Two millennia of Main region (southern Germany) hydroclimate variability

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Abstract. A reconstruction of hydroclimate with an annual or sub-annual resolution covering millennia~~the entire Holocene~~ for a geographically limited region in continental Europe would significantly improve our knowledge of past climate dynamics.~~, but has not been developed so far.~~ With the use of an extensive collection of oak total ring-width series (*Quercus robur* and *Quercus petraea*) from living trees, historic timbers and subfossil alluvial wood deposits from the Main River region in southern Germany, a regional, 2,000-year long, seasonally-resolved hydroclimate reconstruction for the Main region has been developed. Climate-growth response analysis has been performed with daily climate records from AD 1900 onwards. ~~An innovative analysis method for testing~~To test the stability of the developed transfer function, a ~~(~~bootstrapped transfer function stability test~~,~~ (BTFS) as well as a classical calibration / verification approach have been implemented to study climate-growth model performance. Living oak trees from the Main River region show a significant sensitivity to precipitation sum from February 26 to July 06 (spring to mid-summer) during the full ($r = 0.49$, $p < 0.01$, N = 116) and split ($r = 0.58$, $p < 0.01$, N = 58) calibration periods. BTFS confirmed the stability of the developed transfer function. The developed precipitation reconstruction reveals high variability on a high- to mid-frequency scale during the past two millennia. Very dry spring to mid-summer seasons lasting multiple years appeared in the decades AD 500/510s, 940s, 1170s, 1390s and 1160s. At the end of the AD 330s, a persistent multi-year drought with drastically reduced rainfall (w.r.t. 1901–2000) could be identified, which was the driest decade over the past 2,000 years in this region. In the AD 550s, 1050s, 1310s and 1480s, multi-year periods with high rainfall hit the Main region. In the spring to mid-summer of AD 338, precipitation was reduced by 38 % and in AD 357 it increased by 39 %. The presented hydroclimate reconstruction and its comparison to other records reveal interesting insights into the hydroclimate dynamics of the geographically limited area over the Common Era, as well as revealing noticeable temporal differences.

1 Introduction

The observed change in climate in recent decades has already impacted natural and human systems (Stocker et al., 2013). To predict future impacts on the earth system, it is necessary to investigate past~~historical~~ climate dynamics, which~~. Such investigations requires~~rely on various climate proxies that have ~~which~~ preserved past physical characteristics. Tree rings are widely used as a suitable proxy to reconstruct past climate variability and to provide information on climate fluctuations on a sub-annual basis. Changes in air temperature have been intensively investigated with temperature-sensitive tree-ring chronologies (here we refer to Wilson et al., 2016; Anchukaitis et al., 2017 and references therein) on a regional to global scale~~., while~~ A comparable number of studies have also investigated ~~of~~ long-term (century to millennia) hydroclimate variability, rainfall and drought intensity (e.g. Hughes and Brown, 1992; Esper et al., 2007; Cook et al., 2007; Stockton and Meko, 1975; Cook et al., 2004; Ljungqvist et al., 2016; Prokop et al., 2016; Cooper et al., 2013; Wilson et al., 2005; Wilson et al., 2013; Levanič et al., 2013; Ruiz-Labourdette et al., 2014; Cook et al., 2015; Seftigen et al., 2017; Helama et al., 2009; Kress et al., 2014) ~~are much more rare~~. For continental Europe~~, and some of its continental islands (e.g. Great Britain),~~ only a small number~~several~~ of tree-ring hydroclimate reconstructions exist which cover the entire Common Era ~~based on tree rings are available. They cover time periods ranging from centuries to, in a few cases, millennia and allow insights into sub-annual hydroclimate variability. However, due to a lack of samples from ancient (subfossil) wood before the Middle Ages, there are far less hydroclimate reconstructions developed from tree rings before that epoch.~~, and very few~~Nevertheless, some~~ studies addressed the~~is~~ challenge ~~and yield the unique possibility of~~to investigation~~e~~ hydroclimate fluctuations before~~yond the~~ Common Era (Land et al., 2015; Büntgen et al., 2011; Pechtl and Land, in press; Schönbein et al., 2015; Pechtl and Land, 2019). ~~For accurate climate model assessment, it is crucial to understand the full range of natural rainfall variability, which would allow to suit current models. To master this challenge, highly resolved tree ring reconstructions covering time spans as long as possible, at best over several millennia, which preserve fluctuations on short to long frequency scales are needed.~~

The historic instrumental data sets (~150 years) are too short to considerably reduce the uncertainty in hydroclimate projections (Ljungqvist et al., 2016). Thus, reconstructions of past hydroclimate variability from tree rings and from a distinct geographical region over substantial parts of the Holocene would allow us to study the natural ~~(full~~ range~~)~~ of hydroclimatic dynamics on annual to decadal time scales. This would provide a baseline for climate model simulations and improve the verification of model outputs for predicting future droughts and wets~~pluvials~~.

In this study, a set of total ring width series from the Main region in southern Germany was used to achieve a robust reconstruction of spring to mid-summer precipitation variability. As hydroclimate is generally very localized, limiting the geographic extent of our study to the Main region allows us to create a model that can be used to infer rainfall variability over two millennia. An innovative bootstrapped transfer function stability test (Buras et al., 2017) was used to assess the stability of the applied climate-growth model and the representativeness of the presented reconstruction. ~~Additionally, w~~We have chosen this specific region since there might be a high potential to develop a hydroclimate record covering the Early, Mid- and parts of the Late Holocene.~~An innovative bootstrapped transfer function stability test (Buras et al., 2017)~~was used

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~~to assess the stability of the applied climate-growth model and the representativeness of the presented reconstruction.~~ The connectivity to other existing hydroclimate reconstructions is shown and we critically discuss (a) the feasibility of developing a hydroclimate reconstruction spanning over substantial parts of the Holocene, (b) the potential to obtain information on the frequency and intensity of severe droughts / wet~~s periods~~ lasting over seasons or even decades and (c) the

5   independence of our tree-ring data set compared to other reconstructions from Central Europe.

2 Materials and methods

2.1 Tree-ring data

The Main region (hereafter referred to as MR) is located in Germany and gets its name from the Main River. The Main River

10   originates in the Fichtel Mountains (northeast Bavaria, Germany) and after approximately 500 km empties into the Rhine River. The Main River is the fourth largest tributary of the Rhine and runs from east to west, which is rare for Central Europe. From the MR, total ring width (TRW) series were used to construct a composite oak TRW chronology covering the period from AD 1–2015. To achieve this, an extensive set of 1,405 tree-ring series from this distinct geographical region is available. Such data are generally collected and stored in commercial and university dendro labs all over the world and used

15   to develop robust TRW chronologies with sufficient replication. At the University of Hohenheim, for example, a tree-ring archive of ancient pine (Preboreal pine chronology, PPC) and oak samples (Holocene oak chronology, HOC) spanning the entire Holocene (~12,500 years, Friedrich et al., 2004) exists which serves as a suitable archive for studies of past climate variability. The HOC consists of oak samples from quaternary deposits, archeological wood findings, construction timbers and living trees primarily sampled from southern Germany. Together, these form a unique, annually-resolved archive

20   providing an excellent opportunity to study paleoclimate (for details about the PPC and HOC we refer to Friedrich et al., 2004).

The composite TRW chronology contains tree-ring series from living trees, construction timbers (historical) and alluvial deposits (subfossil). TRW series from historical (Büntgen et al., 2010b; Cooper et al., 2013; Wilson and Elling, 2004; Wilson et al., 2005) and archaeological/subfossil material (Kreuzwieser et al., 2004; Land et al., 2015; Schönbein et al.,

25   2015; Pechtl and Land, in press; Pechtl and Land, 2019) have already been used successfully in dendroclimatological studies to reconstruct past hydroclimate variability. All TRW series used for this study originated from a well-defined geographical region between 49.3–50.8° N and 8.2–12.2° E (Fig. 1).
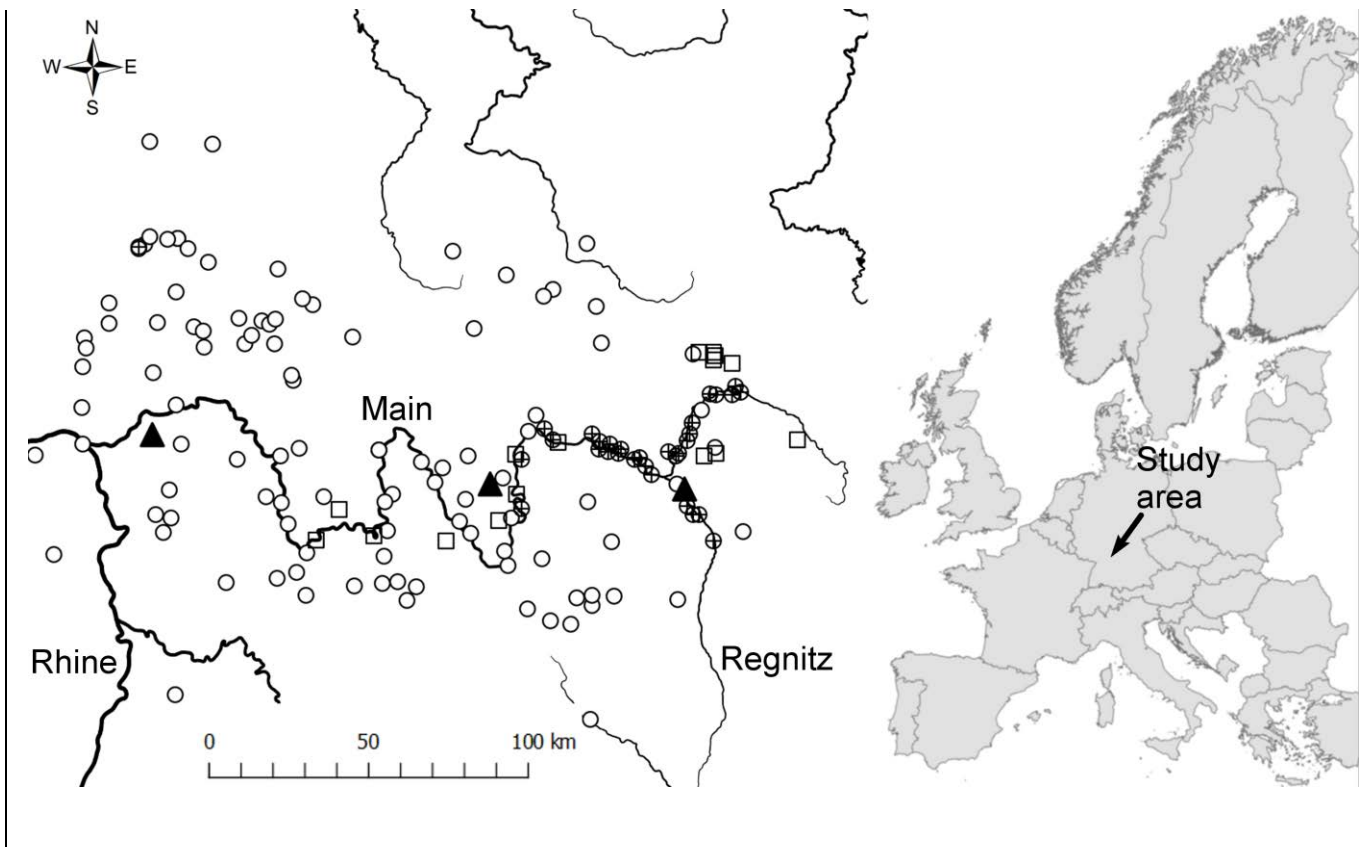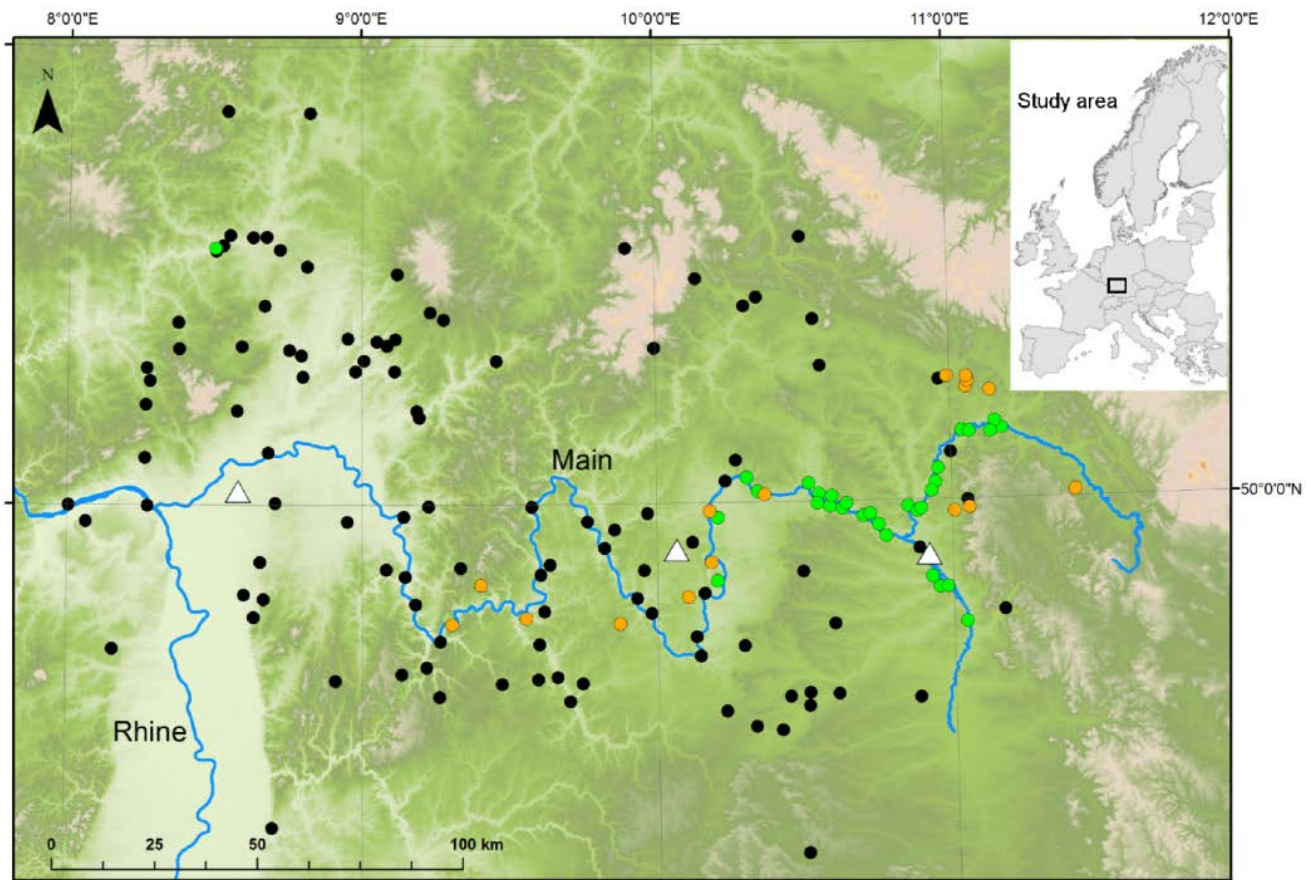
Fig. 1. Study area. Locations of the tree-ring sites and meteorological stations in the Main region. The study area is located between 49.3–50.8° N and 8.2–12.2° E. Sites of living trees (~~orange dots~~squares), localities of historical samples from construction wood (~~black dots~~circles) and gravel pits of alluvial deposit subfossil oaks (~~green dots~~circles with cross hairs) are shown. The three meteorological stations (white triangles) are located in the eastern, middle and western parts of the study area.

