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ORIGINAL ARTICLE

Climate-growth analysis using long-term daily-resolved station records with focus on the effect of heavy precipitation events

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ABSTRACT

Oak tree-ring series contain detailed information regarding climate variability for centuries to millennia. Such reconstructions are compiled with the use of climate response functions that are typically based on monthly precipitation or temperature data sets. We present an approach using a MATLAB® script and long-term daily precipitation and daily mean temperature records to evaluate intervals with daily resolution of radial growth sensitivity and to determine the effect of heavy precipitation events in the Mainfranken region (southern Germany). This allows improved insights into tree-ring response for local climate reconstructions. Annual radial stem growth is highly sensitive to total cumulative precipitation during the current year spring-summer period, but less sensitive to daily mean temperature. Response analysis reveals better results to precipitation records, when (very) heavy precipitation events are omitted (April 14–July 18, $R^2 = 0.31$, $p < 0.01$). Temporal sensitivity analysis of total ring width (TRW) to precipitation response within nine sub-periods revealed that the length of the sensitive intervals stretch between 41 to 141 days, depending on the period investigated. Our study shows that annual radial growth of oak trees is mainly affected by daily precipitation sums (DPS) of less than 10 mm. In contrast, heavy rainfall events do not influence radial increment significantly, but may substantially increase the total precipitation sum of the growing season. We propose that oaks in the Mainfranken region contain low to moderate information in their tree rings regarding heavy precipitation events. Furthermore, we conclude that a disordered sensitivity of TRW to precipitation during the past three to four decades is caused by drought climatologies, increased sulfur dioxide emission in the study area as well as by changes in diurnal temperature range. Thus, climate response functions for hydroclimatic reconstructions may only be developed until the 1970s.

1. Introduction

In Europe an extensive wide tree-ring data network exists often reflecting summer conditions (St. George, 2014). Tree-ring records provide information about past climate conditions and may increase our knowledge of seasonal- to decadal droughts and wet periods. A significant number of multi-century length climate reconstructions developed from living, historical and subfossil tree-ring series have been published in recent years (e.g. Wilson et al., 2005; Büntgen et al., 2011; Cooper et al., 2013; Levanič et al., 2013; Wilson et al., 2013; Cook et al., 2015; Land et al., 2015; Santos et al., 2015; Schönbein et al., 2015; Seftigen et al., 2015; Young et al., 2015). E.g. these reconstructions contain different hydroclimatic signals depending on various factors as the area under investigation, local hydroclimatic behaviour or the duration of trees sensitivity to rainfall within the vegetation period.

Climate-growth response analysis had mainly been conducted applying meteorological records with monthly resolution. These monthly records can be handled easily via the calibration process and such long-term instrumental records are often available as single or gridded station data. In contrast, consistent long-term daily instrumental records lasting for a century or longer are very rare in Europe. Although appropriate software (Schönbein, 2011; Beck et al., 2013) is published and available for free, very few studies have attempted to calibrate tree-ring growth using daily precipitation data (e.g. Pritzkow et al., 2014; Sanders et al., 2014; Castagneri et al., 2015) or reconstruct past hydroclimatic conditions with this technique (Land et al., 2015; Schönbein et al., 2015; Pritzkow et al., 2016). In southern Germany, several century-length daily meteorological records exist (e.g. Bamberg,

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Frankfurt a.M., Karlsruhe, Munich, Stuttgart) and are available via https://climexp.knmi.nl. These records are suitable for studying the correlations between seasonal tree growth and daily instrumental data on a local scale.

However, forest cover, vegetation surface, soil type, soil water-holding capacity as well as canopy water storage capacity and rainfall interception strongly affect the water availability for trees (e.g. Phillips and Ehleringer, 1995; Dohnal et al., 2014) and increase the complexity of the correlation analysis. Water availability for individual trees and the precipitation amount may differ greatly. For example surface runoff and soil water-holding capacity in response to a heavy rainfall event must be considered when analyzing radial growth. Taking into account that rainfall events exceeding 20–30 mm per day may occur several times per month, tree-ring calibration using only monthly station data with rainfall sums may lead to inaccurate interpretations of climate-growth responses. In our study, we aim to determine the effect of heavy daily precipitation events and the sensitivity of oak tree rings using long-term daily hydroclimatic records from Mainfranken (southern Germany).

2. Materials and methods

2.1. Tree-ring series of living oak trees

The tree-ring data archive of the University of Hohenheim (Holocene oak chronology, HOC and Preboreal pine chronology, PPC, Friedrich et al., 2004) contains more than 4000 subfossil, 6000 historical and 700 oak samples from living trees from southern Germany, spanning the Holocene and ranging from 8,480 BCE to the present day. The HOC serves to investigate past hydroclimatic variability on a seasonal to decadal scale (e.g. Land, 2014; Land et al., 2015; Schönbein et al., 2015).

The present study focuses on the Mainfranken region in Northern Bavaria, Germany. Samples from living oak trees of *Quercus robur* L. and *Quercus petraea* (Matt.) Liebl. were collected (Fig. 1) which originate from locations with different site conditions: wet to dry soils as well as groundwater affected forests growing on steep slopes or flat ground (for site descriptions see Table S1). These locations represent a wide variety of site characteristics found in Mainfranken. Two cores per tree were taken at breast height using an increment borer (Suunto, Vantaa, Finland). The samples were attached to wooden supports and the cross-section surface was smoothed with a core-microtome. The cut surface was treated with chalk to enhance visual contrast of the cells for tree-ring measurements. Annual total ring width (TRW) was measured with a commercial software (TSAPWin, Version 4.69b, Rinntech, Heidelberg, Germany) with a resolution of 0.01 mm. A mean TRW series for each tree was built following a visual cross-check of the core measurements and the samples were then dated to a particular end year. A total of 144 TRW series from twelve sites were available for further dendroclimatological analysis with a minimum series length of 81 years and a maximum of 211 years.

