IDŐJÁRÁS
Quarterly Journal of the Hungarian Meteorological Service
Vol. 113, No. 4, October–December 2009, pp. 299–314

Reconstructed precipitation for southern Bakony Mountains (Transdanubia, Hungary) back to 1746 AD based on ring widths of oak trees

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(Manuscript received in final form September 3, 2009)

Abstract—This paper presents a 258-year long precipitation reconstruction for the Balaton Highlands and the southern Bakony Mountains region. The reconstruction based on 22 living and 32 historical tree-ring width series from oak (*Quercus* sp.). Ring width series were standardized by regional curve standardization technique to preserve the low frequency information. Precipitation from August of the year preceding the formation of tree ring to the current July positively stimulates the growth of oaks, albeit May-June precipitation emerges as main growth regulator factor. Very dry period occurred in the late 1740s. Studied region has experienced the wettest period during the late 18th century since 1746. Since that time, a steady decreasing trend prevails over the fluctuations of regional precipitation. From this overall trend, the 1840s, 1860s, and 1940s stand out as drier periods. The post-1980s dry period was placed into a ~250 years context and found to be an unprecedented drought at the Balaton Highlands and the southern Bakony Mountains region.

Key-words: dendroclimatology, tree ring, Central Europe, drought, Balaton

1. Introduction

The only way to decide whether the 20th century climate is extreme or not is to investigate long records stretching well before the anthropogenically forced instrumental period (e.g., *Bradley,* 1999; *Bradley et al.,* 2003).

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Bradley et al. (1987) analyzed 1487 instrumental precipitation series covering the northern Hemispheric land areas and pointed out significant regional differences in the fluctuation of past precipitation. They have already emphasized the dire necessity of investigations of past fluctuation of moisture regime on local-to-regional spatial scale. To fill this pronounced research need, paleoclimatic studies dealing with reconstruction of precipitation regime have taken enormous headway during the past decade. Amongst main sources of information on this field like documentary evidences (e.g., *Rodrigo et al.*, 1999; *Rácz*, 1999; *Garcia et al.*, 2003; *Diodato*, 2007) and speleothems (e.g., *Proctor et al.*, 2000; *Siklósy et al.*, 2009), tree rings play a leading part (e.g., *Brázdil et al.*, 2002; *Oberhuber* and *Kofler*, 2002; *Buckley et al.*, 2004; *Linderholm* and *Chen*, 2005; *Wilson et al.*, 2005; *Touchan et al.*, 2005, 2007; *Čufar et al.*, 2008).

The earliest sporadic instrumental rainfall data were recorded at Buda (1782), but the first continuous observations launched only in the mid-1800s (Buda 1841, Nagyszeben 1851) in the Carpathian Basin (*Hegyfoky*, 1910). These confirm that proxy based precipitation reconstructions have prominent importance also in the entire area girt with the arc of the Carpathians.

In addition, future continuation of warming on a global level is expected to procure reduction of annual precipitation in Hungary (*Bartholy et al.*, 2004, *Mika*, 2004, 2007) and, especially, the lake Balaton, prime tourist resource of Hungary, will be in risk, if precipitation declines in the future over the watershed (*Bartholy et al.*, 1995). So the knowledge about natural variability of moisture over its watershed is interesting not only from scientific but also from social and economical point of view.

This paper presents secular fluctuation of precipitation at the northern hilly part of the catchment area of the Lake Balaton. Variability of precipitation is reconstructed from tree-ring width variations of oak trees between 1746 and 2003. The low-frequency variability of present reconstruction is to be verified against longer instrumental record from the boarder vicinity of the study site. In addition, the tree-ring based reconstruction was compared to two other precipitation reconstructions, which are thought to have relevancy for the past fluctuation of the precipitation regime of the studied area.

2. Materials and methods

2.1. Tree-ring data

Fifteen mature oak trees (*Quercus petrea*, *Quercus pubescens*) were sampled by increment borer in November 2003. One or two cores were extracted from each tree. Due to exclusion of low quality samples, finally fourteen living oak trees (22 series) from Balaton Highland and southern Bakony Mts. (*Fig. 1*) developed a local oak chronology (*Kern*, 2007), and 32 historical timber samples derived from old buildings completed the 309 years long tree-ring width (TRW) chronology (1694 – 2003). Old timbers were collected from four villages close to the site of living trees, namely, Vöröstó, Nagyvázsony, Vigántpetend, and Örvényes (*Fig. 1*).

