (or average) and dry climate (Fig. 8), whereas positive growth anomalies mainly coincided with cold and wet (or average) conditions. However, in some cases these relationships were found to be even opposite as expressed by quartiles or extreme values of indices in corresponding box-plots. Extremely cold winters, such as in AD 1681, 1709, 1784, 1929, and 1956 for example, possibly introduced further biases (see Discussion below for more details). Some statistically significant relationships (differences in mean of extreme TRW years compared to the rest of the period) were obtained between negative fir growth and spring/summer precipitation indices at the regional- and continental-scale, whereas less coherency was found between positive TRW extremes and documentary-based indices. Relationships between dendro-extremes and precipitation (temperature) indices appeared to be stronger (weaker).

Comparison between fir growth and documentary evidence prior to AD 1500 was restricted to Western/Central European spring (MAM) and summer (JJA) temperature and precipitation indices (−3 to +3), but even a simple separation into positive and negative extremes confirmed the post-1500 pattern back to medieval times (Fig. 9). Negative TRW extremes mainly coincide with dry and temperate springs, as well as dry and warm summers. Positive TRW extremes generally match slightly cooler and wetter spring and summer conditions. It should, however, be noted that box-plot values could be influenced by an overall small number of seasonal documentary-based indices available for comparison with the corresponding dendro-based extreme years during the first half of the last millennium. This limitation is most critical for spring patterns while the situation is slightly better for the summer season. Any interpretation prior to AD 1500 is further subject to a reduced number of available documentary indices, as only above- or below-normal seasons clearly prevail, i.e., normal seasons with index 0 are generally missing.

Additional comparison between mean Central European and regional West, Mid, East fir growth extremes and qualitative shortened documentary descriptions of spring/summer weather patterns provides unique insight on climatic drivers and atmospheric pressure patterns, as well as associated agricultural and societal consequences over the past 1000 years (Table 1). These entries generally derive from already published papers related to the area of interest. While some dendro-based extremes are not

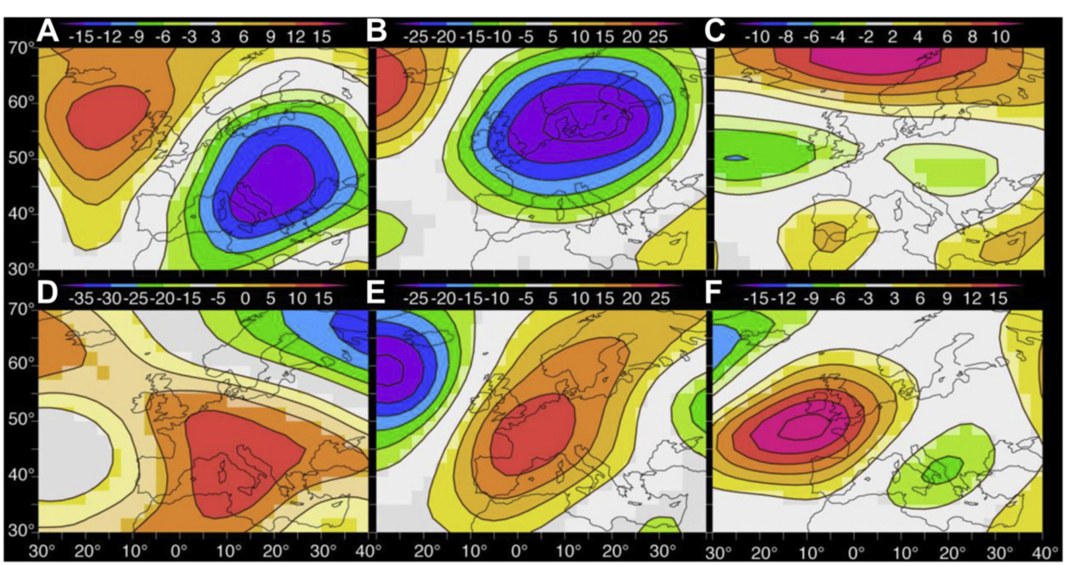

Fig. 6. Composite analysis (AD 1659–1996) of (A) April, (B) May and (C) June 500 hPa geopotential heights (gpm) of the 20 most positive annual fir growth anomalies, whereas (D), (E) and (F) refer to the 20 most negative anomalies, respectively.

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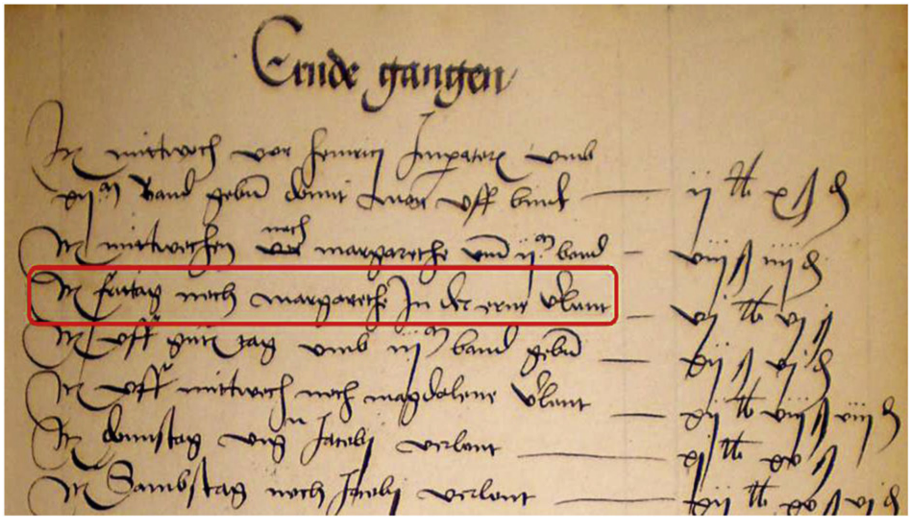