For calibration, living TRW series were used from locations along the middle and upper Main valley. The specific growth sites of construction timbers used in historical buildings are unknown, but provenance is assumed to be of local origin. The historical TRW samples are spread over the entire MR and were obtained from the tree-ring laboratory of the University of Hohenheim and the Hofmann tree-ring laboratory. The TRW series from subfossil oak trunks were derived from quaternary deposits of the upper Main River and the lower Regnitz River.

The entire data set of the original TRW series used for this study is available for public access (see Sect. Data availability).

2.2 Daily meteorological precipitation records

Daily precipitation sum (DPS) records from three long-term meteorological stations (Fig. 1) were used to assess the hydroclimate response of the TRW chronology. The meteorological stations Bamberg (49.88° N, 10.92° E, 240 m a.s.l.), Bergtheim (49.90° N, 10.07° E, 270 m a.s.l.) and Frankfurt a.M. (50.05° N, 08.60° E, 112 m a.s.l.) are located within the MR. The stations were selected due to their long-term DPS records dating back to 1870 (Frankfurt a.M.), 1879 (Bamberg) and 1899 (Bergtheim) as well nearly complete status of these records. The data were provided and verified by KNMI Climate Explorer (http://climexp.knmi.nl., Klein Tank et al., 2002) and from the Deutscher Wetterdienst (DWD). The DPS record from the Bamberg station did not contain any missing data during the entire period, whereas the DPS records of the Frankfurt a.M. and Bergtheim stations had a gap between March and August 1945.

Precipitation sums of each day from all three stations from AD 1900 to 2015 were averaged to obtain a single DPS record representative for the MR. Between March and August 1945, only the Bamberg DPS record was used. This MR DPS was used for climate-growth analysis.

During AD 1901–2000 the mean precipitation sum between Feb. 26–Jul. 06 (spring to mid-summer) was calculated, serving as a reference period. This interval was chosen based on the results of the climate-growth analysis result during calibration.

2.3 Tree-ring series and chronology construction

For this study, precisely dated TRW series from oaks were assembled to construct a two millennia composite chronology (AD 1–2015) representing the seasonal radial growth variability within the MR.

The individual TRW series were primarily obtained from the Hohenheim tree-ring archive containing series from subfossil (*Quercus* sp.), historical (*Q.* sp.) and living (*Q. robur*, *Q. petraea*) trees as well as from the Hofmann tree-ring laboratory (historical series, *Q.* sp.) to establish a well-replicated TRW chronology. Figure 2 shows the growth period, the mean segment length (MSL) as well as the running inter-series correlation (RBAR) and the Expressed Population Signal (EPS) of the TRW data set (Wigley et al., 1984).
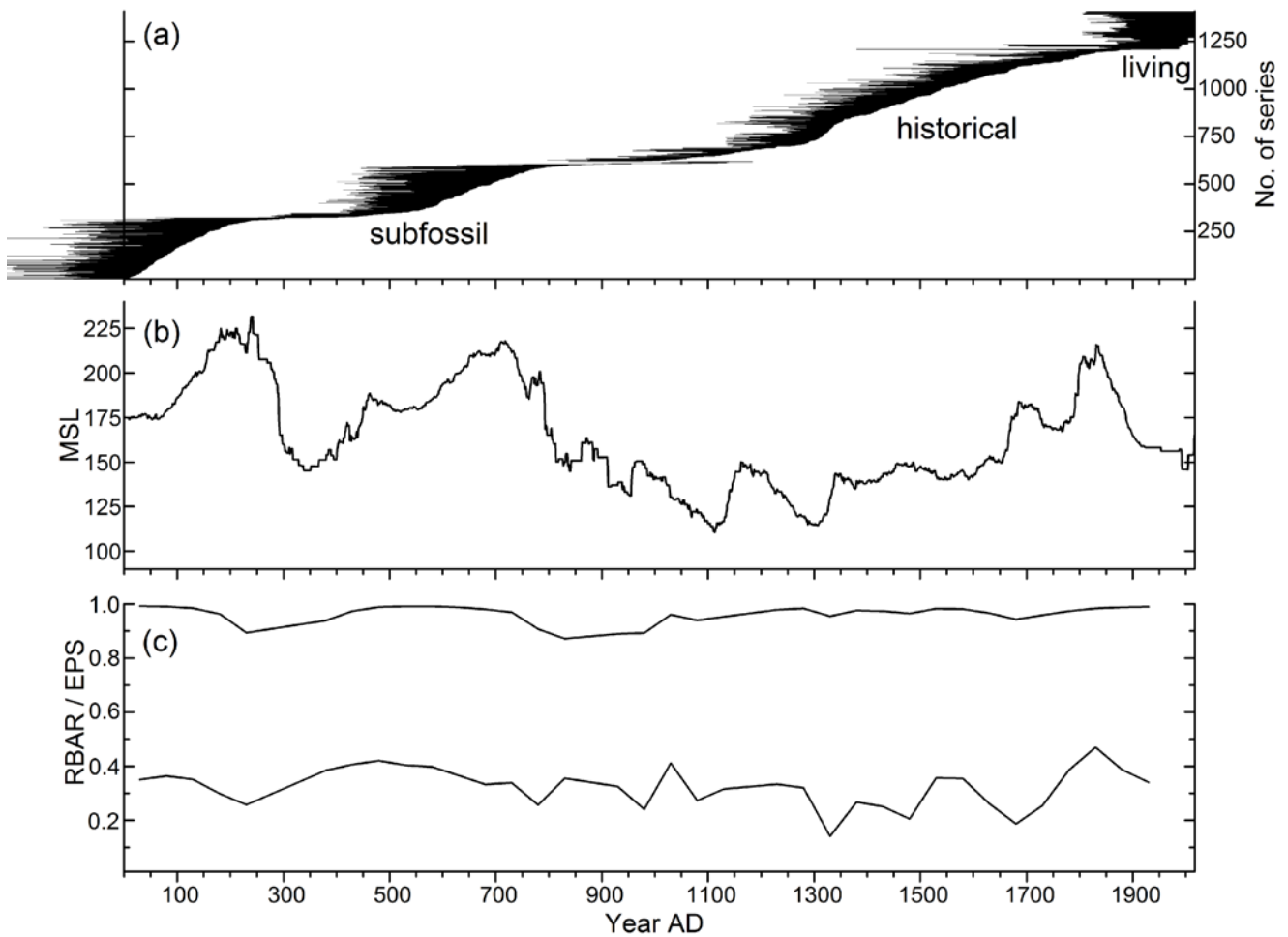
Fig. 2. MR oak trees used for the reconstruction. (a) Growth period of living, historical and subfossil tree-ring series, **(b)** mean segment length (MSL) and **(c)** inter-series correlation (RBAR) and Expressed Population Signal (EPS) statistics.

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For the study, a set of 1,405 precisely dated tree-ring series (Küppers et al., 2018) consisting of 618 subfossil, 586 historical and 201 living trees was available (Fig. 2). The subfossil oaks cover the period until AD 1184 and some individual series go back to 321 before Common Era ~~(BCE)~~. Historical tree-ring series range from AD 797 to 1897 and the living series span the period from AD 1380 to 2015. High fluctuations in the replication throughout the study period can be observed, particularly

10   in the subfossil material, indicating a strong river dynamic which led to low / high deposition frequencies. A sufficient overlap between subfossil and historical as well as between historical and living TRW series was ensured.

The raw TRW series were detrended by fitting a fixed 100-year cubic smoothing spline (Cook and Peters, 1981) to each individual TRW series. A dimensionless index was obtained by calculating the ratio of the raw and predicted values. The

individual detrended TRW series were averaged using the robust bi-weight mean method to develop the standard TRW chronology. Due to fluctuations in the replication, variance stabilization was performed by applying the RBAR-weighted method (Frank et al., 2007; Briffa and Jones, 1990). The above-mentioned standardization procedure was conducted using the ARSTAN software (Cook and Krusic, 2005).

5 Expressed Population Signal (EPS) and inter-series correlation (RBAR) are key statistics in dendroclimatology for assessing the representativeness of a TRW chronology. EPS and RBAR statistics were calculated as a quality criterion of the coherence of the TRW chronology. Running EPS and RBAR were calculated during 100-year periods with a 50-year overlap. An EPS value of > 0.85 was defined as acceptable for a noise-free chronology. Even when concerns regarding the misinterpretation of the EPS threshold have recently been raised (Buras, 2017), we will use the above mentioned EPS

10 threshold to ensure that our study is comparable to others.

2.4 Calibration, verification and reconstruction of hydroclimate variability

Tree-ring climate response was assessed using a) a classical split-period calibration / verification (AD 1900–1957 / 1958–2015) and b) a full period calibration approach (AD 1900–2015). The correlation coefficient (r) was calculated for

15 calibration and the coefficient of efficiency (CE) for verification (Cook et al., 1994) to assess the reconstruction quality. A CE greater than zero was assumed to indicate a robust reconstruction.

To assess the temporal stability of the relationship between ring-widths and DPS, we applied the bootstrapped transfer function stability test (BTFS, Buras et al., 2017). BTFS bootstraps model parameter ratios between calibration and verification periods of equal length (here 58 years) for intercept, slope, and explained variance over 1000 iterations and tests

20 whether the obtained sample differs significantly from one which would indicate instability of the given parameter. Thus, p-values below 0.05 indicate unstable transfer function parameters.

Calibration was conducted between the TRW chronology of the living oak trees and the DPS record. Correlation analysis was performed using a MATLAB® (MathWorks, 1994-2008) script (Schönbein, 2011) which aggregated DPS data for each year, altering the length of the data interval (from 31 to 361 days in steps of ten days) and the date of start (between January

25 1 and December 15). Statistical significance was attained for $\alpha = 5\%$. For details about the running of the script we refer to Schönbein (2011) and Land et al. (2017).

The developed linear climate-growth model was applied to the composite TRW chronology to reconstruct two millennia of hydroclimate variability for the MR. The statistical metric root mean square error (RMSE) was used to measure the climate-model performance.

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2.5 Comparison to other hydroclimate reconstructions and independence of the data set

The developed reconstruction of the MR hydroclimate was compared to other hydroclimate reconstructions available for this region. Pauling et al. (2006) reconstructed the seasonal (spring, summer) precipitation from natural proxies (tree-ring chronologies, ice cores, corals and a speleothem) for European land areas from AD 1500 to 1900 (hereafter referred to as P06sp, P06su). Cook et al. (2015) (hereafter referred to as C15) released a tree-ring based reconstruction of summer droughts and pluvials (calibrated to scPDSI) over Europe and Büntgen et al. (2011) (hereafter referred to as B11) reconstructed April–June precipitation sums over Central Europe, the latest two studies covering the past two millennia. The mentioned reconstruction series were obtained from the National Oceanic and Atmospheric Administration (http://www.noaa.gov) database (grid 49.75° N, 10.25° E, center).

The set of original, single TRW series included in the respective reconstructions used by the mentioned authors is, to the best of our knowledge, not explicitly stated in their work or accessible. This circumstance made a, which makes the comparison between the different respective records impossible extremely difficult. We were therefore unable to check for full independence between the different data sets, meaning that the data set used here might be not fully independent to others, particularly from Middle Ages to the beginning of the modern era. Nevertheless, for the periods in which subfossil and living TRW series have been used, a full independence of the MR exists to C15, B11 and P06. We assume that the historical TRW series MR data set guaranty an independence of at least 55 % over the reconstruction period from AD ~1150 to 1700. At best, the majority (> 80 %) of the MR historical TRW series have not been used by C15, B11 or P06.

It should be mentioned that this is a sub-optimal situation for this study which does not allow us to ensure the necessary independence between the data sets, but is unfortunately unavoidable in light of the data availability. However, the MR TRW data set used here gives the unique possibility to study the hydroclimate dynamic in a geographically limited area over two millennia.

To expose the common power and relative phase in time-frequency space between the aforementioned and the MR reconstruction, cross-wavelet transform (XWT) was evaluated and wavelet coherence (WTC) was measured by using a MATLAB® script from Grinsted et al. (2004). The XWT finds regions with high common power and WTC shows where the compared series co-vary in time-frequency space (even when common power is low). For all calculations, the Morlet wavelet was chosen, providing a good balance between time and frequency localization (Grinsted et al., 2004). Additionally, a 51-year running correlation between the MR reconstruction and P06sp, P06su, C15, B11 was performed. This relatively short window length allows us to study abrupt temporal changes in the behavior of the aforementioned reconstructions.