2.2. Long-term daily precipitation and temperature records

To analyze the correlations between TRW chronologies and daily precipitation sum (DPS) as well as daily mean temperature (DMT), the data records of six long-term climate stations (Table S2) in the Mainfranken region were used (Fig. 1). The Bamberg station has a continuous record of daily precipitation and daily mean temperature (with missing data in 1882) from 1879 to present. The climate station with the shortest record (Schweinfurt) reveals at least a 63-year-long daily record. The stations were selected due to their proximities, their extensive durations and their long-lasting daily records. DPS and DMT data from the used meteorological stations were obtained from KNMI Climate Explorer http://climexp.knmi.nl (Klein Tank et al., 2002). All data sets were checked for missing data (see Table S2).

2.3. Standardization of TRW series and chronology construction

The standardization of oak TRW series was performed via ARSTAN (Cook and Krusic, 2005) using a 70% cubic smoothing spline with a 50% frequency response cut-off, to preserve high- to mid-frequency variability. After transformation, annual indices were calculated as ratios from the fitted growth curves and the TRW series. The variance was adjusted taking into account the changing replication through time in the TRW set. Site-chronologies were constructed using the bi-weight robust mean method. To assess the signal strength of the constructed chronologies, Expressed Population Signal (EPS) and inter-series correlation (RBAR) were calculated to ensure sufficient sample replication over time. A window length of 50 years with 25 years of overlap was applied. A threshold of EPS > 0.85 was accepted as a desirable level for a robust and hypothetical noise-free tree-ring chronology (Wigley et al., 1984). Additionally, a chronology was constructed using all TRW series from the Mainfranken region (hereafter referred to as Composite chronology) applying the same methodology as descripted above.

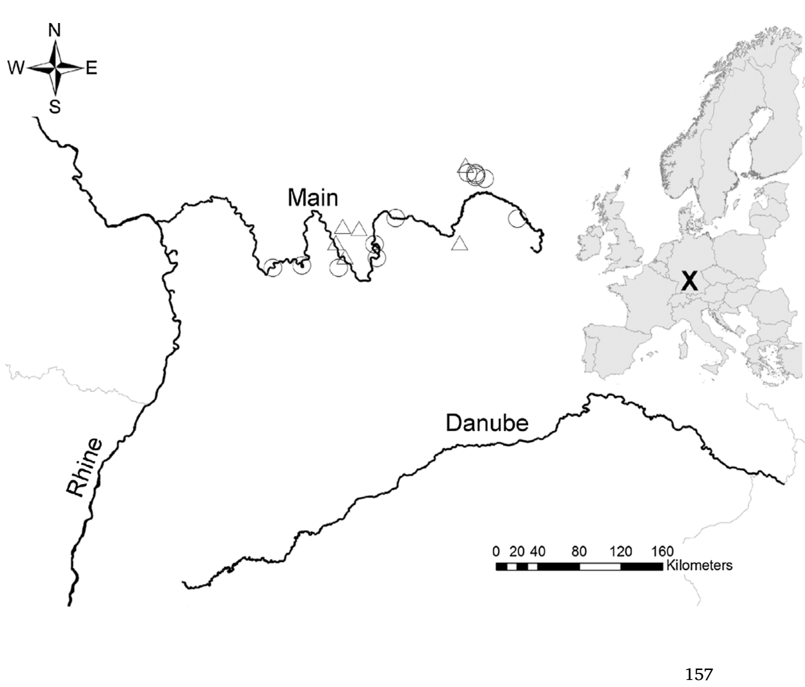

Fig. 1. Location map of climate stations (triangle) with long-term records of daily precipitation and daily mean temperature and tree-ring sites (circles) in the Mainfranken region (southern Germany).

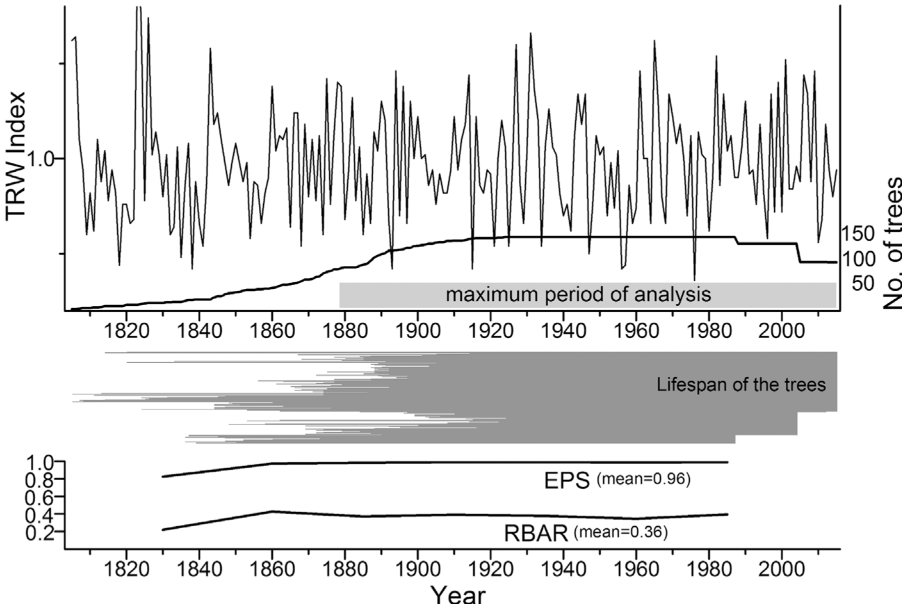

Fig. 2. TRW Index of the Composite chronology, number of trees per year, lifespan of the trees, as well as Expressed Population Signal (EPS) and inter-series correlation (RBAR). Climate-growth analyses have been carried out from 1879 to 2015 (maximum period of analysis).

2.4. *Analysis of climate-growth sensitivity*

2.4.1. *Correlation and regression*

A MATLAB® (MathWorks, 2013) script was developed by Schönbein (2011), which aggregates the daily precipitation sum (DPS)/daily mean temperature (DMT) data altering (1) the length of the data interval used for correlation (from 41 to 211 days in steps of five days) and (2) the starting date of the data derived from September 1 of the previous year. The procedure is repeated but starting from September 15, then from October 1 and so far until the end of the current year is reached. A Pearson correlation between each newly generated DPS/DMT series and the site-chronologies as well as the Composite chronology were calculated. Maximum correlations were selected and response functions generated to determine significant relationships. Statistical significance was attained when *p*-value was less than the level of significance $\alpha = 5\%$. The correlation analyses were performed between each site-chronology and DPS/DMT records from a nearby climate station and Bamberg station. Additionally, climate-growth response was investigated between the Composite chronology and the DPS/DMT records from Bamberg station considering the entire time interval (1879–2015) as well as within overlapping sub-periods (e.g. 1905–1930, 1918–1943) to evaluate changes in temporal sensitivity and stability.