Fig. 7. Example of documentary evidence for AD 1522: the date of daily wage payments to day laborers for grain (i.e., rye) harvest contained in the weekly account books of the Basel Hospital from 1454 to 1705. Such information has been used as a proxy to assess March–July temperatures. "Friday after Margaret (day)" yields July 18th as the starting date for then rye harvest in that year, extracted form the book of expenditures of the hospital of Basel (photo: Oliver Wetter; source: Staatsarchiv Basel-Stadt; Spital F12).

covered by any documentary data, often fluctuates the actual number of available reports from year-to-year. Generally cooler and wetter patterns support positive TRW extremes, while warmer and drier patterns appear favorable for negative growth departures, in line with the results obtained from the documentary indices and the 500 hPa geopotential height composites. Nevertheless, it should be noted that TRW extremes sometimes lagged the responsible weather patterns by one or more years, such as for instance in AD 1541 when a large-scale growth depression lagged the extremely warm and dry climatic conditions of 1540 (Glaser et al., 1999; Pfister, 1999). This response shift is well in line with the high first order auto-correlative structure of the fir TRW data.

4. Discussion

4.1. Strengths

The quality of tree-ring studies, impartially of their different foci (e.g., dendroarchaeology, dendroclimatology, dendrogeomorphology) is generally evaluated by the amount of individual measurement series compiled, by the spatiotemporal extent of such collections, and by the common internal signal strength the samples are able to reflect (Fritts, 1976). In this study, the world's largest collection of annual-resolved living and historical fir ring width measurements was gathered. TRW samples represent three independent regional subsets across Central Europe within a longitudinal belt (~5–15°E) north of the Alpine arc (~48–52°N), and span the past millennium (AD 962–2007). Most remarkable appeared the exceptionally high degree of common growth variability among the raw, non-standardized TRW series, both within and between the three regional subsets. Since events and trends in radial fir increment were found to be similar from the Vosges Mountains in northeastern France all the way to Moravia in the eastern Czech Republic, local causes of such growth coincidence can be excluded. Effects of communal to countrywide forest management, small-scale environmental impacts and/or regional airborne pollution were probable not responsible for the observed homogeneity in Central European fir TRW fluctuations, whereas atmospheric conditions operating at the continental-scale were most likely in control. This is further supported by the coexistence of inter-annual higher frequency and multi-centennial lower frequency growth agreement. Biases of temporal fluctuation in sample replication and an uneven distribution of juvenile wood throughout time that may cause artificial variance changes in TRW chronologies (Frank et al., 2007b) can herein be neglected, because consideration of nearly twelve thousand individual samples >50 years with an average length of 83 years contradicts any abrupt or systematic shift in different tree populations over the past 1000 years.

The ability of composite tree-ring chronologies to properly reflect year-to-year growth variability, and thus to utilize such high-frequency information to reconstruct past changes in the regularity and severity of climatically-induced extreme seasons greatly depends on the structure of the tree-ring dataset employed, the methodological treatment of the individual TRW measurement series during the standardization and chronology development process, and the spatiotemporal robustness of the climatic signal captured during anomalous growth departures (Battipaglia et al., 2010). In this study, a combination of generally short TRW measurement series and their even temporal distribution back into medieval times described a pivotal foundation to overcome data-related limitations in signal preservation (Frank et al., 2007a). Age-trend removal was optimized to emphasize inter-annual signals while eliminating any kind of longer-term background noise (Cook and Peters, 1981). To further ensure optimal high-frequency conservation over time, TRW indices were calculated as residuals after power-transformation (Cook and Peters, 1997), and rigorous variance stabilization of the final TRW chronologies was additionally performed (Frank et al., 2007b). The three regional subsets therefore allowed detailed insight on the spatial synchrony of TRW extremes, and confirmed creation of one single mean dataset, which adequately reflected Central European fir TRW extremes over an exceptional long timescale. Distinct mid-tropospheric pressure patterns were found to be the main climatic controls of the observed TRW extremes over the past ~350 years.