3 Results

3.1 TRW composite chronology

The number of TRW series per year fluctuates over time. The lowest replication can be found around AD 280 / AD 850, while the highest is in the first decade AD (Fig. 2a). Mean segment length (MSL) is longer for the subfossil and living TRW series and shorter for the historical series, but always exceeds 1100 years (Fig. 2b). Thus, the temporal fluctuation in MSL limits the extent to which low-frequency signals can be extracted from the TRW data set, like in many other studies dealing with historical oak tree-ring series (see also e.g. Cooper et al., 2013; Wilson et al., 2013). It is likely that the changes in replication and MSL to some extent do bias the developed reconstruction series, even when EPS is >0.85. Thus, the developed TRW composite chronology might be biased in the periods AD ~300 and ~800. Expressed Population Signal (EPS) is always above the threshold of 0.85 during the entire time span (mean EPS = 0.96). The lowest EPS was observed in the transition period of AD 830 where subfossil and historical TRW series overlap, corresponding with low replication. The mean inter-series correlation (RBAR) is 0.32 (Fig. 2c) showing low values in the first half of the 14th and at the end of the 17th century where the TRW chronology consists of primarily historical TRW series. The decrease in RBAR may lead to a bias in the reconstruction. This is accompanied by increased construction activity in the Main region at the beginning of the 14th century (see the high cutting activity marked by TRW series with similar end of their growth period in Fig. 2a). In regards to the unknown growth location, and thus the correct origin of the historical trees, the low RBAR could be an artefact of timber trading from outside the study area. The exact oak species (*Q. robur*, *Q. petraea*) used for the reconstruction is also unclear. At the end of 17th century a TRW set of very old living oak trees are added to the historical data set and may lower RBAR. In periods where only subfossil and living TRW series were used, RBAR increases and is considerably higher, e.g. prior to AD 500 (subfossil) as well as after AD 1830 (living). Further worth mentioning, is that the subfossil TRW series seem to be much more homogenous in regards to their inter-series growth pattern than the historical series. The relatively small region of deposited subfossil trees (Fig. 1) could provide an explanation and may hold a more accurate and local climate signal than the historical TRW subset.

3.2 Climate-growth model and hydroclimate reconstruction

Figure 3 illustrates the calibration and verification process implemented for the development of the model that was used for further hydroclimate reconstruction.
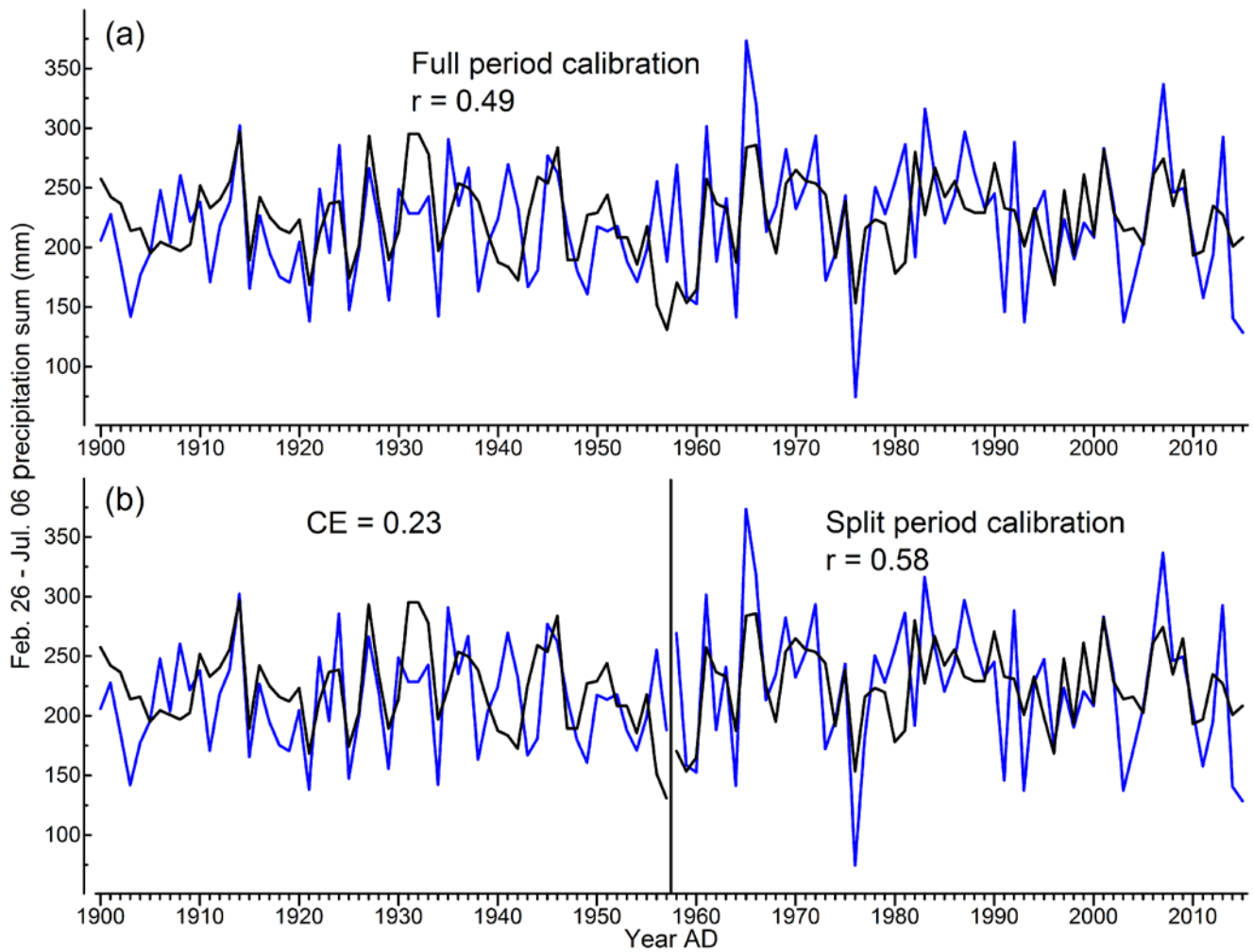
Fig. 3. Calibration and verification of the MR oak climate-response analysis. (a) Full (AD 1900–2015) and **(b)** split (AD 1958–2015) period calibration. The model was verified during AD 1900–1957. Actual precipitation sum from Feb. 26–July 06 (blue) and reconstruction (black) are shown.

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The TRW chronology reveals a significant relationship (p < 0.01) to DPS from Feb. 26–July 06 (spring to mid-summer season) during the full (r = 0.49) and split (r = 0.58) calibration period. For sensitivity test results of the TRW chronology with total precipitation sum for "classical" monthly-resolved seasons, see Table A1. A CE of 0.23 accounts for a robust reconstruction. This indicates that the developed climate-growth model is suitable for reconstructing regional hydroclimate

10 variability.

Nevertheless, as can be seen from Fig. 3, the TRW chronology does not track extremely low (e.g. 1903, 1976, 1991, 1993, 2003, 2015) or high (e.g. 1965, 2007) precipitation rates adequately. Thus, the model underestimates the true sum of precipitation in the spring to mid-summer season. Similar results were published by other authors (Cooper et al., 2013;

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Wilson et al., 2013). Based on the work of McCarroll et al. (2015), we simply defined a 10 % threshold of years in which precipitation sum was low / high during the full calibration period (116 years, 10 % = 11.6 years each) as extremes. After ranking the precipitation data, we checked how many years of the TRW data capture these extremes. Only three years lie beyond the lowest (statistically not significant), but four years beyond the highest threshold (statistically significant, $p <$

5   0.05). Even though a close statistic relationship between DPS and TRW is evident, there is spurious correlation regarding extreme values.

The applied bootstrapped transfer function stability test (BTFS) indicated stability of transfer function parameters (slope, intercept, r^2) over time ($p \geq 0.25$ w.r.t. to the null hypothesis of perfectly stable model parameters). A highly significant sign-

10   test ($p < 0.001$) revealed true collinearity between TRW and DPS over the calibration period. Model residuals were normally distributed and did not express significant autocorrelations. A moving window correlation between TRW and DPS revealed significant temporal correlations over the calibration, however these varied between 0.33 ($p < 0.05$) and 0.60 ($p < 0.001$). Both classic calibration / verification as well as BTFS confirm the sensitivity of TRW to Feb. 26–July 06 precipitation totals.

15   The developed climate-growth model was applied to the composite chronology to reconstruct spring to mid-summer (Feb. 26–July 06) precipitation variability for the MR from AD 2015 back to AD 1. The seasonally-resolved reconstruction series over two millennia is shown in Fig. 4. The reconstruction maintains high seasonal as well as decadal scale fluctuations.
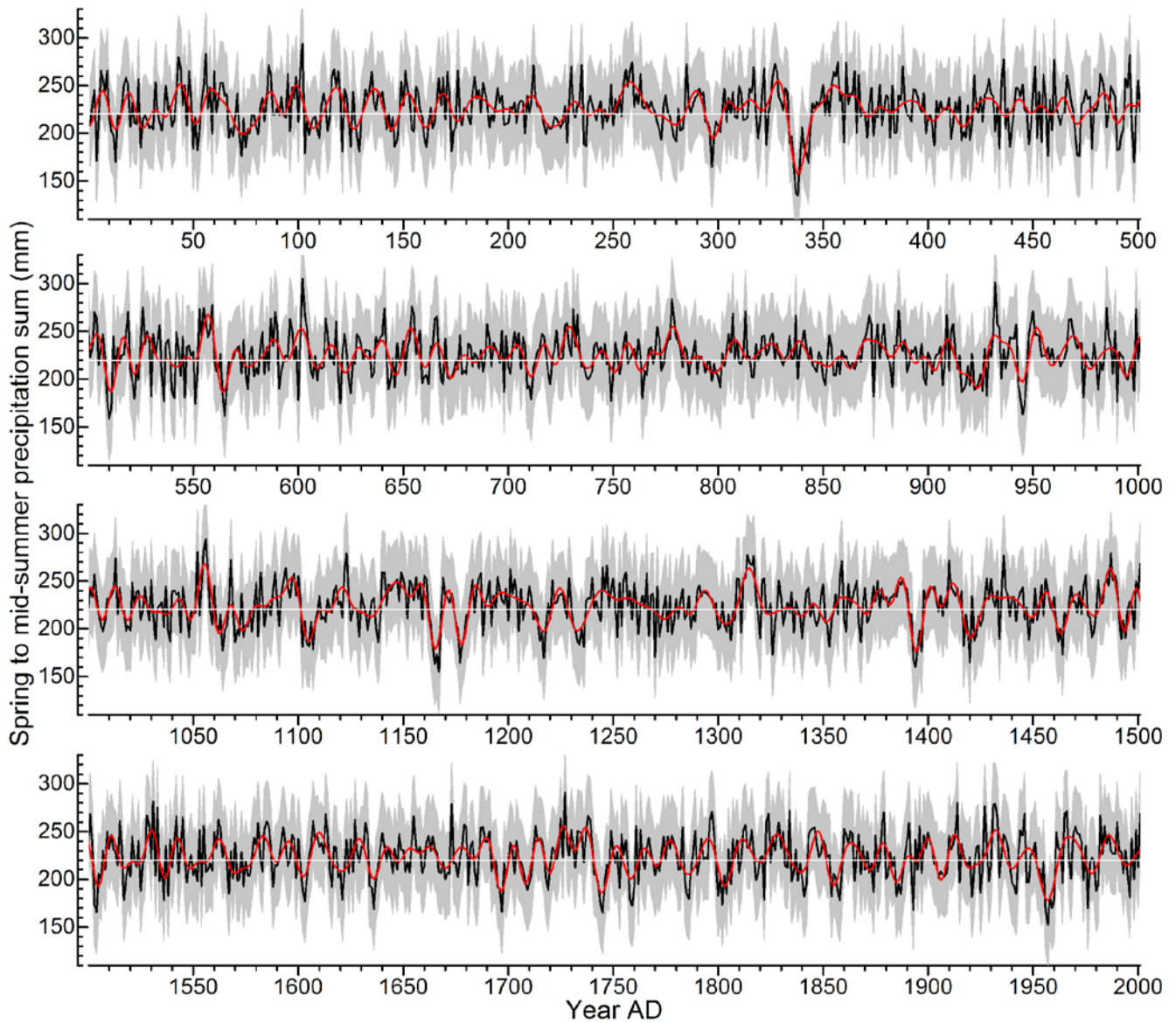
Fig. 4. Reconstruction of spring to mid-summer season precipitation variability for the MR. Reconstruction of precipitation sum from Feb. 26–July 06 (black) and 10-year lowpass filter (red) during AD 1–2000. RMSE = light grey shaded, thin white line = mean precipitation sum during the reference period AD 1901–2000.

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The developed reconstruction shows high variability on an annual to decadal time scale with repeated phases of below / above average rainfall. According to our findings, nine years of less than 25 % of mean precipitation sum (w.r.t. AD 1901–2000) could be detected (Table 1). The years AD 338 and 337 are marked by severe low pluvials in the MR. In the decade

from AD 334 to 344, the MR was exposed to a conspicuous drought far below rainfall average and thus it can be described as an extraordinarily dry period. In the 12th century (around AD 1165 and 1177) and in the last decade of the 14th century (around AD 1395), three additional periods of below average rainfall occurred. Heavy single-season rainfall exceeding the mean precipitation sum by a minimum of 25 % (w.r.t. AD 1901–2000) appeared in 26 individual years during the past two millennia (Table 1). The years AD 357 and 985 appear as the wettest seasons with high deviations from the reference period. Periods of unusually high rainfall lasting five years or longer appear in the mid-6th, mid-11th and at the beginning of the 14th century. The period from AD 1125 to 1138 is characterized by consistently high pluvials exceeding the average seasonal precipitation sum for almost one and a half decades. A detailed list of dry and wet decades is provided in Table A2.