In one district of Mainfranken a massive insect attack of the green oak leaf roller (*Tortrix viridana* L.) was observed during 1948 and 1954-58 (Steger, 1959; Steger, 1960). In spring of the year 1958 insect control was implemented by helicopter causing a *Tortrix*-mortality rate of 98–99%. The wood anatomy of these years was investigated in detail: For these years, density bands as well as a lack of latewood production could be identified (not shown). In order to investigate climatological effects exclusively on TRW, these years were excluded from further analysis.

2.4.2. *Climate-growth analysis and the effect of heavy precipitation events*

In a second step, the Composite chronology was tested against the edited precipitation data sets to determine whether radial growth is sensitive to heavy rainfall events. This was done because heavy DPS does not significantly increase soil moisture but rather cause surface runoff, meaning that radial tree growth may not profit from excessive DPS (e.g. Dohnal et al., 2014). In a third step, climate-growth analysis was performed for nine sub-periods (1879–1904, 1892–1917, 1905–1930, 1918–1943, 1931–1962, 1944–1975, 1963–1988, 1976–2001, 1989–2015), to identify potential temporal changes of tree growth sensitivity to precipitation. Each sub-period contains 26 years (except the sub-period 1989–2015 = 27 years) for climate-growth response analysis. Note, that e.g. in the sub-period 1944–1975 a total of 26 years was available in order to calculate the relationship between tree growth and precipitation.

DPS was ranked according to a common definition (Ranke, 2015). In Europe a rainfall amount of ≥10 mm within 24 h is defined as a heavy precipitation event and ≥20 mm as a very heavy precipitation event. We categorized the available DPS records accordingly with values of ≥10 mm and ≥20 mm corresponding to heavy and very heavy precipitation events respectively. The original DPS record from Bamberg was edited so that heavy precipitation was eliminated in a stepwise fashion by replacing daily values greater than 20 mm to 20, greater than 15 mm to 15 etc. (hereafter referred to as maximum DPS limits that are abbreviated as ≤20, ≤15 etc.), to analyze the effect of heavy precipitation events on TRW sensitivity. To gain information about the sensitivity of the Composite chronology exclusively to high rainfall, DPS less than 30 mm, 20 mm, 15 mm etc. were excluded from the record in further steps, so that only heavy rainfall events remain in the records. These edited precipitation series were used for later climate-growth response analysis in addition to the original precipitation records mentioned above.

3. Results

3.1. *Oak growth variability of Mainfranken region in modern time*

The annual variability of the Composite chronology as well as replication, EPS and RBAR for Mainfranken are displayed in Fig. 2. Very low TRW indices can be seen for the years 1838, 1893, 1915, 1956–57 and 1976. The lowest index of the entire modern period is in 1976. Very high indices were detected for 1843, 1927, 1931 and 1965. High year-to-year variability occurred during the entire modern period, notably in 1921–1936. A period of low variability can be seen from 1901 to 1909. In the years 1823, 1824 and 1826 the TRW indices exceed all other values, but should not be considered for further interpretation as the chronology is neither robust nor noise-free (low EPS values in the related period). From the mid-19th century onwards, the EPS exceeds 0.97 and is continuously higher than the required value of 0.85, RBAR ranges between r = 0.43 and r = 0.35. Given that the climate-growth analysis is carried out from 1879 to 2015 (maximum period of

Table 1
Results of climate-growth response analyses. Each site-chronology was analyzed against the daily precipitation sum and daily mean temperature records of Bamberg and a nearby station. Considered was the time from previous year September to current year December. The correlation coefficient (r) and the corresponding sensitive interval is shown. n.s. = not significant (α > 5%).

Site	Climate station	Precipitation		Mean temperature	
		Current year	Previous year	Current year	Previous year
COB1	Bamberg	0.36 (Feb. 25–Jul. 5)	n.s.	−0.25 (Jun. 1–Jul. 31)	n.s.
COB2	Bamberg	0.26 (Feb. 25–Jul. 5)	0.17 (Sep. 29–Dec. 2)	0.22 (Dec. 13–Mar. 22)	n.s.
DETT	Bamberg	0.44 (Apr. 12–Jul. 21)	n.s.	−0.19 (Jul. 7–Aug. 26)	−0.18 (Nov. 1–Dec. 31)
ESCH	Bamberg	0.55 (Feb. 10–Jul. 20)	n.s.	−0.26 (Mar. 13–Aug. 20)	n.s.
EUER	Bamberg	0.54 (Mar. 28–Aug. 5)	n.s.	−0.27 (Jun. 1–Jul. 31)	n.s.
FREU	Bamberg	0.40 (Dec. 17–Jul. 15)	n.s.	n.s.	n.s.
NEUD	Bamberg	0.40 (Feb. 26–Jul. 5)	n.s.	0.26 (Jan. 12–Feb. 21)	n.s.
OBE1	Bamberg	0.49 (Mar. 27–Jul. 5)	n.s.	−0.31 (Jun. 1–Jul. 31)	n.s.
OBE2	Bamberg	0.31 (Feb. 25–Jul. 5)	n.s.	−0.21 (May 27–Aug. 5)	−0.20 (Oct. 27–Jan. 5)
SONN	Bamberg	0.34 (Feb. 25–Jul. 5)	n.s.	−0.20 (Apr. 12–Jul. 21)	−0.21 (Sep. 12–Dec. 21)
WERT	Bamberg	0.46 (Dec. 17–Jul. 15)	n.s.	−0.28 (Jul. 2–Aug. 31)	n.s.
WUER	Bamberg	0.40 (Apr. 17–Jul. 16)	n.s.	0.21 (Oct. 22–Mar. 12)	n.s.
COMPOSITE	Bamberg	0.51 (Feb. 25–Jul. 5)	n.s.	−0.24 (Jun. 1–Jul. 31)	n.s.
COB1	Oberlauter	0.48 (Feb. 26–Jul. 5)	n.s.	−0.30 (May 7–Jun. 26)	−0.32 (Oct. 22–Jan. 10)
COB2	Oberlauter	n.s.	n.s.	n.s.	n.s.
DETT	Würzburg	0.50 (Mar. 28–Aug. 5)	n.s.	n.s.	n.s.
ESCH	Schweinfurt	0.67 (Feb. 11–Jul. 20)	n.s.	n.s.	n.s.
EUER	Schweinfurt	0.63 (Apr. 27–Jul. 6)	n.s.	n.s.	n.s.
FREU	Thüngersheim	0.56 (Jan. 26–Aug. 4)	n.s.	n.s.	n.s.
NEUD	Heinersreuth	0.32 (Feb. 5–May 26)	n.s.	n.s.	n.s.
OBE1	Oberlauter	0.59 (Apr. 27–Jul. 6)	n.s.	−0.46 (Apr. 12–Jul. 21)	−0.28 (Oct. 12–Nov. 21)
OBE2	Oberlauter	0.53 (Apr. 7–Jul. 26)	n.s.	0.31 (Jan. 20–Apr. 10)	−0.30 (Oct. 12–Nov. 21)
SONN	Oberlauter	0.29 (Feb. 25–Jul. 5)	n.s.	−0.36 (Apr. 11–May 21)	−0.31 (Sep. 22–Dec. 11)
WERT	Thüngersheim	0.48 (Jan. 26–Aug. 4)	n.s.	n.s.	n.s.
WUER	Würzburg	0.50 (Jan. 6–Jun. 25)	n.s.	0.31 (Jan. 12–Feb. 21)	n.s.