Independent multi-proxy (and even model) comparison of the obtained dendro evidence describes an important, ongoing research frontier, which is often hampered by the paucity of palaeoclimatic records (and the inability of regional year-to-year simulations) that mirror the same climatic signal with the same temporal resolution, and the same seasonal weight over similarly

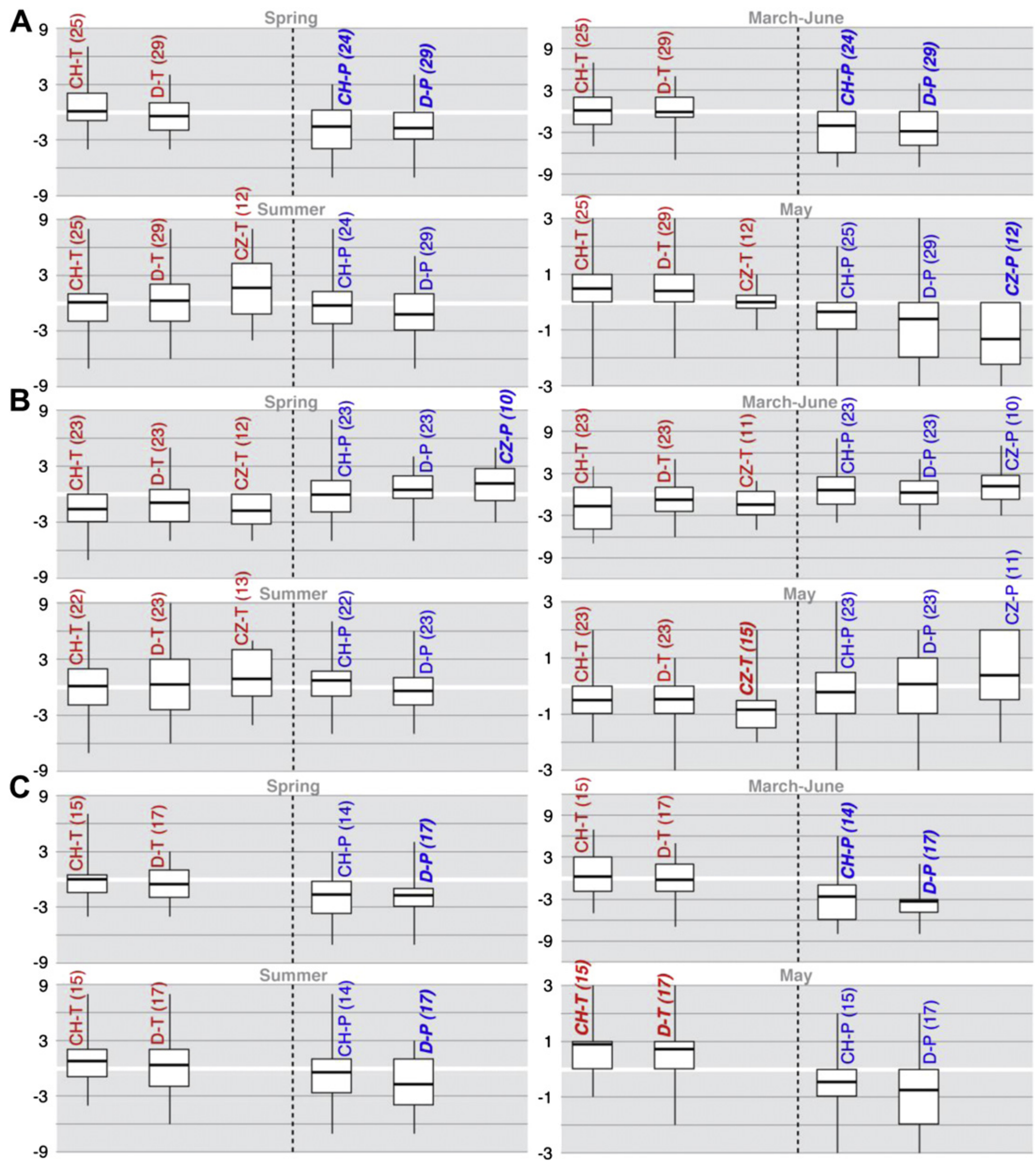

Fig. 8. Box-plots of temperature (T) and precipitation (P) indices from Switzerland (CH), Germany (D) and the Czech Lands (CZ) for (A) all negative extremes, (B) all positive extremes, and (C) negative extremes occurring concurrently in all three regions in the past 500 years attributed to spring (MAM), summer (JJA), March–June and May data. Number of years with indices available is in brackets, and bold-italic values refer to statistically significant difference in means of the corresponding subset and rest of the 500-year period. Box-plot is not shown when number of indices was below 10.

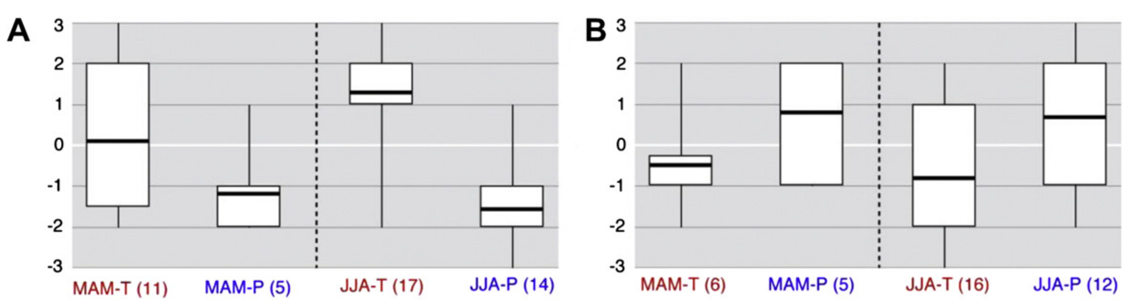

Fig. 9. Box-plots of temperature (T) and precipitation (P) indices of Western and Central Europe for (A) all negative extremes and (B) all positive extremes attributed to spring (MAM) and summer (JJA) before AD 1500. Number of years with indices is in brackets on the *x*-axes.