It can be summarized that the Main region suffered from severe long-lasting droughts and pluvials over the past two millennia, especially during the mid-4th century.

3.3 Comparison of MR reconstruction to others

To evaluate the connection between the MR reconstruction and C15, B11 and P06sp/su, a running correlation (Fig. A1) as well as wavelet analyses between MR and C15 / B11 were performed (Fig. 5).

The 51-year running correlation accounts for temporal variation between the reconstructions. The correlation between MR and C15 / B11 is high from the 12th until the 18th century. Before the 12th and from the 18th century onwards the agreementconnections declined to sporadic cases. Around AD 300 and 400 as well as during the 9th century, the MR shows only weak connections to C15 and B11. In the mid-19th century, MR and B11 hold no statistical relationship. When the MR is compared to P06sp and P06su, a relationship is only evident during short time periods. Especially during the end of the 17th to the mid-18th century as well as over the 20th century, an agreementconnection to P06sp/su is not detectable. In general, MR and P06sp/su are only spuriously related.

Figure 5 shows the cross-wavelet transform (XWT) and the wavelet coherence (WTC) between MR-B11 and MR-C15 over two millennia.
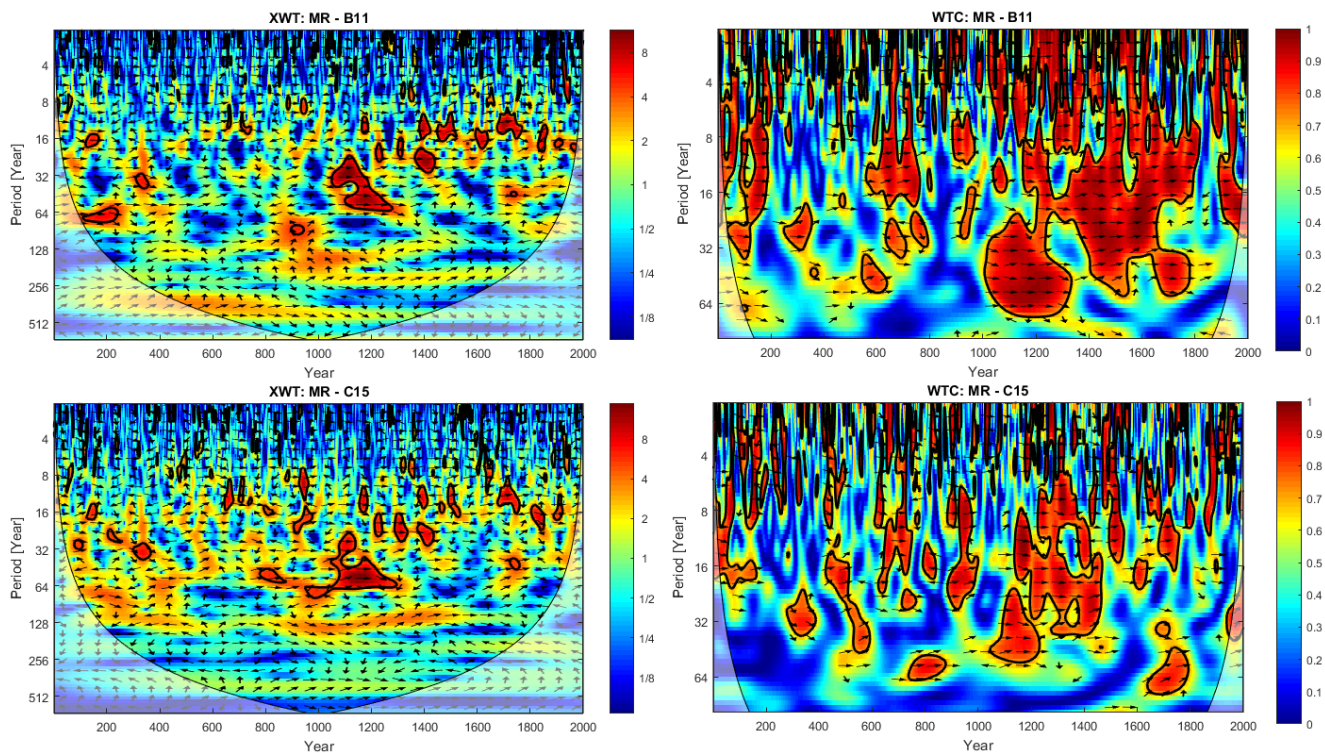
Fig. 5. Cross-wavelet transform (XWT, left) and squared wavelet coherence (WTC, right) between MR-B11 (top) and MR-C15 (bottom) from AD 1–2000. 5 % significance level against red noise is shown as a thick contour. Light shading depicts the cone of influence.

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The XWT between MR-B11 shows significant common power in the ~10–15 year band from the 12th century onwards and in the ~20–60 year band around the 11th and 12th century. The XWT between MR-C15 depicts similar results. Albeit, the ~23–65 year band from AD 1000 to 1300 is more pronounced. Looking at the squared coherence spectrum (WTC) between MR-B11 and MR-C15, the close connections appear on the ~4 year band and are more pronounced on the 10–60 year band, especially after AD 1000. Nevertheless, there is a distinct difference between pre- and post-AD 1000. ~~High c~~Coherence between MR-B11 and MR-C15 is also obvious prior to AD 1000, on short as well as on long terms, but not as high as in the second millennium. The right-pointing arrows in the significant regions (thick contours in the right panels of Fig. 5) indicate that the compared reconstructions clearly swing in phase, holding evidence for close time-frequency connections. The previously mentioned weak connection between MR and C15 in some periods (Fig. A1) becomes more obvious from the WTC. From AD 200–400, for example, no significant connection on shorter and even on longer time scales can be found, supporting the results from the running correlation analysis and indicating substantial differences between the different reconstruction series to the regional MR. The weaker, or even non-significant, connections between MR-B11 and MR-C15

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Figure 6 shows the 20-year lowpass filtered reconstructions from MR, B11 and C15 from AD 1 to 2000 (Fig. 6a) as well as
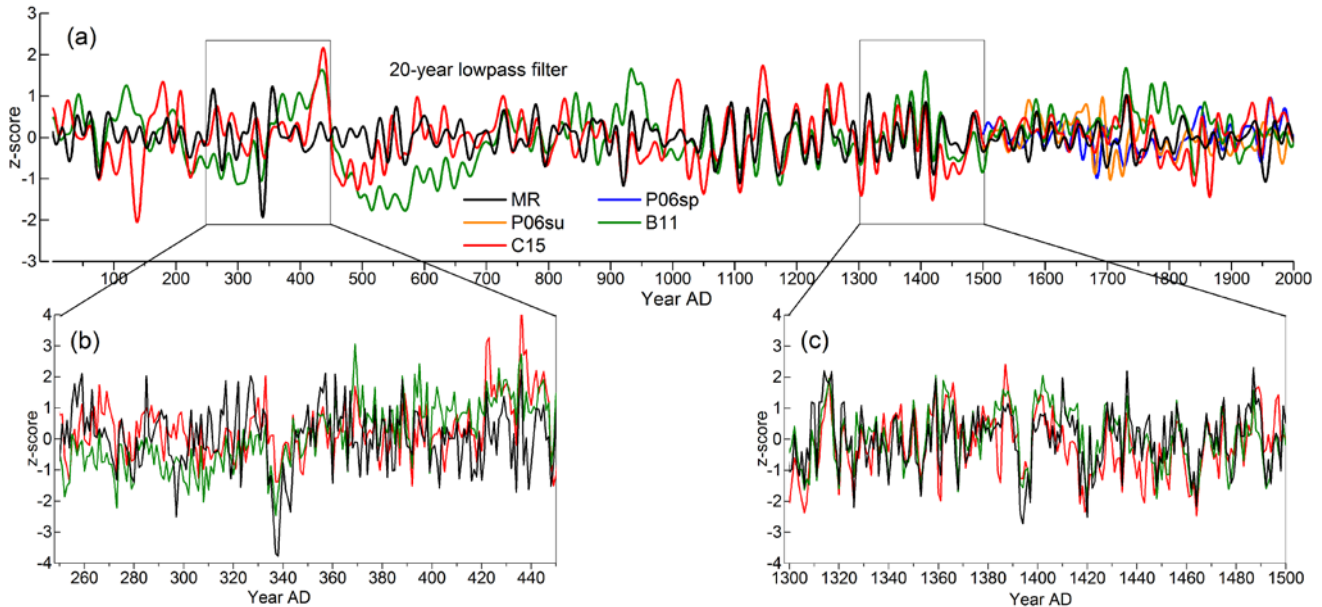5   for two sub-periods with an annual resolution (Fig. 6b/c).

Fig. 6. Smoothed hydroclimate reconstructions from AD 1–2000. (a) 20-year lowpass filtered, **(b)** annual fluctuations from AD 250–450 and **(c)** from AD 1300–1500.

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As shown in the previous section, the reconstruction series contain differences and similarities on year-to-year and on mid-frequency fluctuations. It is obvious from Fig. 6a that MR, C15 and B11 hold strong discrepancies regarding their fluctuations until the end of the 7th century (see also Fig. 5). For example, B11 shows a much higher fluctuation on a longer time scale between AD 250 and 700 than C15 and MR. However, during the aforementioned dry decade around AD 338
15   (Fig. 6b), all three reconstructions independently show similar patterns and document a long-lasting drought. On the other hand, the pronounced long-lasting drought in the 6th century as reconstructed by B11 is not seen in MR or C15. Although C15 and B11 show evidence of a severe wet decade around AD 435, the MR does not confirm this result. On the contrary, the MR shows moderate changes on a mid-frequency scale. From the end of the 11th to the mid-18th century, all reconstruction series show highly similar patterns (Fig. 5; Fig. 6c; Fig. A1) from year-to-year and on mid-frequency, with the
20   exception of P06sp/su. They share changes in the amplitude synchronously even in very wet and severe dry years / periods. In particular from AD 1800 onwards, when full independence of the MR data set is guaranteed, notable differences occur.

Running correlation analyses also account for substantial differences between the MR and the other reconstructions over the last two centuries (see also Fig. A1).

4 Discussion

4.1 Climate-sensitivity of the MR TRW chronology and stability of transfer function

The oak TRW chronology from the Main region (MR) in southern Germany reveals a significant ($p < 0.01$) sensitivity to the precipitation sum from February 26 to July 06 (spring to mid-summer season). During calibration and verification it became clear that TRW does not cover the full range of precipitation variability, resulting in a poor correlation between TRW and extremes. Low and high seasonal precipitation sums are not accurately reflected in the applied climate-growth model, which is also mentioned by e.g. Cooper et al. (2013) and Wilson et al. (2013). Land et al. (2017) pointed out that oak tree-ring series are not sensitive to short, heavy rainfall events during the growing season, which may provide a further explanation for this fact. Another reason could be a loss of photosynthetically active leaf area caused by fungal infestations (e.g. mildew) during such phases of high precipitation. We further note that in the MR, a massive insect attack took place between AD 1954–1958 (Steger, 1959, 1960) which reduced growth considerably and certainly influenced the climate-growth model performance. The complexity of oak growth over the course of the 20th century is also well-established. Friedrichs et al. (2008) showed that oak growth can increase when a combination of warm and dry conditions occur. This leads to the assumption that the control of oak growth remains complex, at least during isolated periods. Altogether, the applied climate-growth model considerably underestimates the total seasonal precipitation sum which leads to a loss of explained variance.

The precipitation sensitivity of the MR oaks does, however, agree with findings from other studies conducted with oak tree-ring series in Europe. Büntgen et al. (2011) reported a sensitivity of the seasonal precipitation sum from April to June (Central Europe), while Friedrichs et al. (2008) (central-west Germany) and Čufar et al. (2008) (southeast Slovenia) for the June rainfall sum. Cooper et al. (2013) (East Anglian), Wilson et al. (2013) (south-central England) and Karanitsch-Ackerl et al. (2017) (northeast Austria) found a close relationship to March–July precipitation sum and Land (2014), Land et al. (2015), Land et al. (2017) and Schönbein et al. (2015) (Franconia, Germany) to spring-summer precipitation. European oak TRW chronologies show an explicit connection to hydroclimate during the growing season, in particular from spring until mid-summer.

4.2 Main region hydroclimate dynamic

The developed climate-growth model leaves a high level of unexplained variance, which is most apparent in seasons with far below / above average rainfall totals. This leads to an inevitable underestimation of past climate variability and is also reported from other authors (Cooper et al., 2013; Esper et al., 2005; Storch et al., 2004; Wilson et al., 2013; Bürger et al., 2006; Christiansen and Ljungqvist, 2017). Thus, we can assume that in the MR, the year-to-year dynamic might be much more variable than suggested by the tree rings due to the tree rings' inability to capture years with extreme low / high precipitation. This would mean that during the past two millennia, very low / high pluvials are much more pronounced and thus the hydroclimate dynamic is stronger than suggested by the presented reconstruction. While the oak tree-ring series used

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here respond very well to spring-summer rainfall during the calibration / verification period, it is not unlikely that, to some extent, warmer / colder phases during the past two millennia (e.g. the Medieval Climate Anomaly or the Little Ice Age) affect the presented reconstruction. It has been shown by Friedrichs et al. (2008) that oak trees from central-west Germany (which is close to our study region) lose their precipitation sensitivity in the anomalously warm decade 1940s. This decreased response to hydroclimatic conditions in central Germany has been confirmed by Büntgen et al. (2010a), whose study revealed that oak TRW sensitivity is greatly reduced to scPDSI in the mid-20th century. A well-established decrease in precipitation sensitivity during the 1940s is also observed in our study (data not shown). With this in mind, it is possible that during extraordinary warm (Medieval Climate Anomaly) or extraordinary cold (Little Ice Age) (Mann et al., 2009) periods, TRW reconstructions may show a certain level of bias. However, it remains unclear to what extent the reconstruction here presented is biased.