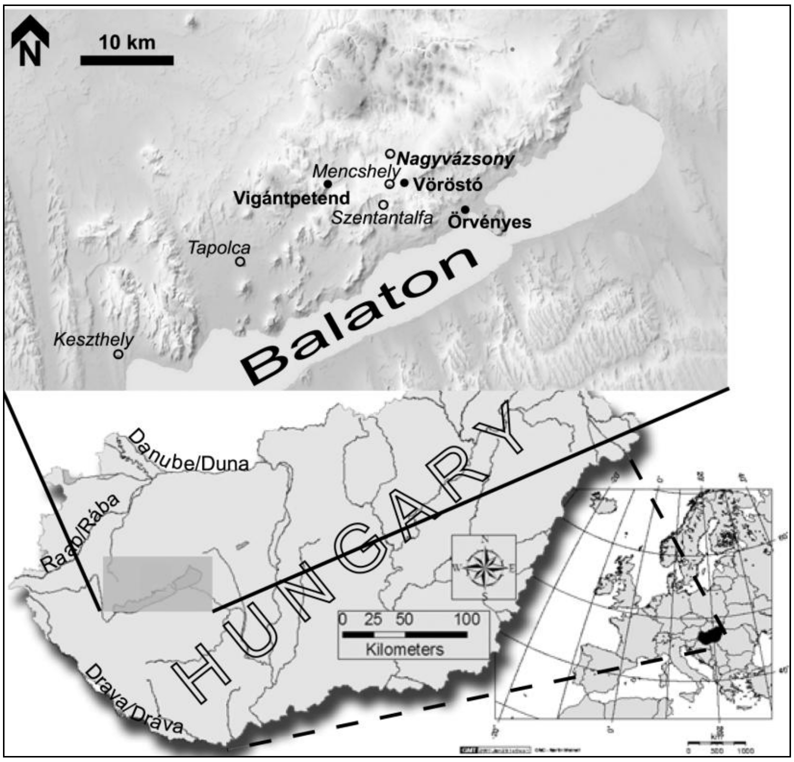

Fig. 1. Location of the study area (grey rectangle) and the precipitation gauge stations (marked by open circles and italics). Villages, from which historical wood samples originated, are marked by filled circles and bolds. From Nagyvázsony, both gauge records and historical timbers were used.

Living trees cover the 1766 –2003 period, while historical samples distribute between 1694 and 1944.

Climate signal in raw ring width series are often biased by non-climatic effects (e.g., *Douglass*, 1919; *Cook*, 1985). To find the adequate method to eliminate non-climatic trends (e.g., age trend) from raw TRW series, the so-called standardization is always crucial in any dendroclimatological study.

Mean segment length (MSL) was 124 years in the data set. Applying any traditional standardization techniques (negative exponential function or digital filtering), frequencies lower than ~3/MSL could hardly be retained (*Cook et al.*, 1995). To avoid the loss of low frequency information, regional curve standardization (RCS) was applied (*Briffa et al.*, 1992; *Esper et al.*, 2003). Utilizing RCS technique, multi-centennial trends could be captured even though the mean sample length is below 50 years (*Wilson et al.*, 2004).

RCS uses the estimated biological growth curve of the studied species in the standardization. The estimated biological growth, regional curve (RC) of oak was determined as follows: first calculating the bi-weight robust mean (*Cook*,

1985) of the age-aligned series, after that fitting a cubic smoothing spline (*Cook* and *Peters*, 1981) with a 50% frequency-response cut-off at 10% of the series length (*Esper et al.*, 2003) (*Fig. 2*).

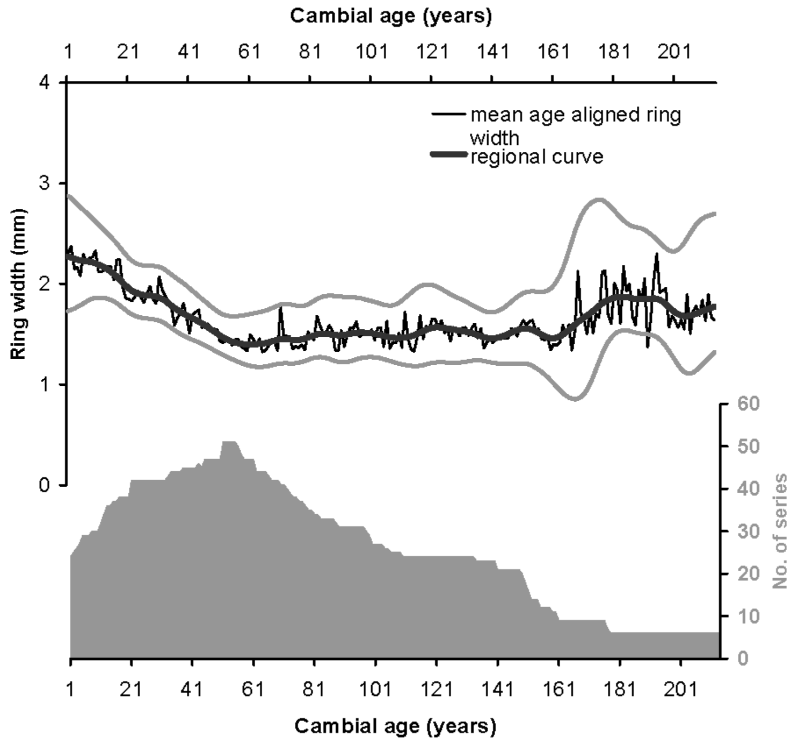

Fig. 2. Biological growth curve of oak. Upper graphics: thin black line: mean of age aligned series; thick black curve: regional curve (RC) obtained by fitting a cubic smoothing spline (50% frequency-response cut-off at 10% length); grey curves: 95% confidence intervals. Lower graph shows replication.