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Table 1
Comparison of fir TRW extremes (+ positive, − negative) with descriptive documentary data between the regions WM = West-Mid, WE = West-East, ME = Mid-East, and across all three regions = all: A = Austria (eA = eastern Austria); eAlp = eastern Alps), CZ = Czech Lands, D = Germany, CH = Switzerland, SSS = Souabe/Switzerland/Alsace (sources: Alexandre (1987) [A1987], Brázdil and Kotyza (1995) [BK1995], Brázdil and Kotyza (2000) [BK2000], Brázdil et al. (2004) [BVK2004], Historical−climatological database [CZdb], Glaser (2008) [G2008], Pfister (1999) [P1999], Rohr (2007) [R2007], Strömmer (2003) [S2003]).

Year	Region	Qualitative description of weather patterns
1035	+WE	No documentary spring-summer data
1052	+all	D: (wet year) [G2008]
1106	+all	D: warm spring and summer [G2008]
1108	+WE	No documentary spring-summer data
1112	−ME	D: warm and extremely dry summer [G2008]
1129	−WE	No documentary spring-summer data
1139	−all	No documentary spring-summer data
1146	+all	D: much rain in the harvest time [G2008]
1150	−WE	D: very cold March [G2008]
1167	−all	D: warm summer [G2008]
1183	+ME	No documentary spring-summer data
1187	+all	SSS: cold and rainy spring [A1987]
1200	−WM	No documentary spring-summer data
1205	−all	D: cold spring, warm and dry summer [G2008]
1217	−all	D: warm and dry summer [G2008]
1229	−ME	D: (warm and dry summer 1228) [G2008]
1231	+WM	SSS: cold and rainy spring [A1987]; D: dry spring (dry year) [G2008]
1236	−all	A: very severe winter [R2007]; SSS: warm summer [A1987]; D: warm summer [G2008]
1240	+WE	No documentary spring-summer data
1244	−ME	A: dry in summer [A1987]; eAlp: warm and dry in summer, often fires [R2007]; D: warm and dry summer [G2008]
1249	+WM	D: (dry summer 1248) [G2008]
1270	−ME	CZ: poor harvest of cereals (dry); very dry summer (e.g., Bavaria, Switzerland) [BK1995]; D: floods in July, otherwise warm and dry in summer [G2008]
1271	+all	D: wet summer [G2008]
1283	+ME	CZ: very dry spring [BK1995]; D: warm spring [G2008]; SSS: warm spring [A1987]
1289	−all	SSS: warm in summer [A1987]; D: warm summer [G2008]
1306	−ME	CZ: great dry (1307) [BK1995]; D: cold spring [G2008]
1316	+all	A: floods in summer [R2007]; CZ: rainy summer, flood; also Austria, Hungary, Germany, Poland [BK1995]; D: floods in May−June [G2008]
1320	−all	CZ: warm summer [BK1995]
1343	+WM	Bavaria, SSS: rainy April, rainy summer [A1987]; D: cold and wet in spring, rainy summer, floods [G2008]
1345	+ME	No documentary spring-summer data
1359	+ME	CZ: wet summer, flood in Prague [BK1995]; A: rainy summer, floods [R2007]; Austria: two rainy months in summer, Bavaria: cold summer, Lusatia: rainy summer [A1987]; D: rainy summer [G2008]
1361	−all	CZ: bad harvest (drought); hot and dry summer (Wroclaw, Poland) [BK1995]; Austria: dry spring and summer, Silesia: warm and dry spring, SSS: warm and dry summer [A1987]; D: hot summer [G2008]
1374	+ME	SSS: two rainy months in summer [A1987]; D: long spells of rain, warm in August [G2008]
1379	−ME	SSS: warm summer [A1987]; D: hot summer [G2008]
1393	−WM	CZ: great drought; same Melk (Austria) [BK1995]; Austria: dry summer, Franconia, Hessen: warm and dry summer, SSS: two warm months in spring, warm and dry summer [A1987]; D: extremely dry [G2008]
1397	−all	Austria: dry and warm April, May and summer, Franconia, Hessen: dry spring and summer, SSS: warm summer [A1987]; D: earlier blossoming and harvest time, warm summer [G2008]
1415	+ME	floods in April−May in Wroclaw (Poland) [BK1995]; rainy year (Poland Minor); poor harvest in Bavaria and Austria; Franconia, Hessen: rainy summer, SSS: rainy summer [A1987]; D: continuous rainy spells [G2008]
1417	−ME	CZ: severe winter, much snow (1416/17); same Klosterneuburg (Austria) [BK1995]
1420	−WM	early onset of phenophases in spring (Bohemia, Austria, Württemberg), dry and warm summer in Württemberg, Baden, Regensburg [BK1995]; D: warm and very dry in spring, earlier ripening [G2008]
1436	+ME	D: continuous rain in spring, flood of the Isar [G2008]
1440	−all	CZ: long, severe winter; also in Silesia and Poland [BK1995]
1457	+all	D: floods in June, drought after rain spells [G2008]
1462	−all	CZ: (heat and drought in summer 1461; also in Silesia) [BK1995]; Silesia: rainy from May to August [BK2000]
1478	+all	snowy and frosty winter (1477/78) in Poland [BK1995]; D: warm and dry summer, good wine [G2008]
1490	+all	CZ: plenty of cereals (enough rain) [BK1995]; A: very rainy in July, floods [R2007]; D: cold summer, rainy, harvest delayed [G2008]
1503	−all	eAlp: very dry, bad harvest, small water in rivers [R2007]; CZ: very dry from May to August; D: dry spring, warm and dry summer [G2008]
1504	−all	CZ: very dry from April to July; D: mild an very dry spring, hot and dry summer [G2008]
1517	−WM	CZ: dry May and summer [BK2000]; CZ: rather dry spring [CZdb]; D: dry spring, warm and hot to mid-July, then rainy [G2008]
1525	−ME	CZ: dry and hot summer, forest fires, good wine [CZdb]; D: dry spring [G2008]
1541	−all	CZ: extremely dry and hot year 1540 in Central Europe [CZdb]; eAlp: drought from end March to mid-August, dried streams [R2007]; CZ: wet summer, late vintage, sour wine [CZdb]; average summer 1541 [BK2000]; D: dry spring, rainy latter part of summer [G2008]
1545	+ME	CZ: dry summer, flood in July [CZdb]; D: warm and dry from May to August [G2008]
1558	+ME	D: rainy in May, warm and partly dry in summer [G2008]
1563	+ME	CZ: hard winter (1562/63), cold and wet summer (very rainy in June−July) [BK2000]; CZ: rainy spring [CZdb]; D: cold and dry spring, rainy in June−July [G2008]
1570	+WM	CZ: average summer [BK2000]; CZ: cold spring [CZdb]; CH: extremely cold March, extremely cold and wet April, extremely cold and wet July [P1999]; D: warm and wet spring, summer − the first part warm and dry, the second cold and rainy [G2008]