analysis), the required EPS is consistently exceeded and thus a robust and noise-free Composite chronology can be used for further analysis.

The site-chronologies show mean EPS values of 0.91–0.97 and mean RBAR values of 0.50–0.68 (Table S1), which indicate that all site-chronologies are robust and noise-free, too.

3.2. Sensitivity of oaks from Mainfranken to DPS/DMT

3.2.1. Response of TRW chronologies to long-term DPS and DMT records

The presented analysis provides information on intervals of trees sensitivity to DPS and DMT records of several climate stations. Table 1 shows detailed results of the conducted site-specific climate-growth response analyses.

TRW chronologies are more sensitive to intervals starting/ending not at the beginning/end of the month. This clearly give evidence using daily-resolved records are more appropriate for local-to-regional climate response analyses than monthly-resolved data.

Site-chronologies reveal a clear positive current year precipitation response when considering the nearby station record (site-chronology of COB2 shows no significance response at all). The onset of sensitivity of TRW starts between January 6 (WUER) and April 27 (EUER, OBE1) and ends between May 29 (NEUD) and August 5 (DETT). When considering the Bamberg station record, all site-chronologies also hold a clear positive current year rainfall signal. The onset of TRW sensitivity is located in winter/spring season (e.g. December 17 of the previous year or April 17 of the current year). TRW sensitivity to precipitation is completed sin mid-summer (between July 5 and August 5). A previous year relationship between TRW and precipitation could only be detected for the site COB2 (Table 1).

The results regarding temperature responses of TRW chronologies are not as clear as for precipitation. Mainly a negative related previous and current year temperature sensitivity is evident for individual site-chronologies. These relationships are not as strong as for precipitation sensitivities (except for SONN) (Table 1).

The Composite chronology shows a high positive sensitivity to the precipitation sum within a 131-day interval (February 25 to July 5) for the Bamberg climate station with a correlation coefficient (r) of 0.51 and a coefficient of determination (R^2) of 0.26 ($N = 131$, $p < 0.01$) (Table 1, Fig. 3) as well as a negative relationship to mean temperature from June 1 to July 31 ($r = -0.24$, $R^2 = 0.06$, $N = 130$, $p < 0.01$). A statistical relationship to previous year DPS and DMT is not evident.

The Composite chronology provides much stronger correlations to precipitation when (very) heavy precipitation events are excluded from daily data sets. Table 2 shows the analysis results (≤ 20 to ≤ 2.5 mm/day) after extreme daily rainfall data were eliminated. The highest statistical relationship is found for the ≤7.5 Bamberg record, where daily heavy precipitation of > 7.5 mm is excluded: $r = 0.56$, $R^2 = 0.31$, $p < 0.01$ (Figs. 3 and 4A–E). In general, the correlation increases when heavy precipitation events are omitted, although at a certain point (≤5 or less), this trend ceases. The length of the sensitive interval decreases from 131 (original) to 96 days (≤7.5), which is at least a difference of one month. Testing the sensitivity of the Composite chronology only against (very) heavy rainfall events (e.g. using DPS ≥ 20 mm for analysis) reduced the strength of the statistical correlation drastically, however it remained significant with $p < 0.05$ and $p < 0.01$ (Table 2). Data from the Bamberg station provides two clear examples which illustrate the differences seen when only heavy rainfall events are included in the analysis: The record consisting of DPS ≥30 mm resulted in a marginally positive significant correlation of $r = 0.18$ ($R^2 = 0.03$, $p < 0.05$). However, the length of the sensitive interval is equal to that of highest relationship, but the interval is located earlier in the year: March 19 to June 17. DPS ≥ 10 mm reveals a correlation of $r = 0.32$ ($R^2 = 0.10$, $p < 0.01$) for a 131-day period from February 26 to July 5.