Twenty-five trees had the pith. In the other cases, missing rings to pith (pith offset) were estimated by the aid of graphics of concentric circles. Pith offset values for ten trees were less than 15, and the highest estimated pith offset was 50.

Indices were calculated as ratio of the measured ring width and the RC predicted value. Standardized series were rearranged by calendar date and average index was determined by bi-weight robust mean (*Cook*, 1985).

Uncertainty of the built chronology is represented by the 95% confidence interval calculated by bootstrap procedure (*Efron*, 1987). Stability of climate related signal preserved in the index series was controlled by the expressed population signal (EPS) statistic. Its widely accepted threshold is 0.85 (*Wigley et al.*, 1984). Mean interseries correlation (Rbar) and EPS were calculated for 50 years moving window with 25 years steps. Standardization and index calculation procedure was carried out using the ARSTAN software (*Cook* and *Krusic*, 2006). Variance adjustment was applied on the derived TRW chronology to minimize variance bias due to changing sample replication and the effect of fluctuating interseries correlation (*Osborn et al.*, 1997; *Frank et al.*, 2007).

2.2. *Precipitation data*

Monthly average precipitation totals were available from four nearby gauge-stations (Nagyvázsony 1901–2005, Tapolca 1901–2005, Mencshely 1960–1996 and 2001–2005, Szentantalfa 1900–1991 and 1998–2000) (*Fig. 1*). Since the use of averaged meteorological series yield better statistical connections in dendro-climatological analysis than individual stations (*Blasing et al.*, 1981; *Yeh et al.*, 2000), regional average precipitation series were estimated from these instrumental data. Monthly data were transformed to percentages of average monthly total of the 1961-1990 reference period (*WMO*, 1989). To accentuate the effect related to individual moisture regime of particular stations, monthly regional mean precipitation index series were calculated as non-weighted average percentage from the individual station-indices. Indices of May-June (MJ) and an annualized series were also determined. The annualized series were calculated as percentage of summarized monthly precipitation totals from the previous August to the current July.

These average percentage series were converted back to "absolute" precipitation values by multiplying each individual percentage data by the corresponding monthly, bimonthly, or annualized grand mean (mean of all stations' mean) calculated for the 1961–1990 reference period.

The longest continuous instrumental precipitation record in the region exists from the near-by Keszthely (*Fig. 1*). Early data (1861–1977) are available from Climate Explorer (*van Oldenborgh et al.*, 2005) and this series was updated to 2001.

2.3. *Relationship between tree growth and precipitation, precipitation reconstruction*

Relationship between annual increment of oak and precipitation was evaluated by computing Pearson's correlation coefficients from May of the previous year to October of the current year of formation of tree rings. In addition, MJ and annualized precipitation series were also involved into the correlation analysis.
To prevent the loss of natural amplitude due to the linear regression (*von Storch et al.*, 2005), rescaling technique was applied in reconstruction (*Esper et al.*, 2005). Period of instrumental precipitation data was divided into two subperiods: P1 (1901–1952) and P2 (1953–2003). Temporal stability of the reconstruction was tested in a split period calibration/verification procedure (*Fritts*, 1976). At first, mean and standard deviation of oak index for P1 were replaced by mean and standard deviation of instrumental data for P2, at second, role of subperiods was reversed.

Skill of reconstruction was tested by R^2 (explained variance), RE (reduction of error) and CE (coefficient of efficiency) statistics (*Cook et al.*, 1994). Values of R^2 are between 0 and 1. Higher value indicates more similarity, 1 means one series is the function of the others and vice versa. Potential values are $-\infty < RE,\ CE < 1$. If $RE > 0$ $(CE > 0)$ it means that reconstruction better approximates data of the verification period than the mean of the calibration (verification) period. Obviously, CE is the more rigorous statistics.