On the other hand, a severely reduced growth of oak trees does not necessarily mean a "true" dry season, but may instead be due to a combination of moderate rainfall, a warm spring season and / or an insect attack. Oak trees are prone to insect attacks, especially under natural forest dynamic processes within a small region. Capturing non-climate-driven tree-ring fluctuations, e.g. caused by insects, would therefore necessitate an investigation of wood anatomy which, due to the high number of wood samples, would be labor-intensive and cost-prohibitive. An attempt of such can be found in Land et al. (2015) and Schönbein et al. (2015). Nevertheless, single seasons with pronounced below (e.g. AD 338) / above (e.g. AD 357) average rainfall totals as well as very dry several-year periods (e.g. around AD 1395) appeared in the MR. Interestingly, Spurk et al. (2002) investigated the depositional frequency of subfossil oaks in the MR, which includes the tree samples used here, and linked them to climatically-induced fluctuations. They found a sudden onset of germination at AD 400 in the MR, indicating humid conditions. From AD 400 onwards, our reconstruction gives no evidence for a continuous long-lasting period with above-average rainfall, but shows distinct high year-to-year fluctuations between AD 420 and 550. Despite that, changes on a low frequency scale over centuries to millennia are masked by the standardization procedure.

Nevertheless, due to the changes in the mean segment length and the highly variable sample replication, the standardization procedure applied here (100-year spline) is suitable for preserving high- to mid-frequency fluctuations, while the low-frequency variance from the TRW data set is removed. Thus no inferences can be made for centennial-long precipitation fluctuations for the study region. When comparing the MR hydroclimate reconstruction to B11 and C15 (both capturing the low-frequency domain e.g. by using RCS detrending), some differences appear on the low-frequency timescale. These are especially apparent in the first millennium AD, where trees from alluvial deposits are available for reconstruction purposes, and is more pronounced between MR-B11 than between MR-C15.

As mentioned by Spurk et al. (2002), human influence could have had a severe impact on forest structure and forest dynamic since the third millennium before Common Era and may have therefore impacted the dynamic of tree growth, perhaps leading to a bias in the established reconstruction. Therefore, investigating epochs where human impact is low, or at best did not occur, is crucial to get a clear picture of pre-human time and its climate dynamic. However, it should be mentioned that humans already settled in the MR over 7,000 years ago (Bickle and Whittle, 2013) and certainly influenced their

environment accordingly. Much more effort must be made in the future to fully understand the hydroclimate dynamic on a small scale (e.g. in the Main region) during the entire Holocene. Even when the tree rings used represent a highly-resolved natural archive, combining different scientific fields, e.g. as recently done by Pechtl and Land (2019), is very necessary to capture potential human effects on former forests. Another factor plays a crucial role: for southern Germany (and for large

5   parts of Central Europe) oak is the only species from which TRW series are available from present back to the Early / Mid-Holocene. It is therefore of tremendous interest for paleoclimate research to interpret the growth fluctuations more precisely and to enhance climate-growth model performance.

4.3 Comparison and independence of MR to other hydroclimate reconstructions

10   The reconstruction of spring to mid-summer precipitation variability for the MR developed here shows high connectivity to C15 (Cook et al., 2015) and B11 (Büntgen et al., 2011) for substantial parts of the past two millennia, which is apparent on different time-frequency domains as well as from continuous in-phase fluctuations. Nevertheless, the results of running correlations and wavelet coherence analyses clearly speak for notable differences during some periods. These differences are particularly obvious around AD 300–400, 750–850 and 1820–1870, accounting for intervals where the MR TRW data set is

15   fully independent from others. The differences can primarily be observed on a mid-frequency scale but are also seen in year-to-year fluctuations. We assume that one reason for this could lie in the differing standardization procedures utilized in chronology construction, whilebut the use of mixed TRW series from various provenance and from different sources (archaeological findings) could also play a considerable roleis also conceivable (for more detail we refer to the mentioned studies). This underlines the significance of this study, as it presents a hydroclimate reconstruction for a small geographical

20   region in southern Germany as well as providing a new time series that can contribute to investigations about past European hydroclimate variability.

The high connectivity between MR-C15 and MR-B11 over ~700 years (end of 11th to mid-18th century) is outstanding and supports the assumption that duplicates within the TRW data are used in the different studies. The exact level of dependency between the different data sets cannot be stated here and remains undetermined. Thus, we assume that during this period our

25   TRW data set might be not as independent as initially considered, which once again highlights the importance of data transparency.

Nevertheless, the MR hydroclimate reconstruction accounts for an on-site variability.

Developing a hydroclimate reconstruction for Central Europe reaching back to the Early / Mid-Holocene requires a large

30   data set with a sufficient number of TRW series. This goal could be achieved with the use of TRW series from the Holocene oak chronology (HOC) Hohenheim (Friedrich et al., 2004), assuming that these subfossil oaks reflect the representative Central European hydroclimate. The results of our study support the assumption that the TRW series from the Main region, consisting of a well-replicated TRW data set (for more details see Friedrich et al., 2004; Leuschner et al., 2002; Spurk et al.,

2002), have the potential to reflect the rainfall variability of Central Europe, at least for southern Germany, as well as regional hydro-regime aspects. Nevertheless, a ten millennia hydroclimate reconstruction would require the inclusion of TRW data from other river systems (e.g. upper Danube, upper Rhine) due to changes in the deposition frequency of oak trunks and the resultant variance in replication (Spurk et al., 2002; Friedrich et al., 2004). Such temporal changes of

5   distribution are known from tree-ring archives of Ireland, northern Germany and the Netherlands (Leuschner et al., 2002; Spurk et al., 2002) as well. Combining such TRW data sets lasting for millennia from different regions or countries across Europe is crucial for the development of a well-replicated reconstruction representing the overall European seasonal rainfall variability during substantial parts of the Holocene. Additional regional investigations of hydroclimate variability that cover multiple millennia must also be conducted.

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5 Conclusions

We conclude that oak TRW in the Main region is suitable to reconstruct past hydroclimate conditions with a~~n annual~~ ~~seasonal~~ resolution during the past two millennia as well as for the investigation of rainfall intensity on a high- to mid-frequency scale. Moreover, the developed hydroclimate reconstruction is, to the best of our knowledge, the only record

15   covering two millennia with seasonal resolution for a geographically limited area in Central Europe. When the presented hydroclimate reconstruction is compared to others, it becomes apparent that significant differences on an annual to decadal scale appear under the assumption of a fully independent TRW data set. This raises the question about the potential to upscale or to transfer these results to a wider geographical extent. Finally, we hypothesize that a tree-ring hydroclimate reconstruction over the entire Holocene is feasible using a large TRW data set from different river systems in southern

20   Germany, which also may hold the unique potential to reveal insights into Central European hydroclimate fluctuations on a seasonal scale.

Data availability

The entire data set of the original TRW series can be accessed: https://zenodo.org/deposit/1453330 (doi:
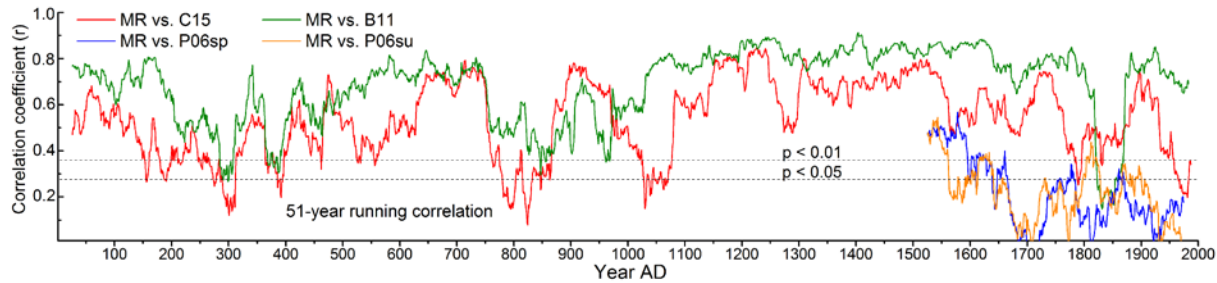
25   10.5281/zenodo.1453330).

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Appendices

Fig. A1. Comparison of MR precipitation reconstruction to other reconstructions of rainfall variability. Statistical comparison (51-year running correlation) between the MR reconstruction and C15 (Cook et al., 2015), B11 (Büntgen et al., 2011), P06sp/su (Pauling et al., 2006).

Table A1. TRW response to total preciptitation sum in different calibration windows (seasons) from AD 1900–2015 (N = 116). r = correlation coefficient, p = probability value, n.s. = not significant.

Calibration window	r	p<
Feb. 26–Jul. 06 (this study)	0.49	0.01
April–June	0.47	0.01
June–August	0.16	n.s.
March–August	0.29	0.01
March–July	0.37	0.01
March–May	0.31	0.01

Table A2. Reconstructed dry and wet decades from AD 1–1900. Dry / wet decade = 10-year average of reconstructed precipitation <190 / >250 mm (w.r.t. AD 1901–2000 = 220 mm).

Dry decades	Wet decades
	40s
	90s
	250s
	320s
330s	
	350s

22

510s
550s
560s
600s
650s
720s
770s
950s
1050s
1090s
1100s
1160s
1170s
1310s
1380s
1390s
1480s
1530s

1690s
1720s
1730s
1740s
1840s

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Author contribution

AL compiled the dendroclimatic analyses, the hydroclimate reconstruction and wrote the manuscript. SR, DR, ME and SH processed the TRW measurements and wrote parts of the manuscript. CZ and AB performed the bootstrapped stability test and wrote parts of the manuscript. JH particularly provided historical TRW data. All authors read and approved the final
5 manuscript.

Competing interests

The authors declare that they have no conflict of interest.

6 References

6 References

Anchukaitis, K. J., Wilson, R., Briffa, K. R., Büntgen, U., Cook, E. R., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B. E., Hegerl, G., Helama, S., Klesse, S., Krusic, P. J., Linderholm, H. W., Myglan, V., Osborn, T. J., Zhang, P., Rydval, M., Schneider, L., Schurer, A., Wiles, G., and Zorita, E.: Last millennium Northern Hemisphere summer temperatures from tree rings: Part II, spatially resolved reconstructions, Quaternary Science Reviews, 163, 1–22, doi:10.1016/j.quascirev.2017.02.020, 2017.

Bickle, P. and Whittle, A. W. R.: The first farmers of central Europe: Diversity in LBK lifeways, Cardiff Studies in Archaeology, Oxbow Books and the David Brown Book Company, Oakville, CT, 2013.

Briffa, K. R. and Jones, P. D.: Basic chronology statistics and assessment, in: Methods of dendrochronology: applications in the environmental sciences, Cook, E. R., Kairiukstis, L. A. (Eds.), Kluwer Academic Publishers, Dordrecht, 137–152, 1990.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K.-U., Wanner, H., Luterbacher, J., and Esper, J.: 2500 years of European climate variability and human susceptibility, Science, 331, 578–582, doi:10.1126/science.1197175, 2011.

Büntgen, U., Trouet, V., Frank, D., Leuschner, H. H., Friedrichs, D., Luterbacher, J., and Esper, J.: Tree-ring indicators of German summer drought over the last millennium, Quaternary Science Reviews, in press, 2010a.

Büntgen, U., Trouet, V., Frank, D., Leuschner, H. H., Friedrichs, D., Luterbacher, J., and Esper, J.: Tree-ring indicators of German summer drought over the last millennium, Quaternary Science Reviews, 29, 1005–1016, doi:10.1016/j.quascirev.2010.01.003, 2010b.

Buras, A.: A comment on the expressed population signal, Dendrochronologia, 44, 130–132, doi:10.1016/j.dendro.2017.03.005, 2017.

Buras, A., Zang, C., and Menzel, A.: Testing the stability of transfer functions, Dendrochronologia, 42, 56–62, doi:10.1016/j.dendro.2017.01.005, 2017.

Bürger, G., Fast, I., and Cubasch, U.: Climate reconstruction by regression - 32 variations on a theme, Tellus, 58A, 227–235, 2006.

Christiansen, B. and Ljungqvist, F. C.: Challenges and perspectives for large-scale temperature reconstructions of the past two millennia, Rev. Geophys., 55, 40–96, doi:10.1002/2016RG000521, 2017.

Cook, E. R., Briffa, K. R., and Jones, P. D.: Spatial regression methods in dendroclimatology: A review and comparison of two techniques, International Journal of Climatology, 14, 379–402, 1994.

25

Cook, E. R. and Krusic, P. J.: Program ARSTAN: A Tree-Ring Standardization Program Based on Detrending and Autoregressive Time Series Modeling, with Interactive Graphics, Tree-Ring Laboratory, Lamont Doherty Earth Observatory of Columbia University Palisades, Palisades, NY, 2005.

Cook, E. R. and Peters, K.: The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies, Tree-Ring Bulletin, 41, 45–53, 1981.

Cook, E. R., Seager, R., Cane, M. A., and Stahle, D. W.: North American drought: Reconstructions, causes, and consequences, Earth-Science Reviews, 81, 93–134, doi:10.1016/j.earscirev.2006.12.002, 2007.