3.2.2. Temporal instability of trees' growth sensitivity to precipitation

For investigating the temporal sensitivity of the Composite chronology, a correlation analysis within sub-periods was conducted. The results for nine sub-periods of the original time span, each analyzed with maximum DPS limits of ≤20, ≤15, ≤10, ≤7.5 and ≤5 applied to

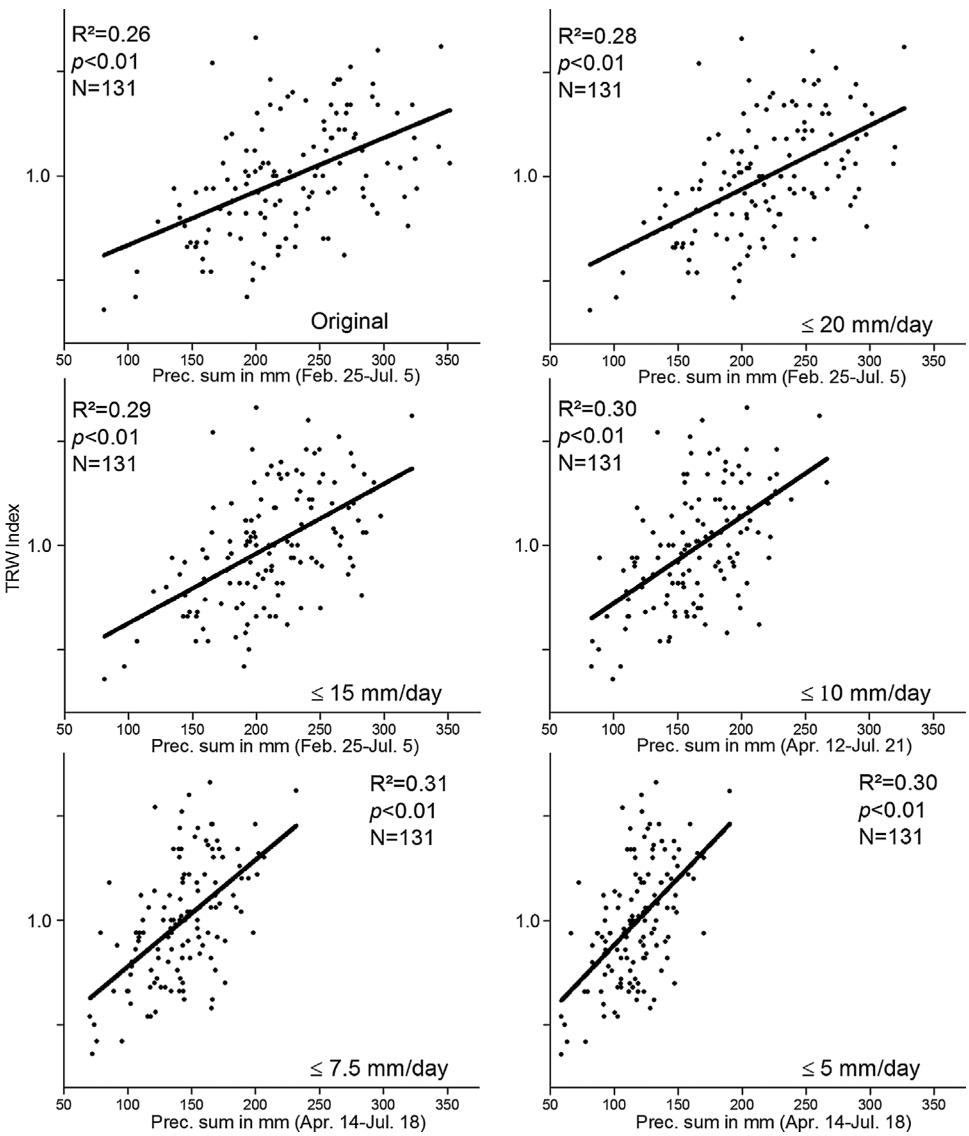

Fig. 3. Scatter plots showing statistical relationships with regression lines (black) between Composite chronology and different precipitation records of the meteorological station Bamberg.

the precipitation records are shown in Fig. 5. As can be seen in Fig. 5A, the correlation coefficients (r) display positive significant correlation values, with all mentioned records throughout the nine sub-periods once again achieve at least on a level of $p < 0.05$. Table S3 shows the varying length of the sensitive intervals for each record and the correlation coefficients. Statistical relationships are consistently high for the ≤7.5 record through the sub-periods. In the sub-period from 1976 to 2001 TRW sensitivity decreases to a minimum for all records, but remains significant ($p < 0.05$).

Considering the length of the interval (in days) to which TRW is sensitive, a distinct variation between the different sub-periods is found (Fig. 5B, for detailed data see Table S3). These sensitive intervals vary from 181 (six months) to 41 days, depending on the data set and the sub-period chosen. In the time interval from 1963 to 1988 the highest correlations for all records have been found during an interval of 41 days in spring (April 11 to May 21). However in the period from 1905 to 1930, for example TRW is highly sensitive in a 131-day or 141-day interval, which is independent from the record used. The highest discrepancy has been found for the sub-period from 1989 to 2015. Throughout all sub-periods and all precipitation records used, the highest sensitivity of the Composite chronology to precipitation was seen for spring and/or summer.

The behaviour of best relationship between TRW and the corresponding precipitation records with fixed length of sensitive intervals during the nine sub-periods is shown in Fig. 5C. An example shall be given here: TRW sensitivity to ≤7.5 shows a highly positive correlation of r = 0.56 ($R^2 = 0.31$, $p < 0.01$) to precipitation from April 14 to July 18 throughout the entire period from 1879 to 2015 (Table 2). This interval reveals a highly positive and significant relationship throughout the sub-periods 1879–1904 to 1963–1988 (Fig. 5C, red line). However, the correlation between the Composite chronology and DPS is not significant for this interval during the last two sub-periods (1976–2001 and 1989–2015). Similar behaviour to each individual interval is found for ≤10 (April 12–July 21) and ≤5 (April 14–July 18). In contrast, for the original record, ≤20 and ≤15 (February 25–July 5 respectively) a shift above the level of significance $p < 0.05$ is observed in the sub-period from 1931 to 1962, while TRW maintains significant correlations to these records for the last two sub-periods. In contrast ≤10, ≤7.5 and ≤5 failed to show a statistical significance.