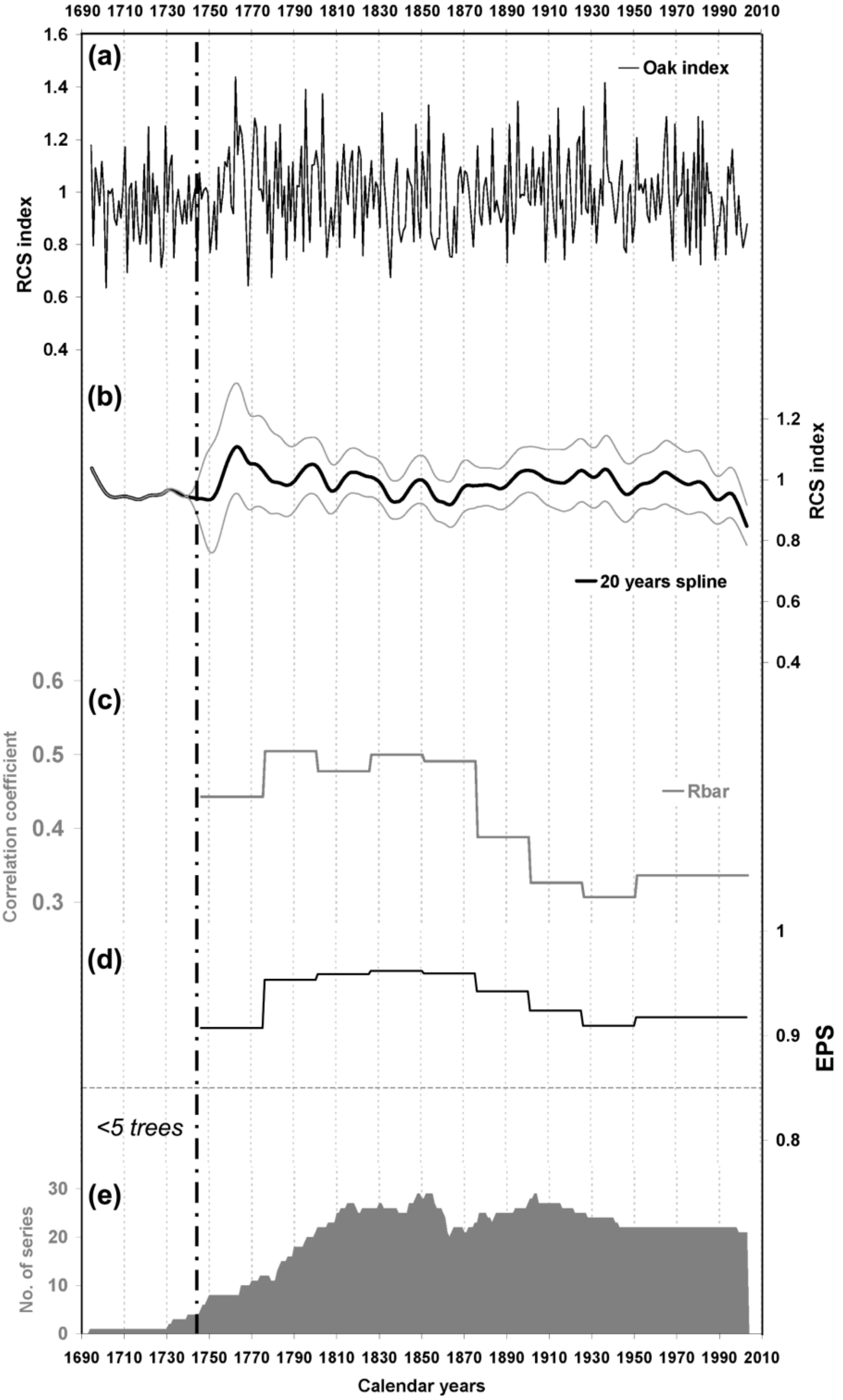

Fig. 3. Standardized oak index (a) and some signal strength statistics. (b) 20 years low pass filtered (cubic smoothing spline) indices. Light grey curves denote the bootstrapped 95% confidence interval. (c) Mean interseries correlation (Rbar). (d) Expressed population signal (EPS). Dashed horizontal grey line indicates the 0.85 level. (e) Sample depth. Dash dotted vertical line indicates 1745 AD. Before this date less than five trees build the chronology.

Two types of error were assigned as source of uncertainty (*Esper et al.*, 2007). On the one hand, chronology error was converted from the 95% confidence interval of the chronology (*Fig. 3b*). On the other hand, two standard error ranges derived from regression of 20 years smoothed reconstruction vs. instrumental data were regarded to quantify the 95% uncertainty designated as calibration error. Error terms were determined separately.

2.4. Independent precipitation reconstructions

Seven-graded monthly, seasonal, and annual precipitation indices were developed from documentary evidences for the Hungarian Kingdom (*Rácz*, 1999, hereafter R99) and available in printed form (*Rácz*, 2001). From the European gridded multi-proxy precipitation reconstruction (*Pauling et al.*, 2006, hereafter P06) seasonal totals could be extracted for the grid-cell (46.25°N; 17.25 × 46.75°N; 17.75°E) covering the studied area via internet (Climate Explorer (*van Oldenborgh et al.*, 2005)). R99 spans 1500 –1850, while R06 spans 1500 –2000.

3. Results

3.1. Characteristics of the TRW data

Chronology is still based on less than five trees before 1745. To avoid unreliable signal due to low replication, reconstruction is restricted to the well replicated period. Maximum replication is 29. Replication reaches its maximum level in three short periods, namely, 1903 – 04, 1852–55, and 1848 – 49 (*Fig. 3e*). Mean Rbar is 0.42 and mean EPS is 0.94 over the 1746 –2003 period. Minimum Rbar is 0.306 during the 1925 – 1960 period. A parting point (1875) appears in the Rbar statistics. Before this date, Rbar values are much higher than after. It indicates stronger common signal in the earlier part of the chronology when role of historical series is more dominant. This finding confirms the strict and excellent crossdate of the historical TRW series. EPS is steadily over the signal acceptance threshold (0.85) over the entire observation indicating robust chronology (*Fig. 3d*).