(*continued on next page*)

Table 1 (*continued*)

Year	Region	Qualitative description of weather patterns
1590	−ME	eAlp: dry from Easter to August, forest fires [R2007]; CZ: very cold winter (1589/90), cold March, dry and hot in summer [BK2000]; D: dry March and April, hot and dry summer [G2008]
1608	−ME	CZ: hard and snowy winter (1607/08), delay in harvest (cold) [BK2000]; CH: extremely cold and wet July [P1999]; D: normal and wet spring, cold summer [G2008]
1616	−all	CZ: drought from April over the whole summer, hot [BK2000]; CH: extremely warm and dry June–July [P1999]; D: very dry from April, dry and hot summer [G2008]
1624	−WM	CZ: severe winter 1623/1624, dry from end April to mid-June, dry in summer and autumn [CZdb]; D: dry May, hot summer, dry only in some areas [G2008]
1636	−all	CZ: mildly dry year [BVK2004]; CH: extremely warm and dry May [P1999]; D: dry from March to June, rainy in July [G2008]
1641	+all	CZ: cold May, summer and autumn [BVK2004]; D: cold and rainy [G2008]
1653	−all	CZ: dry before 1 June, dry year [CZdb]; CH: extremely warm and very dry May, extremely warm and dry June [P1999]; D: dry and warm from April to July [G2008]
1675	+all	CZ: rainy summer, floods in June [CZdb]; CH: extremely cold and wet June, very cold and wet August [P1999]; D: dry in beginning of spring, wet at its end, cold and rainy summer [G2008]
1681	−all	CZ: very severe winter 1680/1681, dry spring, hot in May, dry summer [CZdb]; CH: extremely warm and dry August [P1999]; D: dry spring, warm and dry summer [G2008]
1685	−WM	CZ: dry and wet spells in spring, cold summer (mainly June) [CZdb]; CH: very cold March, extremely cold and very wet June, very cold and wet July [P1999]; D: cold spring, cold and rainy summer [G2008]
1693	+WM	CZ: cold and rainy in May, rainy in June and July [CZdb]; D: cold and wet spring, cold and rainy summer [G2008]
1697	−all	CZ: cold May–June, wet summer [CZdb]; D: cold March, warm May, dry in May–June [G2008]
1709	−ME	CZ: extreme severe winter 1708/1709, cold March, dry summer, good wine [CZdb]; CH: extremely cold January and February, very cold and wet May [P1999]; D: extreme severe winter 1708/1709, cold and wet spring, variable weather in summer [G2008]; eA: severe winter 1708/1709, sour wine [S2003]
1713	+ME	CZ: warm March–mid-April, cold in May, rainy summer, sour wine [CZdb]; CH: extremely cold April, extremely cold and wet July [P1999]; D: cold March–April, cold and rainy summer [G2008]; eA: rainy in May, flood in June, late vintage [S2003]
1714	+WE	CZ: rainy summer, floods in June–July [CZdb]; CH: extremely cold and very dry April [P1999]; D: cold and rainy mid-April to May, continued in summer [G2008]; eA: rainy and floods in July, sour wine [S2003]
1720	−all	CZ: cold March, dry in spring, warm summer, good wine [CZdb]; D: cold and rainy in summer [G2008]
1724	+all	CH: very warm May, extremely warm and very dry June, very warm and very wet July [P1999]; D: variable spring, dry summer [G2008]; eA: rainy April, hot and very dry summer [S2003]; CZ: dry year [CZdb]
1759	+WM	CZ: hot and dry between 20 July and 19 August [CZdb]; eA: high water in the Danube in August [S2003]
1762	−all	CZ: dry spring and summer [CZdb]; CH: extremely cold March, very warm and very dry April [P1999]; eA: mild spring, warm summer [S2003]
1772	+ME	CZ: cold and rainy in June–July [CZdb]; eA: rainy from May to mid-July, then hot and dry [S2003]
1784	−WM	CZ: very severe winter 1783/1784, cold March, cold and rainy April, very dry summer [CZdb]; eA: very severe winter 1783/1784, cold March and April, normal summer [S2003]
1787	+WM	CZ: cold May, rainy in July [CZdb]; eA: cold and rainy spring (cold and flood in May), flood in June, warm and dry from July to September [S2003]