Fig. S1A shows the total number of days exceeding a precipitation sum of 30, 20, 10 and 7.5 mm/day for the nine sub-periods, according to the data from the Bamberg station between April 14 and July 18. The number of DPS records exceeding a given limit (e.g. 20 mm/day) remains stable throughout time as well as no clear change in total annual precipitation sum from 1879 to 20015 can be detected (Fig. S1B). This

Table 2
Results of climate-growth response analyses between the Composite chronology and different precipitation records (Bamberg station) during the entire study period (N = 131). Assessing the effect of (very) heavy precipitation events on annual tree growth, the original daily precipitation record was edited to develop series of several daily precipitation sum (DPS) limits (e.g. 20 mm/day or less, ≤ 20). Correlation coefficient (r), coefficient of determination (R^2), length of sensitive interval (in days), sensitive period and level of significance (*p*) are displayed. Highest response is indicated in bold.

Precipitation record	r	R^2	Sensitive interval (days)	Sensitive period	*p*
Original	0.51	0.26	131	Feb. 25–Jul. 5	< 0.01
≤ 20	0.53	0.28	131	Feb. 25–Jul. 5	< 0.01
≤ 15	0.54	0.29	131	Feb. 25–Jul. 5	< 0.01
≤ 10	0.55	0.30	101	Apr. 12–Jul. 21	< 0.01
≤7.5	**0.56**	**0.31**	**96**	**Apr. 14–Jul. 18**	**< 0.01**
≤ 5	0.55	0.30	96	Apr. 14–Jul. 18	< 0.01
≤ 2.5	0.52	0.27	136	Feb. 22–Jul. 7	< 0.01
≥ 30	0.18	0.03	96	Mar. 16–Jun. 17	< 0.05
≥ 20	0.23	0.05	191	Dez. 27–Jul. 5	< 0.01
≥ 15	0.25	0.06	131	Feb. 26–Jul. 5	< 0.01
≥ 10	0.32	0.10	131	Feb. 26–Jul. 5	< 0.01
≥7.5	0.40	0.16	131	Feb. 26–Jul. 5	< 0.01
≥ 5	0.46	0.21	131	Feb. 26–Jul. 5	< 0.01

indicates that insensitivity of radial stem growth to precipitation from April 14 to July 18 in the period from 1976 to 2015 seems not to be triggered by a changing precipitation regime.

4. Discussion

4.1. Climate-growth sensitivity of Mainfranken oak trees

The site-chronologies as well as the Composite chronology of Mainfranken oak trees are highly sensitive to current year total rainfall sum primarily in spring/summer season. These positive precipitation sensitivities agree with findings for oak from e.g. the western Black Sea region (Akkemik et al., 2005), England (Cooper et al., 2013; Wilson et al., 2013), Sweden (Drobyshev et al., 2011), central-west and southern Germany (Friedrichs et al., 2008; Schönbein et al., 2015; Land, 2014; Land et al., 2015), central Europe (Büntgen et al., 2011), the north Aegean (Griggs et al., 2007) and Switzerland (Fonti et al., 2009) which report a positive spring/summer response.

4.2. Sensitivity of Mainfranken oak trees to heavy precipitation events

Our results clearly indicate that heavy precipitation events (> 15 mm/day) are less reflected in annual radial increment of oak trees, and thus the Composite chronology underestimates the actual seasonal rainfall. From 1879–2015 a continuously strong relationship between annual radial growth and daily precipitation sum (DPS) less than 7.5 mm/day is observed for the 96-day interval April 14–July 18. The insensitivity to high daily rainfall amounts could be explained by water uptake from groundwater reserves, as confirmed by Phillips and Ehleringer (1995), Bréda et al. (1995), Miller et al. (2010) and Matheny et al. (2016). These authors found evidence that ring-porous oak species utilize water throughout the growing season mainly from deep-soil moisture sources or groundwater.