3.2. Relationship between oak index and precipitation

Correlation analysis revealed highly significant positive relationship between oak growth and May–June monthly precipitation of the year of tree-ring growth. The correlation coefficients are 0.36 and 0.41, respectively, exceeding the 99.9% significance level (*Fig. 4*). Calculating bimonthly (MJ) cumulated precipitation, the correlation coefficient reached 0.57 for the 1900 –2003 period. All remaining months developed coefficients below 99% significance level. However, it is worthy to note that from August of previous year (pAug) to July, each coefficient is positive. Some of them (e.g., pDec, July) are above or (e.g., pAug, pSep) just slightly below the 90% significance level. This perception motivated the calculation of an annualized total precipitation summing monthly totals from previous August to current July. Involving this annualized precipitation into the analysis, correlation coefficient has even further improved (0.62). We can conclude that precipitation of May and June is the main growth regulator factor for oak growth in the southern Bakony Mts. and the Balaton Highlands, but moisture regime of complementary part of the previous August–current July period has also important effect. In the further steps, oak indices are to be calibrated against the annualized (i.e., previous August – current July) precipitation totals.

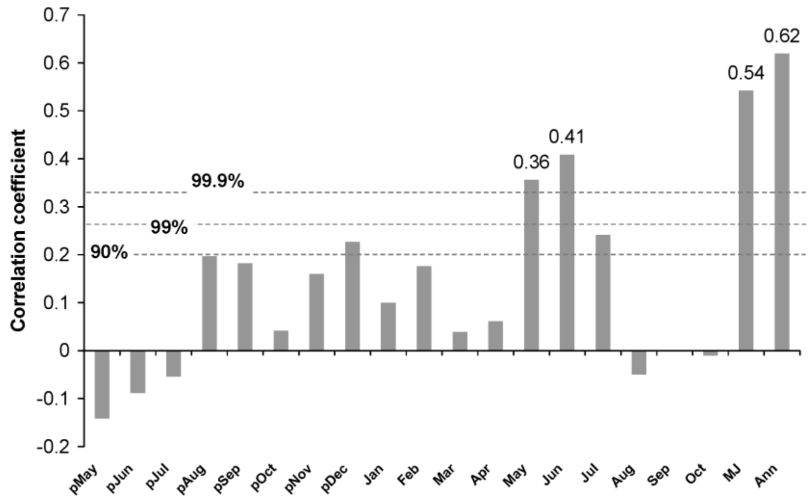

Fig. 4. Correlation coefficients computed between monthly precipitation and oak tree-ring index. Dashed horizontal lines denote 90%, 99%, and 99.9% significance levels for n=104 (1900 –2003). Abbreviated months with 'p' mark months in the preceding year to formation of tree ring. 'MJ' means May–June bimonthly precipitation total. 'Ann' means annualized precipitation total summed from August of the previous year of growth to July of the current year. In the case of 'Ann' and months of previous year, comparison was restricted to 1901–2003.

3.3. Calibration and reconstruction

Split period calibration/verification procedure ensured the stability of reconstruction utilizing the rescaling technique (*Fig. 5*). RE and CE statistics yield above zero values in each case. In addition, verification statistics are fairly high, and squared correlation (R^2) exceeds the RE value settling any doubts about spurious significance (*McIntyre* and *McKitrick*, 2005).

As rescaling technique was well verified, final reconstruction (hereafter called OAK) has been prepared as mean and variance of oak index for the entire instrumental period (1901–2003) were set equal to mean and variance of regional precipitation (*Fig. 6a*).

The wettest and driest reconstructed years are 1795 (1033 mm) and 1768 (396 mm), respectively. The wettest decade in the OAK reconstruction is 1795 – 1804 (785 mm/yr). Driest decade on record is 1746 –55 (613 mm/yr) and the second one is 1855 – 64 (620 mm/yr) (*Table 1*, *Fig. 6a*).

In general, a gradual long-term decreasing trend emerges as the dominant pattern of past changes. The trend seems to accelerate since the 1970s.