Cook, E. R., Seager, R., Kushnir, Y., Briffa, K. R., Buntgen, U., Frank, D., Krusic, P. J., Tegel, W., van der Schrier, G., Andreu-Hayles, L., Baillie, M., Baittinger, C., Bleicher, N., Bonde, N., Brown, D., Carrer, M., Cooper, R., Cufar, K., Dittmar, C., Esper, J., Griggs, C., Gunnarson, B., Gunther, B., Gutierrez, E., Haneca, K., Helama, S., Herzig, F., Heussner, K.-U., Hofmann, J., Janda, P., Kontic, R., Kose, N., Kyncl, T., Levanic, T., Linderholm, H., Manning, S., Melvin, T. M., Miles, D., Neuwirth, B., Nicolussi, K., Nola, P., Panayotov, M., Popa, I., Rothe, A., Seftigen, K., Seim, A., Svarva, H., Svoboda, M., Thun, T., Timonen, M., Touchan, R., Trotsiuk, V., Trouet, V., Walder, F., Wazny, T., Wilson, R., and Zang, C.: Old World megadroughts and pluvials during the Common Era, Science advances, 1, 1–9, doi:10.1126/sciadv.1500561, 2015.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., and Stahle, D. W.: Long-Term Aridity Changes in the Western United States, Science, 306, 1015–1018, doi:10.1126/science.1102586, 2004.

Cooper, R. J., Melvin, T. M., Tyers, I., Wilson, Rob J. S., and Briffa, K. R.: A tree-ring reconstruction of East Anglian (UK) hydroclimate variability over the last millennium, Clim Dyn, 40, 1019–1039, doi:10.1007/s00382-012-1328-x, 2013.

Čufar, K., Luis, M. de, Eckstein, D., and Kajfez-Bogataj, L.: Reconstructing dry and wet summers in SE Slovenia from oak tree-ring series, International Journal of Biometeorology, 52, 607–615, doi:10.1007/s00484-008-0153-8, 2008.

Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J., and Xoplaki, E.: Long-term drought severity variations in Morocco, Geophysical Research Letters, 34, 2007.

Esper, J., Wilson, R. J.S., Frank, D. C., Moberg, A., Wanner, H., and Luterbacher, J.: Climate: past ranges and future changes, Quaternary Science Reviews, 24, 2164–2166, doi:10.1016/j.quascirev.2005.07.001, 2005.

Frank, D., Esper, J., and Cook, E. R.: Adjustment for proxy number and coherence in a large-scale temperature reconstruction, Geophysical Research Letters, 34, doi:10.1029/2007GL030571, 2007.

Friedrich, M., Remmele, S., Kromer, B., Spurk, M., Hofmann, J., Hurni, J. P., Kaiser, K. F., and Küppers, M.: The 12.460-year Hohenheim oak and pine tree-ring chronology from Central Europe- a unique annual record for radiocarbon calibration and palaeoenvironment reconstructions, Radiocarbon, 46, 1111–1122, 2004.

Friedrichs, D. A., Büntgen, U., Frank, D. C., Esper, J., Neuwirth, B., and Löffler, J.: Complex climate controls on 20th century oak growth in Central-West Germany, Tree Physiology, 29, 39–51, doi:10.1093/treephys/tpn003, 2008.

Grinsted, A., Moore, J. C., and Jevrejeva, S.: Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlinear Processes in Geophysics, 11, 561–566, 2004.

26

Helama, S., Meriläinen, J., and Tuomenvirta, H.: Multicentennial megadrought in northern Europe coincided with a global El Nino-Southern Oscillation drought pattern during the Medieval Climate Anomaly, Geology, 37, 175–178, doi:10.1130/G25329A.1, 2009.

Hughes, M. and Brown, P.: Drought frequency in central California since 101 B.C. recorded in giant sequoia tree rings, Climate Dynamics, 6, 161–167, doi:10.1007/BF00193528, 1992.

Karanitsch-Ackerl, S., Holawe, F., Laaha, G., Wimmer, R., and Grabner, M.: Parameter-specific hydroclimatic sensitivity of a low-elevation network of living and historical tree-ring series from north-eastern Austria, Dendrochronologia, 39–51, 2017.

Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., van Engelen, A. F. V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L. V., and Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment, Int. J. Climatol., 22, 1441–1453, doi:10.1002/joc.773, 2002.

Kress, A., Hangartner, S., Bugmann, H., Büntgen, U., Frank, D. C., Leuenberger, M., Siegwolf, R. T.W., and Saurer, M.: Swiss tree rings reveal warm and wet summers during medieval times, Geophys. Res. Lett., 41, 1732–1737, doi:10.1002/2013GL059081, 2014.

Kreuzwieser, J., Papadopoulou, E., and Rennenberg, H.: Interaction of flooding with carbon metabolism of forest trees, Plant Biology, 6, 299–306, 2004.

Küppers, M., Remmele, S., Hofmann, J., and Land, A.: Two millennia of Main region (southern Germany) hydroclimate variability [data file], doi:10.5281/zenodo.1453330, 2018.

Land, A.: Holzanatomische Veränderungen als Reaktion auf extreme Umweltereignisse in rezenten und subfossilen Eichen und deren Verifizierung im Experiment, PhD-Thesis, Institut für Botanik, University of Hohenheim, Stuttgart-Hohenheim, 2014.

Land, A., Remmele, S., Schönbein, J., Küppers, M., and Zimmermann, R.: Climate-growth analysis using long-term daily-resolved station records with focus on the effect of heavy precipitation events, Dendrochronologia, 156–164, 2017.

Land, A., Schönbein, J., and Friedrich, M.: Extreme climate events identified by wood-anatomical features for the Main region (Southern Germany) - A case study for 3000-2000 BC, in: 2200 BC - A climatic breakdown as a cause for the collapse of the old world?, Meller, H., Arz, H. W., Jung, R., Risch, R. (Eds.), 595–602, 2015.

Leuschner, H. H., Sass-Klaassen, U., Jansma, E., Baillie, M. G. L., and Spurk, M.: Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate, Holocene, 12, 695–706, 2002.

Levanič, T., Popa, I., Poljanšek, S., and Nechita, C.: A 323-year long reconstruction of drought for SW Romania based on black pine (*Pinus nigra*) tree-ring widths, International Journal of Biometeorology, 57, 703–714, doi:10.1007/s00484-012-0596-9, 2013.

Ljungqvist, F. C., Krusic, P. J., Sundqvist, H. S., Zorita, E., Brattström, G., and Frank, D.: Northern Hemisphere
5   hydroclimate variability over the past twelve centuries, Nature, 532, 94–111, doi:10.1038/nature17418, 2016.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, 2009.

MathWorks: MATLAB - The language of technical computing, 6.5th ed., 1994-2008.

10 McCarroll, D., Young, Giles H. F., and Loader, N. J.: Measuring the skill of variance-scaled climate reconstructions and a test for the capture of extremes, The Holocene, 25, 618–626, doi:10.1177/0959683614565956, 2015.

Pauling, A., Luterbacher, J., Casty, C., and Wanner, H.: Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation, Climate Dynamics, 26, 387–405, doi:10.1007/s00382-005-0090-8, 2006.

15 Pechtl, J. and Land, A.: Tree rings as a proxy for seasonal precipitation variability and Early Neolithic settlement dynamics in Bavaria, Germany, PLoS ONE, 14, e0210438, doi:10.1371/journal.pone.0210438, 2019.

Prokop, O., Kolář, T., Büntgen, U., Kyncl, J., Kyncl, T., Bošeľa, M., Choma, M., Barta, P., and Rybníček, M.: On the palaeoclimatic potential of a millennium-long oak ring width chronology from Slovakia, Dendrochronologia, 40, 93–101, doi:10.1016/j.dendro.2016.08.001, 2016.

20 Ruiz-Labourdette, D., Génova, M., Schmitz, M. F., Urrutia, R., and Pineda, F. D.: Summer rainfall variability in European Mediterranean mountains from the sixteenth to the twentieth century reconstructed from tree rings, International Journal of Biometeorology, 58, 1627–1639, doi:10.1007/s00484-013-0766-4, 2014.

Schönbein, J.: Zur Rekonstruktion von Hochwasserereignissen in Europa aus holzanatomischen Parametern und historischen Quellen, Dissertation, Institut für Physische Georgrafie, Universität Freiburg, Freiburg, 2011.

25 Schönbein, J., Land, A., Friedrich, M., Glaser, R., and Küppers, M.: Seasonal Reconstruction of Summer Precipitation Variability and Dating of Flood Events for the Millennium Between 3250 and 2250 Years BC for the Main Region, Southern Germany, in: Integrated Analysis of Interglacial Climate Dynamics (INTERDYNAMIC), Schulz, M., Paul, A. (Eds.), SpringerBriefs in Earth System Sciences, Springer International Publishing, Cham, 127–131, 2015.

Seftigen, K., Goosse, H., Klein, F., and Chen, D.: Hydroclimate variability in Scandinavia over the last millennium-insights
30 from a climate model-proxy data comparison, Clim. Past, 13, 1831–1850, doi:10.5194/cp-13-1831-2017, 2017.

Spurk, M., Leuschner, H. H., Baillie, M. G. L., Briffa, K. R., and Friedrich, M.: Depositional frequency of German subfossil oaks: Climatically and non-climatically induced fluctuations in the Holocene, The Holocene, 12, 707–715, doi:10.1191/0959683602hl583rp, 2002.

Steger, O.: Zur Eichenwicklerbekämpfung 1958 im Hochspessart, Forstwissenschafltiches Centralblatt, 78, 108–120, 1959.

Steger, O.: Spätfröste und Massenwechsel von *Tortrix viridiana* L. (Lep. Tortr.), Zeitschrift für angewandte Entomologie, 213–216, 1960.

Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley P. M. (Eds.): IPCC 2013: Climate Change 2013: The Physical Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, United Kingdom and New York, NY, USA, 2013.

Stockton, C. W. and Meko, D. M.: A long-term history of drought occurrence in western United States as inferred from tree rings, Weatherwise, 28, 244–249, 1975.

Storch, H. von, Zorita, E., Jones, J. M., Dimitriev, Y., González-Rouco, F., and Tett, Simon F. B.: Reconstructing Past Climate from Noisy Data, Science, 306, 2004.

Wigley, T.M.L., Briffa, K. R., and Jones, P. D.: On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, Journal of Climate and Applied Meteorology, 23, 201–213, 1984.

Wilson, R., Anchukaitis, K., Briffa, K. R., Büntgen, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krusic, P. J., Linderholm, H. W., Myglan, V., Osborn, T. J., Rydval, M., Schneider, L., Schurer, A., Wiles, G., Zhang, P., and Zorita, E.: Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context, Quaternary Science Reviews, 134, 1–18, doi:10.1016/j.quascirev.2015.12.005, 2016.

Wilson, R. and Elling, W.: Temporal instability in tree-growth/climate response in the Lower Bavarian Forest region: implications for dendroclimatic reconstruction, Trees - Structure and Function, 18, 19–28, doi:10.1007/s00468-003-0273-z, 2004.

Wilson, R., Miles, D., Loader, N. J., Melvin, T., Cunningham, L., Cooper, R., and Briffa, K.: A millennial long March-July precipitation reconrtruction for southern-central England, Climate Dynamics, 40, 997–1017, doi:10.1007/s00382-012-1318-z, 2013.

Wilson, R. J. S., Luckman, B. H., and Esper, J.: A 500 year dendroclimatic reconstruction of spring-summer precipitation from the lower Bavarian Forest region, Germany, Int. J. Climatol., 25, 611–630, doi:10.1002/joc.1150, 2005.

Tables

Table 1. List of years with reconstructed far below / above ~~rainfall~~pluvials (Feb. 26–Jul. 06) depicted as deviation (%) from the reference period AD 1901–2000.

Year AD	Low rainfall~~pluvials~~	Year AD	High rainfall~~pluvials~~
338	-38	357	39
337	-37	985	37
1167	-29	526	34
510	-28	1533	34
1394	-27	654	32
565	-26	1317	29
945	-26	1436	29
1165	-26	460	29
1177	-25	1314	28
		436	28
		559	28
		1673	27
		1123	27
		1487	27
		43	27
		1052	26
		1531	26
		496	26
		1055	26
		56	26
		778	26
		1727	26
		102	25
		1056	25
		932	25
		602	25

Referee #1

RC#1: Dear authors, I very much appreciate the attempt of analyzing and publishing some (why not all) of the unique oak ring-width data stored at the University of Hohenheim, Germany. This is a very important step towards generating exciting new science.

RC#1: However, I am reluctant in recommending acceptance of the submitted work, mainly because it represents an intermediate step rather than drawing methodological-sound conclusions from a final dataset (i.e. entire Holocene). This stepwise publishing procedure seems unnecessary in the case of central European oak ring-width measurements, as it has been successfully demonstrated in the recent past that such data are useful (and most relevant indeed) for reconstructing hydroclimate (i.e. a more complex reflection of spring to early-summer soil moisture availability instead of simple precipitation totals) on inter-annual to multi-centennial time-scales. While this has been done for several regions in Germany, France and England, Ed Cook's OWDA describes a European-wide milestone with regard to spatially explicit reconstructions of droughts and pluvials during the Common Era.

AC: I think there is a misunderstanding here. Ring-width data stored at the University of Hohenheim (Germany) are regularly contributed to different projects/studies to generate exciting science. Tree-ring data from the dendrolab Hohenheim are contributed to a wide variety of different dendro projects (only a few examples are given): 1) "Five millennia of European hydroclimate" (head of the project: W. Tegel, University of Freiburg, Germany; U. Büntgen, University of Cambridge, UK), 2) "Long-term trends in European tree growth over the past 1000 years - an interspecies comparison" (head of the project: A. Seim, University of Freiburg, Germany, funded by the DFG, project no. 389131207). Most of the Hohenheim ring-width data are already provided via data repositories (e.g. Zenodo or PANGAEA). Smaller data(sub)sets are indeed not published yet and are only accessible via personal contact/correspondence. This is mainly ring-width data from very local findings or sites (e.g. from the Rhine river) spanning a few centuries within the Holocene, but NOT the entire Holocene. For the presented study, tree-ring series (you called that a data(sub)set) from a specific region (here the Main region, southern Germany) were needed to develop a regional hydroclimate record and to compare this record to already existing reconstructions (during the past two millennia). The original (raw) dataset used here is made accessible to give others the opportunity to specifically reproduce our results and to have unrestricted access to all data underlying our study. This is transparent, in line with the data policy of the Copernicus Publications and good practical science. This is not in any way "politically" motivated or "strategically" aligned. Any suspicions that we have deliberately withheld tree-ring data are completely unfounded. We, as a research group, have strived in recent years to make our institution a positive example of transparency and scientific cooperation. We are more than happy to collaborate with and provide our data to others in the hopes of gaining new insights into past climate.