However, this is contradicted by Sánchez-Pérez et al. (2008), who

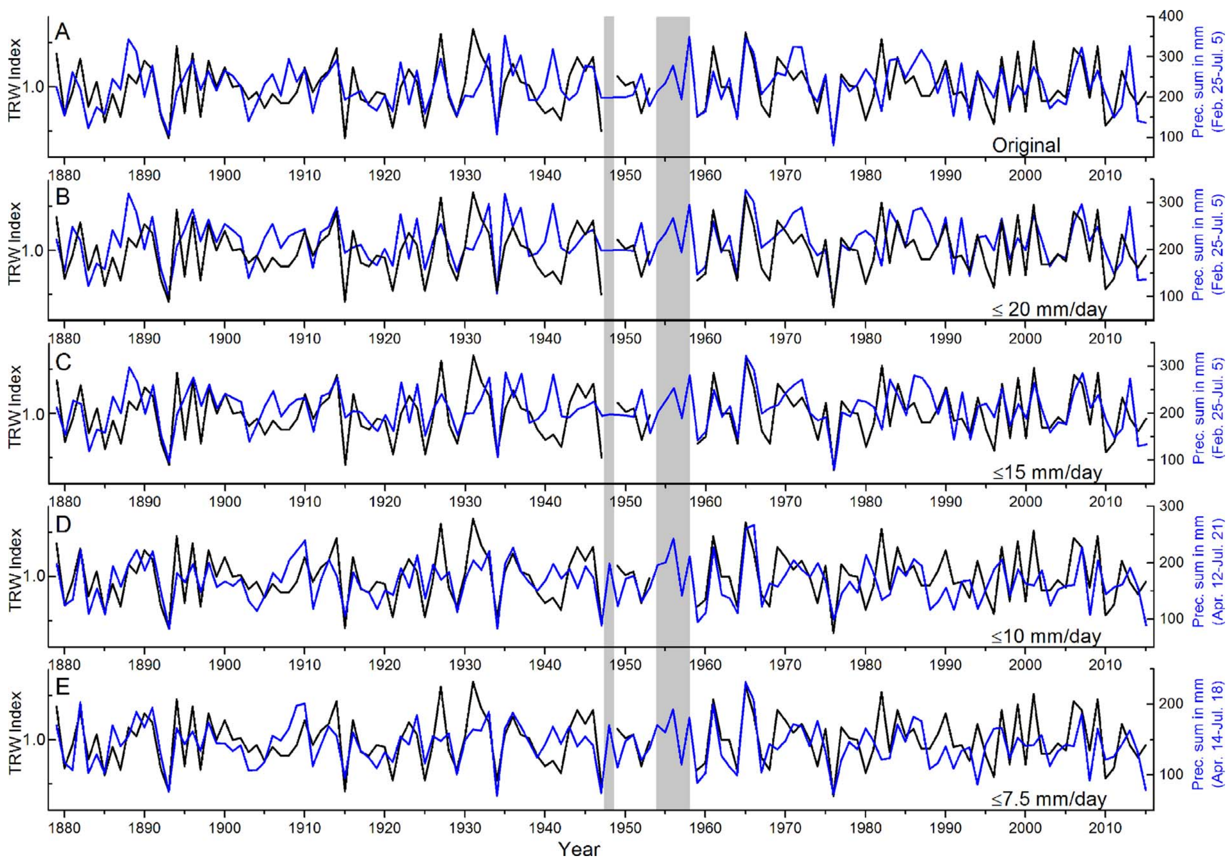

Fig. 4. (A–E) Year-to-year variability of the Composite chronology (black) and several precipitation records of Bamberg (blue) from 1879 to 2015. Composite chronology and several precipitation records of Bamberg are very synchronous from 1879 to 1980, with rising conformity from A–E. During the past three to four decades (since 1980 approximately) the relationship is seen to reverse. Increasing correlation is then found from E–A (for additional data see Fig. 5C). Grey rectangles indicate *Tortrix viridiana* outbreaks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

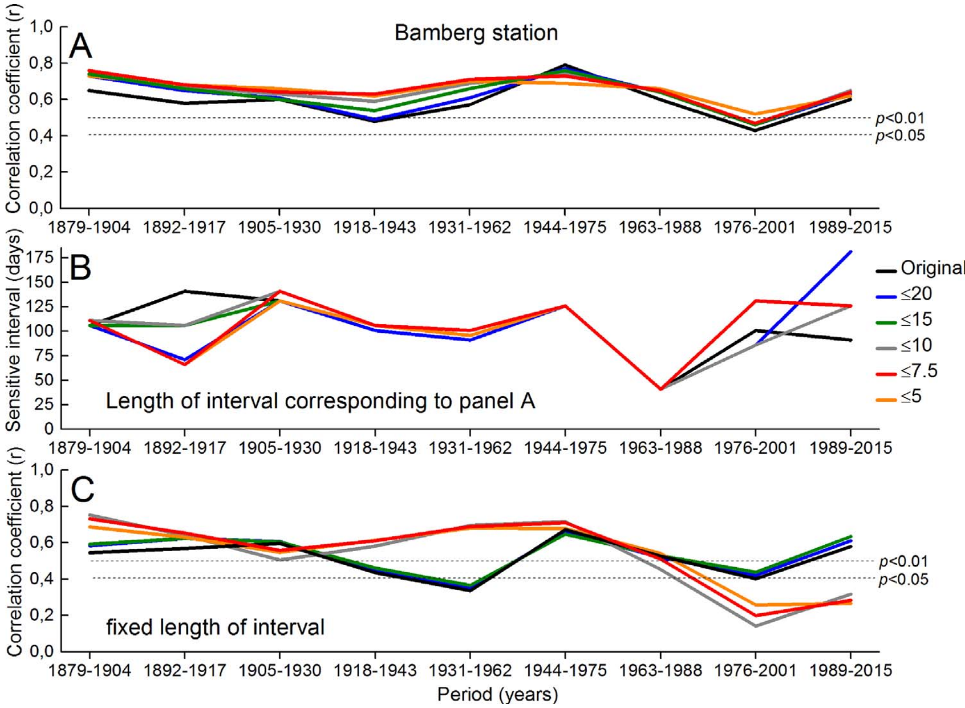

Fig. 5. Results of climate-growth relationships within different sub-periods (Bamberg station) are illustrated. (A) Maximum statistical relationships of Composite chronology to original (black), ≤20 (blue), ≤15 (green), ≤10 (grey), ≤7.5 (red) and ≤5 (orange). Within all sub-periods, the Composite chronology is significantly sensitive ($p < 0.05$ and $p < 0.01$) to the mentioned precipitation records. (B) shows the sensitive interval in days of the corresponding correlation analysis of (A). Aside from the sub-period from 1892 to 1917, the length of the sensitive interval shows high homogeneity between the different calculations for the first six sub-periods, varying from 91 to 141 days. A rapid decrease is detected during 1963–1988 (41-day interval). (C) Same as in (A), but with fixed interval length during the sub-periods (for detailed data see Table S3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conclude that water uptake in a riparian hardwood forest takes place in the upper soil layer. Miller et al. (2010) stated that water from deep-soil layers or from the groundwater table "provide a buffer to rapid changes in their hydroclimate" and Volkmann et al. (2016) pointed out an "adjusted root uptake to vertical water availability patterns under drought, but readjustment toward the rewetted topsoil was delayed" by sessile oak. Considering the rainfall interception by the tree canopy, the reduction in precipitation reaching the soil during a growing season can be considerable (~34%, e.g. Dohnal et al., 2014). Throughfall is highly variable within stands and is strongly affected by the character of precipitation (e.g. Dohnal et al., 2014). This may lead to the assumption that radial growth is not so much a reflection of heavy rainfall, but rather of deep-soil moisture availability and the water table. Annual total ring width is thus sensitive to a subset of seasonal precipitation sum, which leads to an underestimation of the actual rainfall sum when reconstructing past hydroclimate variability on a local to regional scale.

4.3. Temporal changes in rainfall sensitivity from the mid 1970s onwards

The temporal sensitivity of Mainfranken oak trees to precipitation (DPS ≤10 mm) is not consistent over time. Several studies report a change in the sensitivity of radial growth to rainfall for oak trees during the 20th century. Friedrichs et al. (2008) showed that oak trees in central-west Germany switched from a general precipitation sensitivity to a temperature and vapor pressure response during a severe warm period in the 1940s. Climate-response results of this study indicate a decrease in precipitation sensitivity for the original precipitation record in the mid-20th century (1931–1962). In contrast, the response of the investigated oak trees to the precipitation records, in which heavy daily precipitation sum is omitted, remains very high for this period. Furthermore, within the past four decades TRW is no longer sensitive to DPS ≤10 mm, but shows sensitivity to heavy precipitation variability. This behavior could be explained by changes in the hydroclimate within the past decades. Spinoni et al. (2015) investigated European drought climatologies pointing out that severe, long-lasting droughts increased during the past six decades and potential evapotranspiration (PET) is the leading driver of drought in Central Europe due to the temperature rise. These trends may cause an increase of transpiration rates in oak trees and rising water consumptions leading to a higher sensitivity regarding heavy rainfall events.