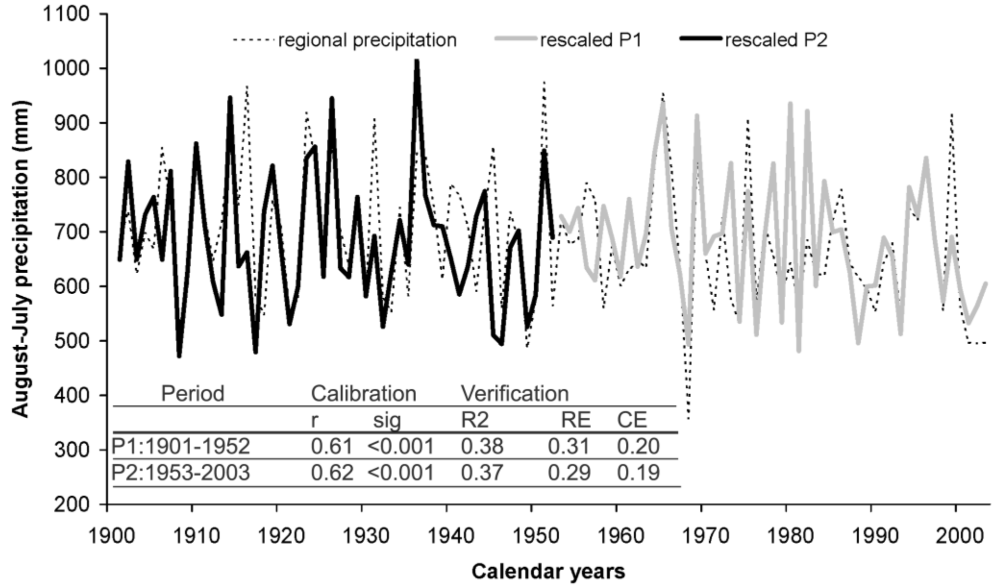

Fig. 5. Temporal stability of reconstruction by rescaling technique was tested. Dotted line: regional August–July precipitation. Grey line: estimated August–July precipitation rescaled by P1 period. Black line: estimated August–July precipitation rescaled by P2 period. Inset table: Split period calibration/verification statistics. r: Pearson's correlation coefficient, sig: significance of 'r', R2: explained variance, RE: reduction of error, CE: coefficient of efficiency.

4. Discussion

4.1. Extreme events and trends of past precipitation

On interannual scale, weak similarity can be found in extremes between instrumental and tree ring derived record (*Table 1*). Solely the driest instrumental year (1968) appeared and ranked third among the extremes of the modern part of OAK. Much more concurrences were found in the set of extreme decades. The driest rescaled decade is practically corresponding to the second driest instrumental one. Third driest decade is the same, but the driest decade from the instrumental period has also prominent place, ranked fourth, in the rescaled record. In addition, the wettest instrumental decade agrees, within a year shift, with the second one from the modern part of the rescaled record. Finally, the wettest rescaled decade significantly overlaps the third wettest instrumental one. Same as the instrumental data, each of the three rescaled driest decades appears in the second half of the century and practically the total post-mid-1980s period, covered by two non-overlapping decades, ranked into the drought top three. These correspondences further confirm the successful preservation of low-frequency precipitation signals in the OAK.