RC#1: In addition, the authors suggest that some of their data has been already incorporated into earlier studies (Büntgen et al., 2011, Cook et al., 2015), therefore only limited comparisons with these reconstructions are possible. Why did not the authors clarify this before? I am confident Büntgen and Cook would provide this information to the authors.

AC: I am pretty sure, and so I do agree with your comment, that if requested, Büntgen and Cook would have provided their datasets for a detailed analysis regarding duplicates in the dataset used here, which would allow for a clear statement of independence/dependence between the different reconstructions. Perhaps I am totally wrong and the original datasets are accessible via a data repository, or there were good reasons not to make these datasets accessible/public for unknown reasons. The widely accepted data policy of scientific journals

requires all authors to make materials, data etc. available. So one could argue that an independent study should be feasible (even without a direct correspondence during the publication process). I would like to mention that the mistake in this regard could be that I have simply failed to find the data (and the original datasets are accessible/public), meaning that this part of the manuscript has to be reanalyzed and modified.

RC#1: In short, the submitted work does not provide any ground-breaking methodological and/or intellectual novelty, and the relatively small data(sub)set does not appear to be robust between 800 and 1100 C.E. and again during the 4th century C.E. when the sample size dramatically drops (see Fig. 2 of the submitted draft). Although the EPS is above the common applied threshold of 0.85, the temporal replication changes can strongly affect the chronology behavior. Possible uncertainties might emerge from the integration of predominantly juvenile or mature/adult wood during these periods. Moreover, it is a pity that the low-frequency hydroclimate variability is not expressed in the presented reconstruction.

AC: In this study we used precipitation records with a daily resolution, which is relatively new to dendroclimatology (chapter 2.4 Calibration, verification and reconstruction of hydroclimate variability). The applied bootstrapped transfer function stability (BTFS) test to assess the temporal stability of the relationship between ring-widths and daily precipitation data (first introduced by Buras et al. 2017) is another example for a new (and innovative) method that was used. While I do agree that most of the presented results were obtained using standard and widely accepted dendroclimatological methods, the presented results nevertheless show e.g. that in the first millennium C.E. (fully-independent dataset) differences to other reconstructions (B11, C15) appear, which could be due to local/regional precipitation characteristics (see chapter 3.3 Comparison of MR reconstruction to others, Fig. 5, Fig. 6). This underlines the need to set up as much as possible local/regional hydroclimate reconstructions (even when standard methods are applied) to study spatial and temporal rainfall variability in the near future. Thus, this work does indeed provide additional information leading to a more detailed understanding of climate variability.
In the past few years intensive sampling of subfossil trees in the Main region was conducted, but did not lead to an increase in sample size in the 4th century and from 800-1100 C.E. The drop in sample size (as well as in the mean segment length) in the mentioned periods give evidence for fundamental environmental changes in the Main valley. It is possible that uncertainties in the reconstruction could emerge from the use of predominantly juvenile trees in these periods, but it underlines the statement (see previous comment) that there is a strong need to develop hydroclimate reconstructions on local/regional scale with tree-ring width datasets to ensure whether the uncertainty occurred from e.g. changing sample size.

Referee #2:

RC#2: Dear editor and authors of the manuscript "Two millennia of Main region (southern Germany) hydroclimate variability". To the best of my knowledge, the 2000 years long chronology is a novel idea through integration all available tree-ring width samples in this work, which would be an important contribution in the denderochronology community. Another new information is to calibrate the tree-ring width chronology using the daily instrumental data. However, the robust of the reconstruction should be furtherly analyzed, and the mechanism of precipitation variability should be conducted for reader to understand the origin of variability in the high-impart journal Climate of the past. Thus, I suggest that the manuscript should be accepted for publication after a revision.

RC#2: There are very long chronologies in Europe where is a hotspot in dendroclimatology. It is highly encouraged to carefully review the previous studies to place much more stress on innovation or difference of this study. The current motivation of this study is not very attractive to me. e.g. the first sentence in the abstract, the climate reconstruction covering the entire Holocene is important, but the TRW chronology in this study only covers the past two millennia.

AC: In a previous version of the manuscript we deeply reviewed other accessible reconstructions from Europe as well as from southern Germany. For example: Wilson et al. 2013 (DOI 10.1007/s00382-012-1318-z), Cooper et al. 2013 (DOI 10.1007/s00382-012-1328-x) or Wilson et al. 2005 (DOI 10.1002/joc.1150) to place much more stress on spatio-temporal differences between them and how important it is to get a long (two millennia) highly-resolved precipitation reconstruction entirely developed from a small region (here the Main region, southern Germany). But this was criticised by a colleague, which caused us to use reconstructions only from the same grid box (here from Pauling et al. 2006, Cook et al. 2015) and for Central Europe (Büntgen et al. 2011).

Author's changes: The first sentence in the abstract will be rephrased.

FINAL Author's changes: A reconstruction of hydroclimate with an annual or sub-annual resolution covering millennia for a geographically limited region in continental Europe would significantly improve our knowledge of past climate dynamics.

RC#2: The mechanism and origin of the precipitation variability (e.g. the influence of the Northern Atlantic Oscillation) should to be furtherly analyzed through comparison of the other reconstructions or model simulation. Another option is to select a more specific journal, e.g. dendrochronologia or Tree-Ring Research. The readers of Climate of the past would like to know some information about the mechanism of climate variability not only the phenomena.

AC: To my best knowledge the NAO, SO, AMO ENSO etc. have no significant influence on long-term rainfall variability in Central Europe. Thus I would assume that there should be no significant influence also on our dataset. As can be read in Qian et al. (2000, https://doi.org/10.1029/2000JD900102): […The North Atlantic Oscillation plays an important role in nonseasonal variability over the sector and leaves a significant signature in precipitation. But it does not seem to be the most important signal of atmospheric variability in precipitation over Europe, although it does in winter.]. Brázdil et al. (2015, https://doi.org/10.1002/joc.4065) studied the forcings of spring-summer droughts in the Czech Land and found that […solar irradiance and Southern Oscillation (SO) made only minor contributions to central European drought variability, while the effect of … Atlantic Multidecadal Oscillation (AMO) were weaker and statistically insignificant.]. But on the other hand a study performed by Miksovsky et al. (Clim. Past Discuss., https://doi.org/10.5194/cp-2018-61) might give some hints that long-term drought variability could be forced by AMO.

Author's changes: Actually we intensively compare/analyse the influence of reconstructed AMO from Gray et al. (2004, doi: 10.1029/2004GL019932), Mann et al. (2009, doi: 10.1126/science.1177303), Singh (2018, https://doi.org/10.5194/cp-14-157-2018), sunspot number etc. on our developed spring-summer precipitation time series via cross-wavelet analysis and other suitable methods. In the revised version these results could be part of the discussion or part of a new section. Currently no results/Figures can be provided. But we work on this topic very intensively together with some other specialists.

FINAL Author's changes: After intensively analyses of a possible (long-term) mechanism /origin of the reconstructed precipitation variability in the Main region (e.g. via cross-wavelet analyses, XWTs), we conclude that the influence of large-scale circulation patterns (e.g. Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), Artic Oscillation (AO), Sea Level Pressure (SLP)) remains unclear. Please find attached a Figure with results from two XWTs. This is just a small sub-set of the conducted analyses / calculations. At first glance, these "promising" results indicate that the AMO (here two reconstructed AMO time series were used (Gray et al. 2004 / Mann et al. 2009)) may trigger the rainfall variability at the study area (Main region) on a long-term perspective (~16-20 and ~30-60 year frequency band). BUT when the phases (arrows in the Figure) are considered, they shift from phase (arrows pointing to the right) to anti-phase (arrows pointing to the left). Especially on the shorter frequency bands the results indicate that the relationship between AMO (as well as NAO, AO etc.) is not as clear as these XWTs (and our other performed analyses) suggest. Other studies (see Küttel et al. 2011, DOI: 10.1007/s00382-009-0737-y or Jacobeit et al. 2003, DOI: 10.1007/s00382-002-0278-0 and references therein) showed the pronounced complexity of the large-scale atmospheric circulation and European climate (especially for central Europe!). In other regions, like western North America or for parts of Asia, the connection between atmospheric circulation patterns and "regional / local" weather / climate is, to some extend, closer related.
So, in our opinion this phenomenon needs to be generally investigated much more intense for that specific study area from a meteorological point of view. We are aware that this is very unsatisfactory from a scientific point of view, but an intense investigation about the relationship of these large-scale circulations on the weather / climate in the study area, however, would blow up the content of this manuscript. We would therefore recommend not to include all these results / analyses, as this would make the clear presentation in the actual manuscript lost.

RC#2: The logic of the article is a bit problematic. The main target in this study is to reconstruct the precipitation variability over the past millennia. However, the following some evidences and discussion do not support this reconstruction. e.g. Page 10, line 9 'The TRW chronology does not track extremely low or high precipitation rates adequately.' The sections 4.3 also shows this weak relationship between the TRW chronology and the instrumental precipitation. Even the authors emphasize that the human influence may have a severe impact on forest in Page 17, lines 12-20. All prove that it is not very reasonable to reflect the extreme precipitation events over the past millennia. Another option to try to reconstruct the 'mixed' variable, e.g. the PDSI index.

AC: This is a crucial point. In most of the tree-ring studies dealing with oaks this fact is present in the data. But only in a few of them it is explicitly mentioned/shown that extreme low rainfall is only poorly modelled by oak ring-width data (e.g. see Wilson et al. 2013 (Fig. 7, DOI 10.1007/s00382-012-1318-z), Copper et al. 2013 (Fig. 10, DOI 10.1007/s00382-012-1328-x) and many, many others). In my opinion this point needs more attention in general and thus it is explicitly mentioned in our work. So, the logic of the manuscript is not problematic.

RC#2: Specific Comments: 1. Page 1, Lines 18-19. The bootstrap method is not an innovative analysis in dendroclimatology, please see the literatures e.g. (Guiot 1991; Till and Guiot 1990).

Author's changes: The sentence will be rephrased: To test the stability of the developed transfer function a bootstrapped transfer function stability test (BTFS) as well as …

FINAL Author's changes: Done

RC#2: Page 2, Line 3. It is difficult to predict future impact through climate reconstruction. The climate model is usually used to project the future scenario.

AC: As also mentioned by Referee #3 the Introduction needs some rewording and will be rephrased.

FINAL Author's changes: See changes in the chapter Introduction.

RC#2: Page 6, Line 13. Why is the 100-year cubic smoothing spline used to detrend the tree growth? To my knowledge, the standard standardization method depends on the special situation of each sample.

AC: The 100-year cubic smoothing spline was used to preserve as much as high- to mid-frequency as possible. Due to the minimum in the MSL of ~100 years, the length of the chosen smoothing spline is appropriate. Using the standard chronology does not severely impact how much decadal and longer term information is extracted from these data.

RC#2: Page 8. The section 2.5 should be moved to the introduction to emphasize the innovation of this paper through a review of previous reconstructions.

Author's changes: Parts of the section 2.5 will be moved to the Introduction.

FINAL Author's changes: Due to the required changes in the chapter Introduction, this point is taken up. Please see changes in the text.

RC#2: Page 8, Line 26. The reason selecting 51-year should be given. As we known, the window size would affect the results of running correlation.

AC: The relatively "short" 51-year window length was chosen to show agreements between the time series even on short time scale. At the beginning of the project a 101-year running window was also used, but the results remain more or less the same.

Author's changes: A sentence will be added to state why a 51-year window was used.

FINAL Author's changes: The following sentence was added: This relatively short window length allows us to study abrupt temporal changes in the behavior of the aforementioned reconstructions.

RC#2: The discussion of phase variability in the cross-wavelet transform and squared wavelet coherence is ignored. e.g. The MR and B11 has an obvious variability in phase in the upper right panel of Figure 5.

Author's changes: A section about phase variability will be added in the discussion part.

FINAL Author's changes: Due to the importance of the coherence analyses a section in chapter 3.3 was added: Coherence between MR-B11 and MR-C15 is also obvious prior to AD 1000, on short as well as on long terms, but not as high as in the second millennium. The right-pointing arrows in the significant regions (thick contours in the right panels of Fig. 5) indicate that the compared reconstructions clearly swing in phase, holding evidence for close time-frequency connections. The previously mentioned weak connection between MR and C15 in some periods (Fig. A1) becomes more obvious from the WTC. From AD 200–400, for example, no significant connection on shorter and even on longer time scales can be found, supporting the results from the running correlation analysis and indicating substantial differences between the different reconstruction series to the regional MR. The weaker, or even non-significant, connections between MR-B11 and MR-C15 in the first millennium AD show that there is a particularly low coherence between the regional hydroclimate reconstruction (MR) and B11 / C11 when an independent data set (see chapter 2.5) is used.

In the discussion section (see first part of chapter 4.3), this topic is taken up again. Please see changes in the text.

RC#2: Page 18, Line 24. The seasonal resolution would lead a misunderstanding. Here, it is really an annual resolution.

Author's changes: Will be changed in annual resolution.

FINAL Author's changes: Done

Referee #3:

RC#3: This article has a potential to be a valuable scientist contribution but it needs, in my opinion, much additional work prior to publication. There are a number of issues that I would like to see addressed, or at least discussed, by the authors. In order to make them easier to follow, I list them in bullet points below (in no particular order of importance):

RC#3: A discussion is needed with regard to what extent any, likely non-linear, temperature sensitivity in the data affects the precipitation reconstruction. Given the region, some temperature influence on the reconstructed precipitation signal is likely to exists and such a signal is likely to be non-linear and thus different between warmer and colder climate states during the past two millennia.

Author's changes: A section within the discussion will be added.