1796	+all	CZ: mild winter 1795/1796, cold April, rainy in June [CZdb]; CH: extremely cold and very dry March [P1999]; eA: mild winter 1795/1796, warm in spring, very rainy in June–July [S2003]
1812	−all	CZ: cold April, rainy summer [CZdb]; CH: extremely cold and extremely dry April [P1999]; eA: cold and rainy summer [S2003]
1817	+WM	CZ: rainy from May to July [CZdb]; CH: extremely cold and extremely dry April [P1999]; eA: cold March and April [S2003]
1829	+ME	CZ: rainy spring and summer [CZdb]; eA: cold and rainy spring, cold and floods to mid-June [S2003]
1835	−all	CZ: dry spring and summer [CZdb]
1846	+ME	CZ: dry from May to July [CZdb]; CH: extremely warm June [P1999]
1858	−WM	CZ: dry spring (several weeks before 13 June without rain), drought continued to July [CZdb]; CH: extremely warm and dry June [P1999]
1861	+WE	CZ: cold April–May, thunderstorms with rains in June [CZdb]
1863	+WM	CZ: dry and wam spring, dry summer (very dry mainly from May to July) [CZdb]
1865	−all	CH: extremely cold March, extremely warm and extremely dry April, extremely warm and dry May [P1999]; CZ: dry April, dry and hot May, dry summer, hot July [CZdb]
1890	+all	CZ: cold and rainy summer (mainly August), sour wine [CZdb]
1893	−WM	CH: extremely warm and extremely dry April [P1999]; CZ: dry spring and May–July, hot June–July, bad harvest [CZdb]
1898	+WM	CZ: rainy May and July, wet year, good harvest, sour wine [CZdb]
1916	+all	CH: extremely cold and extremely wet June [P1999]; CZ: cold and rainy in the time of tree blossoming, rainy summer [CZdb]
1922	−all	CZ: very dry spring, dry summer [CZdb]
1929	−all	CH: extremely cold February [P1999]; CZ: extremely cold winter (particularly February), frosts to mid-April, hot in May, very dry and warm summer [CZdb]
1940	−ME	No documentary spring–summer data
1956	−all	CH: extremely cold February, very cold and dry June, very wet July, very cold and very wet August [P1999]; CZ: cold spring, rainy April–May, late blossoming of trees [CZdb]
1959	+ME	CZ: very mild January–February, rainy summer, mainly July and August [CZdb]
1974	−WE	CZ: blossoming tree in March, damage due to late frosts, dry and warm summer [CZdb]
1976	−all	CH: extremely warm and extremely dry June [P1999]; CZ: dry year [CZdb]

long timescales (e.g., IPCC, 2007; Jones et al., 2009). In this study, a unique collection of documentary sources ensured regional- to continental-scale verification of the annual fir TRW extremes back into medieval times. Quantitative indices and qualitative descriptions were used to provide insight on the possible causes and consequences of the hydroclimatic spring/summer events that drove anomalous fir growth. Documentary evidence from chronicles tend to focus on the occurrence of unusual or extreme events, which suggests that such years considering a large quantity of sources are relatively complete and open to cross checking. Prominent examples of a successful dendro-documentary approach include, for instance AD 1361, a year for which spring-summer (March–August) temperatures in England were estimated from the beginning of grain harvest dates to be significantly warmer than the long-term instrumental mean back to AD 1659. In fact, the "detrimental drought lead to scant grain and hay harvests", and the manorial accounts from Sussex and of the Bishopric of Winchester even noted problems "pro magno calore in estate" (on behalf of exceeding heat in summer), which were very rare in England. Spring and summer climate in AD 1361 was also characterized by warm and very dry conditions in France, Belgium, Holland, Germany, Austria, the Czech Lands, and Poland (Alexandre, 1987), which points to a persistent anticyclone situation across Central Europe.