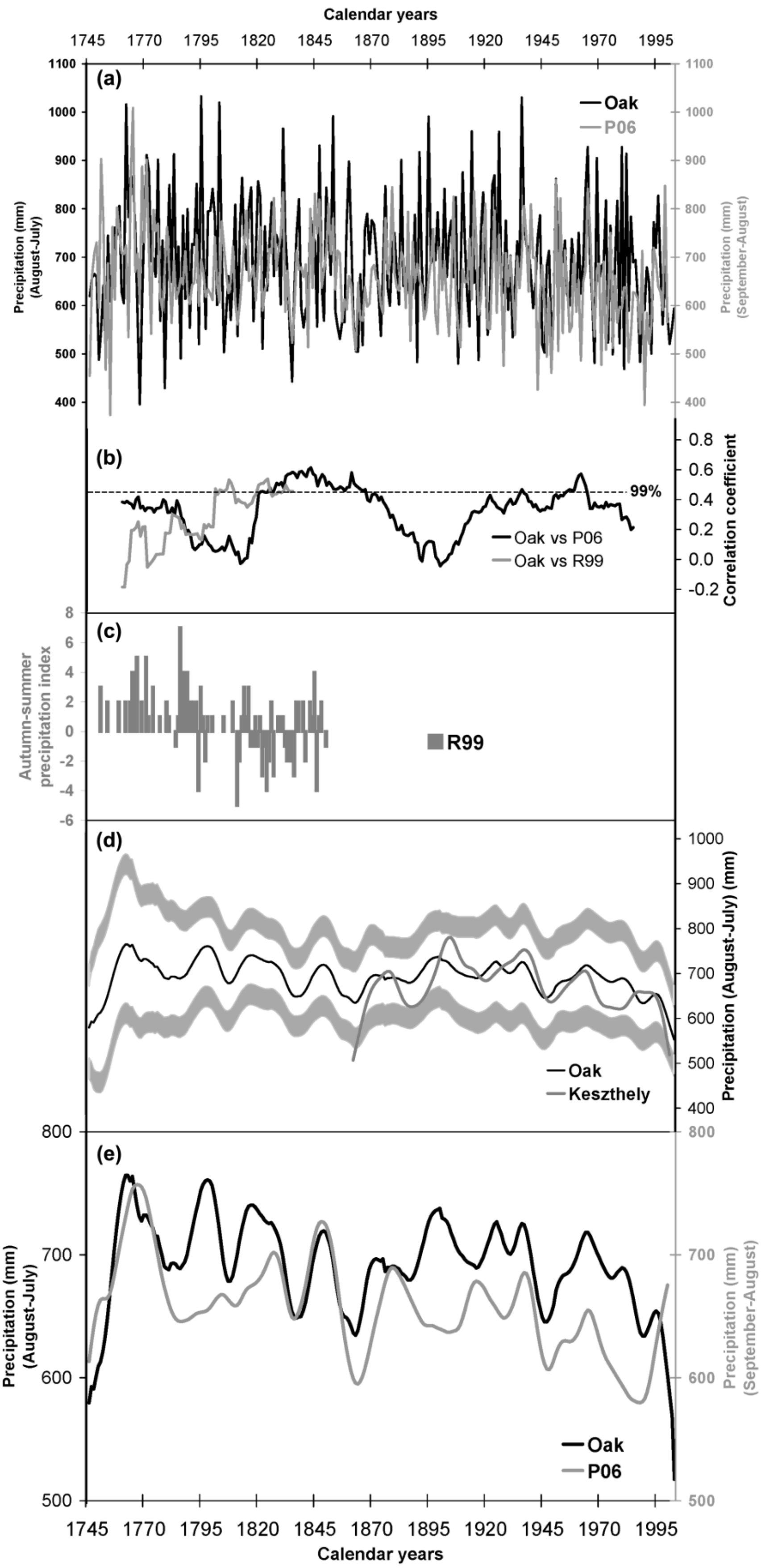

Fig. 6. (a) Reconstructed……→

Table 1. Three most extreme years and non-overlapping decades are listed from the instrumental and reconstructed era. Date in the 'year' column refers to the period from the previous August to the current July (i.e., 1968 means the period from August 1967 to July 1968). Date in the 'decade' column refers to the period from August ten years before to the current July (i.e., 1976 means the period from August 1965 to July 1976). 'Instrumental' means regional mean precipitation calculated from gauge records (see Section 2 for details)

		Instrumental (1901–2003)		**Rescaled (1901–2003)**		**Reconstruction (1746 –1900)**	
		Year	**Decade**	**Year**	**Decade**	**Year**	**Decade**
Dry	1	1968	1976	1981	1994	1768	1755
	2	1949	1993	1908	1950	1779	1864
	3	2002	2003	1968	2003	1835	1842
Wet	1	1951	1945	1936	1927	1795	1804
	2	1916	1919	1914	1944	1803	1766
	3	1965	1932	1926	1973	1762	1821

Peering the extreme years in the reconstructed period, 1835 is nicely coinciding with the driest detected summer since 1800 in the eastern sector of Alps (*van der Schrier et al.*, 2006). The second driest (wettest) year was found as strong negative (positive) anomaly in reconstructed June aridity in southeast Slovenia (*Čufar et al.*, 2008).

The first studied decade was reconstructed as the driest one, but due to the larger uncertainty (mostly due to the widening chronology error (*Fig. 6d*)), absolute values are still less reliable. However, the second driest decade on record is a prominent dry period in the Alps (*Casty et al.*, 2005), especially in the eastern Alps (*Auer* and *Böhm*, 1994; *van der Schrier et al.*, 2006). Extreme Transdanubian drought from the late 1850s to the mid-1860s is nicely corroborated by documented desiccation of the lake Fertő (*Kiss*, 2001, 2004).

The wettest and the third wettest decades are in line with the statements of *van der Schrier et al.* (2006), as the first two decades of the 19th century was exceptionally wet periods also in the eastern part of the European Alps.

Fig. 6. (a) Reconstructed August–July precipitation of the Balaton Highlands and the southern Bakony Mts. over 1746 – 2003 based on oak ring widths (black line) and autumn-summer (previous September – current August) precipitation of the corresponding grid-cell of the P06 (*Pauling et al*., 2006) reconstruction. (b) Coefficients of 31 years sliding window correlation computed between tree-rings based reconstruction and P06 (black) and R99 (grey). Dashed horizontal line denotes the 99% significance level. (c) Columns represent indices of the R99 reconstruction (*Rácz*, 1999). (d) Low-pass filtered (20 years cubic smoothing spline) reconstruction (black) and Keszthely gauge record (dark grey). The 95% uncertainty interval is presented as two separate bands related to chronology error (white) and to calibration error (grey). (e) Low-pass filtered (20 years cubic smoothing spline) tree-ring based reconstruction (black) and P06 (grey).

The longest continuous gauge record (Keszthely) was smoothed by a 20 years low-pass filter to verify the low-frequency signal of TRW based reconstruction (*Fig. 6d*). The independent record fits very well the fluctuation of OAK. Keszthely record excurses out from the range of uncertainty, solely, during its early decade. Though the ‘low value’ patterns are coherent between the records, it might be suspected that extreme low early gauge records are suffered from some negatively biasing homogeneity problem. Nevertheless, the similarity found with this independent record further confirms the fidelity of the oak ring width based precipitation reconstruction from the Balaton Highlands and the southern Bakony Mts.