But further suggestions should be considered. Wilson et al. (2013) reported the weakest correlation of oaks tree rings in southern-central England during the 19th century when air was highly polluted by smoke and sulfur dioxide (SO_2). SO_2 emissions increased consistently in Germany, starting in the late 19th century with a rapid boost in the 1950s and exceeded 8000 giga gram (Gg) for the first time in history in 1963 (Smith et al., 2011). From 1985 onwards the emissions decreased to a rate comparable to the 1920s within one decade. From 1963–1988, we found that the oak trees do respond positively to a very short interval of 41 days in spring (April 11–May 21). Similarly, a highly diminished rainfall response is observed during the past four decades (1976–2015). The rising atmospheric SO_2 concentration and the deposition into forest ecosystems may also have diminished the tree-ring response to rainfall. One explanation for that phenomenon could be the fact that SO_2 deposition decreases soil pH leading to a loss of fine-roots and thus water uptake is disturbed. This is confirmed by Wilson and Elling (2004) for Norway spruce and silver fir regarding tree-growth/climate response in the Lower Bavarian Forest region (southwest Germany), located ~200 km from the Mainfranken region. They also found an instability in precipitation response of spruce trees starting in the mid 1970s and suggested that the instability was caused by the local rise in SO_2, which agrees with our findings. Barrelet et al. (2008) and Sheppard et al. (2008) reported a corresponding effect of sulfur content in the atmosphere and sulfur within tree rings. Furthermore, Böttger et al. (2014) and Sensula (2016) found evidence of a clear interaction between sulfur dioxide/aerosols and isotope values in the wood of *Abies alba* in Franconia (Germany) for 1979–2006. Choi et al. (2014) investigated *Alnus sieboldiana* in Japan after a volcanic eruption and found a low photosynthetic rate as well as reduced tree growth when exposed to high SO_2 concentrations. Karolewski et al. (2005) reported an increase in radial growth of oak trees contaminated with nitrogen and sulfur in Poland. There seems to be no doubt that aerosols can influence tree growth, and thus could also be the driving factor for changes in the observed precipitation response of oak trees in the Mainfranken region.

When discussing the decrease of rainfall sensitivity, we propose that not only should a direct chemical influence of e.g. sulfur immissions be considered, but also the trends in surface solar radiation (SSR) may be strongly affected by aerosol air content. Recent studies from Stanhill and Cohen (2001), Streets et al. (2006), Norris and Wild (2007), Wild (2009, see also references therein) and Wild (2012) present striking evidence for a close relationship between SSR and the content of atmospheric aerosols, which lead to a dimming effect from the 1950s to the 1980s and to a more recent brightening effect. Makowski et al. (2008) and Wild (2009) observed the diurnal temperature range (daily maximum minus daily minimum temperature, DTR) of the Northern Hemisphere and over Europe. They reported a distinct connection between DTR, shortwave radiation and sulfur emissions and noted a substantial decrease of DTR over land surfaces from the 1970s onwards.

It seems likely that tree-ring sensitivity in the Mainfranken region during the last four decades was influenced by a combination of a) changes in hydroclimatic conditions, b) an increasing effect regarding the content of atmospheric aerosols, c) SO_2 immissions into forest ecosystems and d) changes in DTR and SSR. On the one hand, these factors may lead to an internal response within trees by reducing the net photosynthetic carbon uptake rate and consequently altering root-shoot carbon allocation. On the other hand, the fine-root turnover may be negatively affected by a high sulfate (SO_4^{2-}) and nitrogen (N) load (e.g. Nellemann and Thomsen, 2001). Deposition of sulfate and nitrogen over the past decades in central European forests (Fischer et al., 2012) has been high, resulting in increased above ground growth (Fischer et al., 2012), a decreased root/shoot ratio and less vital fine roots (e.g. Matzner and Murach, 1995). It seems likely that root water uptake is hereby disturbed, resulting in increased competition for water resources and leading to a diminished rainfall sensitivity.

We found that the oak trees from the Mainfranken region show a clear positive precipitation signal during the second half of the 19th century until the 1970s but are less sensitive due to changes in the hydroclimate, in atmospheric aerosol content, sulfur dioxide immissions and changes in SSR and DTR. Therefore, we propose omitting the last four decades when developing reconstructions of the local-to-regional hydroclimate variability for this area from tree-ring data. Because a century-length daily precipitation record is available from the Bamberg weather station, there is a high potential to develop a relatively unbiased climate-growth model for the Mainfranken region based on oak tree-ring data.

5. Conclusions

The presented findings show that radial growth of oak trees responds strongly to precipitation during the vegetation period in the Mainfranken region. However, severe rainfall events (e.g. > 30 mm/day) during the growing season do not affect radial growth significantly. We therefore conclude that oak trees from this region are less sensitive to daily heavy precipitation events. This leads to the assumption that such rainfall events during spring and summer, as part of past hydroclimate conditions, cannot be reconstructed when using ancient oak samples. From a critical point of view, a tree-ring based reconstruction of past hydroclimate may not provide information of DPS exceeding 10 mm, and thus the seasonal rainfall sum is underestimated. When performing oak tree-ring reconstruction from Mainfranken region or from any other area scientists have to take into account, that the reconstruction may be limited regarding such heavy rainfall events. Even when trees are not sensitive to a one-month period but rather to an entire growing season, which is the case in most of such studies, this fact seems to hold true. When developing climate-growth response functions for the Mainfranken region, neglecting the past four decades is recommended, because of an altered growth-precipitation-system, which seems to be biased due to man-made air pollution like sulfur dioxide emission and other aerosols. Likewise, local-to-regional climate-growth analysis should be intensively investigated with the use of appropriate software solutions to process long-term daily instead of monthly gauging records and to analyse temporal behaviour.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dendro.2017.08.005.

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