4.2. Weaknesses

Although the above concert of data-related and methodological-induced strengths implies a step forward, our results are still limited in many aspects and contain a variety of different uncertainty levels. Abrupt historical sample cessation ~1000 years ago occurred simultaneously in all three regional subsets and therefore defines a sharp restriction to extend the dendrochronological fir record in Europe prior to medieval times (e.g., Strassburger and Tegel, 2009). This situation is likely representative for many other species and results from a high medieval construction boom in almost all Central European towns in the 12–14th centuries, during which former building evidence was rigorously destroyed and replaced by those materials that form the Central European dendrochronological records afterwards (Büntgen et al., 2011c).

The species-specific wood density and net weight of fir facilitated its floating capacity, and subsequently yielded vital transportation activities along many Central European rivers (Eckstein and Wrobel, 2007). Frequent ancient timber trade consequently complicated the actual dendrochronological provenancing of most of the ancient construction wood, which directly impacts our understanding of the ecological site conditions and the former biotic and abiotic drivers of fir growth, including climate. Two strategies may appear opportune in our perspective to overcome biases associated with wood provenancing: i) Enhancing the degree of archaeological and historical metadata and socio-economic, as well as cultural background information necessary to trace the origin of the wood material, and/or ii) performing a random update sampling of abundant living trees that foster adaptation of the recent to the historical data (Tegel et al., 2010). We are actually in favor of option ii) as it appears rather unlikely to gain much more insight on most of the historical construction timber, whereas a random update sampling of living material at sawmills and lumberyards scattered over those regions from where the historical data derived appears relatively unproblematic. Due to the subsequent artificial signal-degradation of the randomly updated samples, will the amount of site control and ecological understanding of the modern material be equally low as it is for the historical part, and the chronology internal signal-to-noise ratio will remain uniform throughout time (Tegel et al., 2010; Büntgen et al., 2011c). A caveat to this approach, however, likely emerges from systematic differences between modern and ancient conditions in the species-specific growth habitat. In fact, it should be noted that fir was the most common tree species up to the 19th century in Bohemia where fir occupied all type of sites from 400 to 900 m asl, but actually mainly occurs on steep slopes and/or inaccessible sites (Hoffmann et al., 2009), because most of the former fir stands have been replaced by spruce or pine.

Nevertheless, we believe a random update sampling strategy to be of particular importance in case tree-ring datasets reflect overall weak relationships with traditional climatic parameters, as done in this study. In fact, correlations between radial fir growth and monthly resolved temperature means and precipitation totals were often not very high and only significant for some specific monthly and seasonal means. The majority of pairings remained even non-significant, which implies a critical limitation of our data. It further remains unclear, how effects of snow cover and snowmelt may possibly translate into enhanced soil moisture availability at the onset of the growing season (Vaganov et al., 1999), which is likely inferred by positive correlations with late winter and particularly February temperature. In this context, it should also be noted that severe winter climate, such as in 1956 can imply harmful consequences on fir TRW formation. Such negative effects most likely emerge from frost events that appear particularly destructive in tandem with reduced snow cover. Consequences of previous year climate on current year ring width formation can further complicate the assessment of (traditional) growth–climate response patterns (Frank et al., 2007a), and must definitively be considered for fir (Carrer et al., 2010). Lagged effects may explain some of the observed offset with the precisely dated documentary evidence. In fact, the positive growth anomaly in AD 1316 might to some extent result from the hydroclimatic situation in 1315, which was, alike 1816, a year without summer in Central Europe, albeit much wetter. In Louvain (Belgium), for instance, large crowds of desperate people everywhere held daily processions to stop the rain, as "abundant and continuous rain fell from early May to early November" was characteristic for this year. The situation in 1316, however, was not much better, and repeated floods were reported from many places across the continent (Alexandre, 1987).

Even though the temporal instability between proxy and target timeseries is not within the prime scope of our extreme year analysis, we advocate a much more comprehensive assessment of fir growth that places modern (anthropogenic) trends in a Holocene-long (natural) context (Pearman et al., 2008). A careful examination of possible impacts of airborne pollution on fir growth should also range from the local site to the continental network and ideally cover the entire industrial era from the mid-19th century until post-Soviet times (Wilson and Elling, 2004).

Beside data-related biases appear methodological-induced limitations most critical to properly estimate the frequency and severity of TRW extremes over centuries to millennia (Battipaglia et al., 2010). Moreover should be noted that our results are not only optimized to best preserve inter-annual high-frequency variability, but they are certainly also limited in reflecting any long-term variation associated to solar variability and/or internal climate oscillations, such as the NAO. Linking decadal to multi-centennial fluctuations in Central European fir growth to possible external forcing agents, however, remains subject to a follow-up paper.