4.2. Comparison with independent data

For the sake of better comparability of OAK, representing previous August–current July precipitation total as discussed above, with the seasonally resolved R99 and P06 ones were also annualized. Seasonal precipitation totals for P06 and indices for R99 were summed over the autumn-summer periods, respectively. By this way R99 and P06, in this study, differ from the original annual values of the reconstructions. Here they, indeed, represent the previous September– current August period. The one month shift in the theoretical time window of the reconstructions compared to OAK is unlikely to significantly affect their similarity or dissimilarity. Note that from 1800 to 1808 and before 1776, gaps are present in R99.

Sliding window correlation analysis revealed that OAK reconstruction and R99 shows significant similarity back to ~1800 (*Fig. 6b*). Similarity declines abruptly before. Observed worsening of relationship partially could be a consequence of gaps in R99. But we are to note that R99 gathered written evidences, practically, from the entire Carpathian Basin, so inherently and artificially reduced the ability to mirror reliably past changes on smaller spatial scales. For instance, 1786 designated as the wettest year in the observed period of R99 (*Fig. 6c*), based strongly on written evidences from the region of Miskolc and Sárospatak (northeast Hungary) (*Rácz*, 2001) and, in contrast, ranked seventh driest year by OAK during the reconstructed period in the southern Bakony Mts. (*Fig. 6a, b*).

Sliding window correlation analysis revealed that OAK reconstruction and P06 shows stable and significant similarity between ~1810 and ~1870 and quite well similarity (fluctuating around the 99% significance level) back to ~1920 (*Fig. 6b*). P06 lacks similarity in their interannual variability from the 1780s to 1810s and from the 1870s to the 1910s. Same periods present also the largest discrepancy in the low-frequency variability. In the latter case, the Keszthely gauge record verifies the fluctuation of OAK reconstruction. So we dare to conclude that P06 poorly reconstruct the fluctuation of precipitation during the above mentioned periods over the Balaton Highlands and the southern Bakony

Mts. region. After the 1910s, P06 presents similar fluctuations as OAK, but absolute values are consecutively below OAK (*Fig. 6e*). Another strange feature with P06 is that the trend for the recent decades is opponent with OAK. This sharply decreasing trend of OAK is verified by the local gauge records (*Fig. 4*, *Fig. 6d*). Since P06 also based on station data in recent century, an inadequate interpolation technique or non-representative station selection problem might be suspected.

However, the low precipitation at the earliest part of the record is coherent with P06 confirming the existence of the dry conditions during the late 1740s. In addition, the secular record of wet in the 1760s and the gradual decreasing trend since that time also agree in these independent precipitation reconstructions from the Balaton Highlands and the southern Bakony Mts. region.

5. Conclusion

We have presented a dendroclimatological reconstruction of August–July precipitation for the Balaton Highlands and the southern Bakony Mountains region since 1746. The reconstruction based on 22 living and 32 historical tree-ring width series from oak (*Quercus* sp.) samples. Ring width series were standardized by regional curve standardization technique (*Briffa et al.*, 1992; *Esper et al.*, 2003), regarding the biological character of oak's growth in the standardization procedure. By this way the low frequency climatic information was also effectively preserved in the tree-ring index.

A steady decrement has been appeared as an overall trend in the precipitation fluctuation since the mid-1700s. From this main pattern the 1840s, 1860s, and 1940s stand out as drier periods. The 1740s preceding the onset of this decreasing trend likely was also very dry. Derived precipitation reconstruction placed the late-20th century dry period into a secular context and suggests that the post-1980 drought period is unprecedented since 1746 at least. The low-frequency trend of the reconstruction from the mid-1800s century was verified by comparison with the longest nearby gauge record (Keszthely 1861–2001).

Present study pointed out weaknesses of two earlier precipitation reconstructions for the investigated region. A reconstruction developed on the base of written evidences (R99) aggregated documentary data over wide spatial distance, namely the entire Carpathian Basin, so owing to this methodological step, peculiarly in the case of precipitation, potential of R99 to detect past climate changes in local to regional scales has significantly reduced.

Data extracted from the corresponding grid from the European multi-proxy precipitation reconstruction (P06) showed poor similarity with this local reconstruction from the 1780s to the 1810s and from the 1870s to the 1910s. In addition, some problem (inadequate interpolation, non-appropriate station selection) during the instrumental era also might be suspected.

Reconstructed long-term gradual reduction of the precipitation associated with a changing seasonality (i.e., enhancing Mediterranean character (*Fogarasi*, 2004)) underlines that the climate of the Balaton Highlands and the southern Bakony Mts. significantly changed during the past centuries. Scenarios predict increasing aridity for Hungary (*Bartholy et al.*, 2004, *Gálos et al.*, 2007), especially over Transdanubia (*Szalai* and *Mika*, 2007) in future decades. Present results call the attention that agriculture and forestry have to face with this altered moisture regime by heavily depleted groundwater reservoirs.

Presented precipitation reconstruction also serves an objective basis to assess climatic conditions related to past historical events. Finally, we note that further improvements (e.g., extending the reconstructed time-span and reducing uncertainty) are possible and in progress.

***Acknowledgements*—**The research was funded by OTKA T43666 and OTKA K67583. Budapest Tree-Ring Laboratory contribution No. 18.

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