FINAL Author's changes: A section was added (4.2): While the oak tree-ring series used here respond very well to spring-summer rainfall during the calibration / verification period, it is not unlikely that, to some extent, warmer / colder phases during the past two millennia (e.g. the Medieval Climate Anomaly or the Little Ice Age) affect the presented reconstruction. It has been shown by Friedrichs et al. (2008) that oak trees from central-west Germany (which is close to our study region) lose their precipitation sensitivity in the anomalously warm decade 1940s. This decreased response to hydroclimatic conditions in central Germany has been confirmed by Büntgen et al. (2010a), whose study revealed that oak TRW sensitivity is greatly reduced to scPDSI in the mid-20th century. A well-established decrease in precipitation sensitivity during the 1940s is also observed in our study (data not shown). With this in mind, it is possible that during extraordinary warm (Medieval Climate Anomaly) or extraordinary cold (Little Ice Age) (Mann et al., 2009) periods, TRW reconstructions may show a certain level of bias. However, it remains unclear to what extent the reconstruction here presented is biased.

RC#3: I would like to see some "sensitivity tests" in the use of calibration window by using other seasonal windows than February 26 to July 6. It would be interesting to see how sensitive the skill of the reconstruction is to particular seasonal windows, especially as the presently used seasonal window is extremely well-defined down to single dates rather than months.

AC: These sensitivity tests were conducted at the beginning of the project. The temporal changes as well as the changes in the length of the sensitive interval were studied including the well-defined interval Feb. 26-Jul. 06 as well as "classical" seasonal window lengths (e.g. April-June, March-July). This can be provided as a Figure/Table (or in the text) in the Appendices. However, the "classical" seasonal windows are always well-defined, too: e.g. April-June = April 01-June 30. So to me our well-defined interval is nothing else than a prolonged "classical" window.

FINAL Author's changes: A new Table (Table A1) was added in the Appendices and the following sentence was added in section 3.2: For sensitivity test results of the TRW chronology with total precipitation sum for "classical" monthly-resolved seasons, see Table A1.

RC#3: I would like to see a longer discussion about the implication is the huge differences in MSL (see, e.g., Fig 2b). In my opinion, this is likely to result in a bias of the results to a larger extent than the authors acknowledge. Even if the problem cannot be solved (although it may

be possible to use a subset of the data of the same segment length to conduct a "sensitivity test"), it needs to be discussed much more critically.

AC: Here I would like to mention, that the minimum MSL is 110 and the maximum is 230 years. In the Figure 2b the fluctuation in MSL seems to be huge, because of the scale (y-axis) ranging from 90-240. The range of this axis was explicitly used to give the reader a more detailed information about the fluctuation of MSL. The fluctuation of MSL is not as "huge" as the line graph implies. Compared to other oak tree-ring studies, in my opinion, it is not really dramatic (even normal when dealing with subfossil and historical tree-ring series).

Author's changes: However, this issue will be addressed and critically discussed in the associated sections.

FINAL Author's changes: This section (3.1) was rephrased to address your comment. For detailed changes please see text.

RC#3: It would be better to present all the result with regard to the climate mean of 1961–1990 instead of the mean of 1901–2000. This would make the results more comparable to other studies.

AC: Mean precipitation sum (Feb. 26-Jul. 06) in the investigated Main region is 219.7 mm during the past century (1901-2000), whereas the mean precipitation sum from 1961 to1990 is 241.0 mm. The reason for choosing the one-century reference period has the following reason: "outside" 1961-1990 some more droughts appeared (e.g. 1921, 1934, 1991, 1993) characterising the climate of the region. When the previous millennia are compared to the reference period 1901-2000, in my opinion, it becomes much clearer that in some periods the droughts/wets are more "outstanding". In many other studies the reference period 1901-2000 is also used (and sometimes 1971-2000 can be found), see also e.g. Karl et al. 2009: Global Climate Change Impacts in the United States or Meehl et al. 2003: Solar and greenhouse gas forcing and climate response in the twentieth century. Journal of Climate, 16, 426-444, DOI:10.1175/1520-0442(2003)0162.0.co.

RC#3: The implications of the detrending choice much critically be discussed and the possibilities, or limitations, to apply RCS detrending (or "signal-free" detrending) must be seriously addressed.

AC: The 100-year MSL (~ minimum) restricts the potential to get low frequency information from such data, and one can use a 100-year smoothing spline. But indeed, our discussion about that topic is not seriously addressed.

Author's changes: In the revised version of the manuscript this point will be seriously addressed/critically discussed.

FINAL Author's changes: The following passage was added to the discussion section 4.2: Nevertheless, due to the changes in the mean segment length and the highly variable sample replication, the standardization procedure applied here (100-year spline) is suitable for preserving high- to mid-frequency fluctuations, while the low-frequency variance from the TRW data set is removed. Thus no inferences can be made for centennial-long precipitation fluctuations for the study region. When comparing the MR hydroclimate reconstruction to B11 and C15 (both capturing the low-frequency domain e.g. by using RCS detrending), some differences appear on the low-frequency timescale. These are especially apparent in the first

millennium AD, where trees from alluvial deposits are available for reconstruction purposes, and is more pronounced between MR-B11 than between MR-C15.

RC#3: Page, 1, lines 13–15: This first sentence of the Abstract seems a bit out of place as the article only addresses the past two millennia and not the whole Holocene.

Author's changes: The sentence will be deleted.

FINAL Author's changes: Due to required changes of Reviewer #2, this sentence was rephrased: A reconstruction of hydroclimate with an annual or sub-annual resolution covering millennia for a geographically limited region in continental Europe would significantly improve our knowledge of past climate dynamics.

RC#3: Page, 1, lines 27–28: The exact amplitude of the precipitation reduction is likely very sensitive to scaling/regression method.

AC: Please specify this comment.

RC#3: Page 2, lines 1–3: The introduction is a bit vague and a bit out of place here. It is simply too general and not clearly related to the research problem in the article.

Author's changes: The introduction will be rephrased to clearly relate to the research problem.

FINAL Author's changes: The Introduction was revised to make it more clear and concise. Please see our changes in the text.

RC#3: Page 2, lines 6–8: This is actually wrong. A number of two millennium-long calibrated precipitation reconstructions do exist. This is especially true for western North America. Moreover, MORE millennium-long hydroclimate reconstructions from tree-rings exist to date than millennium-long tree-ring based reconstructions of temperature. This whole part needs to be rewritten and up to date with the present state of research.

Author's changes: This part will be rewritten.

FINAL Author's changes: This part has been specified. Please see changes in the text of the Introduction.

RC#3: Page 2, line 8: I would also cite here:
Cook, E.R., Woodhouse, C.A., Eakin, M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the western United States. Science 306, 1015–1018.
Ljungqvist, F.C., Krusic, P.J., Sundqvist, H.S., Zorita, E., Brattström, G., Frank, D., 2016. Northern Hemisphere hydroclimate variability over the past twelve centuries. Nature 532, 94–98.

Prokop, O., Kolá˘r, T., Büntgen, U., Kyncl, J., Kyncl, T., BošeÄ¿a, M., Choma, M., Barta, P., Rybní˘cek, M., On the palaeoclimatic potential of a millennium-long oak ring width chronology from Slovakia. Dendrochronologia 2016, 40, 93–101.

Author's changes: Cook et al. 2004 and Ljungqvist et al. 2016 will be cited.

FINAL Author's changes: Cook et al. 2004, Ljungqvist et al. 2016 and Prokop et al. 2016 was cited.

RC#3: Page 2, line 13: I would also cite:
Büntgen, U., Trouet, V., Frank, D., Leuschner, H.H., Friedrichs, D., Luterbacher, J., Esper, J., 2010. Tree-ring indicators of German summer drought over the last millennium. Quat. Sci. Rev. 29, 1005–1016. https://doi.org/10.1016/j.quascirev.2010.01.003.
Helama, S., Meriläinen, J., Tuomenvirta, H., Multicentennial megadrought in northern Europe coincided with a global El Niño–Southern Oscillation drought pattern during the Medieval Climate Anomaly. Geology 2009, 37, 175–178.
Klippel, L., Krusic, P. J., Brandes, R., Hartl, C., Belmecheri, S., Dienst, M., Esper, J., A 1286â˘A ˘ Ryear hydroâ˘AR˘ climate reconstruction for the Balkan Peninsula. Boreas 47 2018, 1218–1229.
Kress, A., Hangartner, S., Bugmann, H., Büntgen, U., Frank, D.C., Leuenberger, M., Siegwolf, R.T.W., Saurer, M., 2014. Swiss tree-rings reveal warm and wet summers during medieval times. Geophys. Res. Lett. 41, 1732–1737.
http://dx.doi.org/10.1002/2013GL059081

Author's changes: Helama et al. 2009 and Kress et al. 2014 will be cited.

FINAL Author's changes: Done

RC#3: Page 2, lines 16–18: Strange formulation here. What is said is unclear to me.

Author's changes: The sentence will be rephrased.

FINAL Author's changes: The sentence was deleted.

RC#3: Page 4, Fig. 1: The Figure can be much improved, i.e. using ArcGIS or similar software, as well as be in colour for better clarity.

AC: In general, a black/white map is as good as a coloured one as long all relevant information can be gained. But I do agree, that some additional information (e.g. Long./Lat.) can be added.

Author's changes: A coloured Figure will be provided. Long./Lat. will be added (see attached Figure).

FINAL Author's changes: Done (see new Fig. 1 in the revised manuscript). The Figure caption has been adjusted accordingly.

RC#3: Page 5, Section 2.2: Are any references available for the various instrumental datasets from the various stations?

AC: The references are stated (line 7 on page 5).

RC#3: Page 5, line 22: Please, provide the standard references for RBAR and EPS.

Author's changes: Wigley et al. (1984). J Clim Appl Meteorol 23:201–213 will be provided.

FINAL Author's changes: Done

RC#3: Page 8, line 5: It should be mentioned that the Old World Drought Atlas is calibrated to scPDSI.

Author's changes: It will be mentioned.

FINAL Author's changes: Done

RC#3: Page 8, lines 8–9: Are there any references to these datasets?

AC: The references are mentioned in lines 2-6.

Author's changes: … from the above mentioned references… will be added.

FINAL Author's changes: Changed in: The mentioned reconstruction series…

RC#3: Page 8, line 10: For the Old World Drought Atlas (Cook et al., 2015), all included datasets are listed in the Supplement to the article in a table there.

AC: This is correct. All included datasets are listed.

Author's changes: The sentence will be rephrased: The set of original, single TRW series included in the respective reconstructions by the mentioned authors is, to the best of our knowledge, not explicitly stated in their work or accessible. This circumstance made a comparison between the respective records extremely difficult.

FINAL Author's changes: Done

RC#3: Page 9, lines 7–9: Please, discuss the implication of these RBAR values more in detail.

Author's changes: A more detailed discussion will be given.

FINAL Author's changes: This section (3.1) was rephrased to address your comment. For detailed changes please see text.

RC#3: Page 9, lines 12–13: A more detailed discussion about this problem is needed here.

Author's changes: A more detailed discussion will be given.

FINAL Author's changes: This section (3.1) was rephrased to address your comment. For detailed changes please see text.

RC#3: Page 10, lines 11–12: A number of other references could also be added here.

Author's changes: To make clear that the given references are only a small selection "e.g." will be added.

FINAL Author's changes: Done

RC#3: Page 13, lines 17, 21: The word "connection" here could be replaced with "agreement" or "correlation".

Author's changes: The word connection will be replaced by agreement.

FINAL Author's changes: Done

RC#3: Page 16, line 28: The same problem has also extensively been discussed in numerous other studies, e.g.:
Bürger, G., and U. Cubasch (2005), Are multiproxy climate reconstructions robust?, Geophys. Res. Lett., 32, L23711, doi:10.1029/2005GL024155.
Bürger, G., I. Fast, and U. Cubasch (2006), Climate reconstruction by regressionâ˘AˇT32 variations on a theme, Tellus A, 58, 227–235.
Christiansen, B. (2011), Reconstructing the NH mean temperature: Can underestimation of trends and variability be avoided?, J. Clim., 24, 674–692.
Christiansen, B. and Ljungqvist, F. C. 2017: Challenges and perspectives for largescale temperature reconstructions of the past two millennia, Reviews of Geophysics, 55, 40–96.
Smerdon, J. E., A. Kaplan, D. Chang, and M. N. Evans (2011), A pseudoproxy evaluation of the CCA and RegEM methods for reconstructing climate fields of the last millennium, J. Clim., 24, 1284–1309.
Wang, J., J. Emile-Geay, D. Guillot, J. E. Smerdon, and B. Rajaratnam (2014), Evaluating climate field reconstruction techniques using improved emulations of real-world conditions, Clim. Past, 10, 1–19.

Author's changes: The following references will be added: Christiansen and Ljungqvist (2017) as well as Bürger and Cubasch (2005).

FINAL Author's changes: Done

RC#3: Page 17, line 4: Would blue intensity be an alternative to traditional density measurements in this context?

AC: To our best knowledge, traditional density and blue intensity (BI) measurements were only performed on coniferous wood. As our investigation deals with oak trees this would not be an alternative.

RC#3: Page 19: Would not storage at the ITRDB also be a good option for long-term availability?

AC: Storage at the chosen data repository (Zenodo) is a good option for long-term availability and due to the assigned doi number easy to access.

RC#3: Page 27: It would be informative to also have a table for the wettest and driest decades.

Author's changes: Table 1 will be extended. Wettest and driest decades will be added.

FINAL Author's changes: A new Table (Table A2) was added in the Appendices and a sentence was added to section 3.2: A detailed list of dry and wet decades is provided in Table A2.

RC#3: Page 27: "Low pluvials" appears a strange expression to me. Do the authors means "Droughts" here?

Author's changes: "Low pluvials" will be changed in "Droughts" and "High pluvials" will be changed in "Wets".

FINAL Author's changes: Pluvial was replaced by rainfall.