It must be further noted that extreme events reproduced by the fir TRW data not always match documentary evidence for severe climatic anomalies, as European spring/summer weather patterns associated with radiation-driven weather regimes are generally of limited spatial extent. Indication for limited spatial representation of reconstructed extremes is further confirmed by the existence of

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fir growth extremes, which are often restricted to one or two out of three regional subsets. Disagreement in the occurrence of extreme years in fir and documentary data could also be related to climatic factors other than spring/summer conditions affecting radial ring formation (Frank et al., 2007b). Similarly, documentary archives also may indicate the occurrence of extreme events such as flooding, heat waves or cold snaps that are rather short in duration and may not leave obvious fingerprints upon the longer process of TRW formation (Brázdil et al. 2005, 2010; Dobrovolný et al., 2010b). Comparing Table 1 to recent evidence of March–July temperatures for Switzerland and southwest Germany based on grain harvest starting dates and narrative evidence, reveals that some of the warmest March to July spells documented for this region (e.g., 1473, 1483, 1540, 1603, 1611, 1645, 1718, 1822, 1947), as well as some very wet and cold spring–summer periods (e.g., 1716, 1816, 1860) are missing. The same is valid for extreme summer temperatures reported for the Czech Lands (Dobrovolný et al., 2010a).

Beside the possible noise inherent to the tree-ring chronologies may emerges additional bias from the documentary evidence itself. European documentary sources are copious between the mid-16th and the early 19th centuries (Brázdil et al., 2005, 2010; Dobrovolný et al., 2010b), but evidence decreases not only further back in time, but also towards present, particularly when early meteorological observations started. Reports by individuals are rather short lived, ending at the latest with the death of the observer. Therefore, they are inherently inconsistent in a longer-term time/space framework (Brázdil et al., 2010). Sources prior to AD 1170 tend to be less consistent and rich in content (Alexandre, 1987). Indirect data from institutional sources may also be subject to similar types of biological uncertainties as with the tree-ring data, unless they are crosschecked with direct narrative data. Rutishauser et al. (2007) and Meier et al. (2007) claimed that the relation between phenological dates and temperatures was not stationary. According to them, the cultivation methods and the general political background could have influenced the harvest. They also claim that the meteorological and socio-economical contexts in which grape ripening and harvesting took place were not known well enough to confidently support the statistical approaches based on grain harvest dates series. Garnier et al. (2011) tried to remove health-medical and socio-economic biases from series of grape harvest days from Besancon, France. Finally, converting a data field to an index involves some loss of information due to the more coarse precision.

All of the above advises caution when interpreting our results. This is particularly the case for any quantitative estimation of the intensity of the reconstructed hydroclimatic extremes and their completeness. Possible biases of the obtained extreme year frequency should also be considered. More high-resolution and absolutely dated proxy records that span the past millennium and may even cover the entire Common Era are needed and should ultimately be combined in multi-proxy approaches (Luterbacher et al., 2004), and compared with independent output from state-of-the-art model simulations (Büntgen et al., 2011b).

5. Conclusions

Numerous laboratories, institutes and universities independently developed a unique pool of nearly twelve thousand living and historical fir TRW measurement series from northeastern France, northern Switzerland, southern Germany, and the Czech Republic. This worldwide unique conifer compilation continuously spans from medieval times into the 21st century, and was now for the first time, dendro-climatologically analyzed. Three regional subsets reveal an exceptionally high amount of common fir growth variability on inter-annual to multi-centennial timescales. An overall weak relationship between ring formation and climate variation, however, contradicts the pronounced year-to-year growth coherency across the lower elevation Central European mountain systems north of the Alpine arc. Frequency and severity of regional- to continental-scale fir TRW extremes was equally distributed over the past millennium, and was likely controlled by anomalous departures in Central European April–June precipitation totals. Positive growth extremes were associated with wet conditions that coincided with low-pressure, whereas negative TRW departures were related to dry conditions and high-pressure. Independent documentary evidence confirms many of the TRW extremes back into medieval times. Quantitative indices and qualitative descriptions provide exclusive high-resolution insight on ambient climate conditions, including detailed information on possible causes and consequences of hydroclimatic anomalies. Cross checking tree-ring reconstructions of extreme events with corresponding narrative documentary sources is indispensable for detecting possible disagreement in specific years. Uncertainties in our results comprise methodological limitations related to the tree-ring standardization and chronology development techniques used, complex and possibly lagged responses of fir growth to climate change, some temporal mismatch between the dendro and documentary data, and statistical trials associated with the index calculation methods applied. Nevertheless, our study does allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations, and may possibly also offers a realistic and independent benchmark to improve the absolute dating of lower resolution proxy archives, and even to constrain climate model simulations over pre-industrial timescales. Beside its palaeoclimatic value will this interdisciplinary dataset and approach likely appear beneficial for biologists, ecologists and archeologists, and will ideally also stimulate the re-assessment of additional and possibly even older historical tree-ring measurements that exist in Europe and have so far widely been ignored for purposes other than dating.

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