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April–August temperatures in the Czech Lands, 1499–2012, reconstructed from grape-harvest dates

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Abstract. Viticulture has long been essential to the commercial and social well-being of parts of the Czech Lands (recently the Czech Republic), and detailed records have been kept for centuries of the timing and relative success of the grape crop. Using such documentary data from the Bohemian wine-growing region (mainly north-west of the capital, Prague), series of grape-harvest dates (GHDs) were created for the 1499–2012 period. Because warmer temperatures lead to earlier harvest dates and vice versa, GHD series, together with instrumental mean temperature series starting in 1801, were used to reconstruct mean April–August temperatures for the region from 1499 to 2012. Linear regression (LR) and variance scaling (VS) methods were used for calibration and compared in terms of explained variance and their ability to capture extreme values. It emerged that LR does not significantly underestimate temperature variability. However, VS shows far greater capacity to capture extremes. GHDs explain 64% of temperature variability over the full calibration period. The 1971–2012 period was identified as the warmest of the past 514 years, an observation consistent with recent global warming. The highest April–August temperatures appeared in reconstruction for the year 1540, which was warmer than the next two very warm, and far more recent, seasons in 2000 and 2003. The coldest period occurred at the beginning of the 20th century (1900–1929). The series reconstructed for the Czech Lands is in close agreement with other (central) European reconstructions based on other proxies. The series created here makes an important contribution to a better understanding of long-term spatio-temporal temperature variability in central Europe.

1 Introduction

A specific set of climatic circumstances is crucial to the achievement of complete vine grape maturation, and climate variability determines year-to-year differences in the yield and quality of the wine produced (Jones and Hellman, 2003). Temperature and solar irradiance are particularly critical variables, since they have a direct effect on the length of the growing season, phenological stages, grape yields, and the synthesis and accumulation of sugars, organic acids, polyphenols, vitamins and aromatic compounds in the berries (Jones et al., 2005; Keller, 2010). The warming trend in recent climate change has accelerated ripening and induced changes in grape composition (Jones et al., 2012).

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Documentary data may provide important proxies for the study of past climate evolution (Brázdil et al., 2005, 2010; Jones et al., 2009). Grape-harvest dates (GHDs) are well suited to the reconstruction of interannual variations in spring/summer temperatures over large parts of Europe. The prevailing temperatures during the stages before flowering and *veraison* (colour and profound composition changes) have been established as the most influential upon GHDs (Chuine et al., 2004; Garcia de Cortázar-Atauri et al., 2010). GDHs have been used for reconstruction of temperature series in France (Le Roy Ladurie and Baulant, 1980; Chuine et al., 2004; Le Roy Ladurie, 2005; Menzel, 2005; Etien et al., 2008; Garnier et al., 2010), Switzerland (Pfister, 1981, 1984; Burkhardt and Hense, 1985; Meier et al., 2007), Germany (Glaser and Hagedorn, 1991), Austria (Strömmer, 2003; Maurer et al., 2009), Italy (Mariani et al., 2009) and Hungary (Kiss et al., 2011).

Daux et al. (2012) created an open-access dataset of GHD data from different parts of Europe. However, when addressing GHD series, a number of uncertainties should be taken into account, largely associated with changes in varieties, viticulture techniques, climatic impacts on vines at interannual and decadal scales, and missing data (Meier et al., 2007; Garcia de Cortázar-Atauri et al., 2010; Krieger et al., 2011).

Wine production in the Czech Lands (since 1993 the Czech Republic) is limited to two regions – southern Moravia and north-western Bohemia. In an analysis of the long-term viticultural data available in the Czech Lands, Brázdil et al. (2008) concluded that temperature reconstruction prior to AD 1800 was rendered difficult by insufficient data coverage. However, newly-acquired records of grape-harvest days from the Bohemian wine-growing region have now allowed a longer-term chronology of GHDs to be created, and it makes extended temperature reconstruction possible. In the light of this, the aim of this study is a reconstruction of April–August temperatures for the Czech Lands over the 1499–2012 period. This contribution describes the area studied and outlines basic data and methods used for reconstruction (Sections 2 and 3), presents a new Czech temperature reconstruction, its fluctuations and some comparisons with other temperature reconstructions in Central Europe (Section 4) and discusses the results achieved (Section 5). The final section contains some concluding remarks.

2 Area and data

The Czech Republic is located in central Europe and is characterised by a moderate, humid climate, with the year divided into four distinct annual seasons (Tolasz et al., 2007). The Bohemian wine-growing region is comparatively small, situated near the capital Prague in the north-west of the country, near the Vltava, Ohře and Elbe rivers. It features protected slopes facing south, south-west and south-east at elevations between 170 and 260 m. The vineyards are located around the city of Prague and the towns of Litoměřice, Roudnice nad Labem, Mělník, Most, Slaný, Kutná Hora, Louny and Karštejn (Fig. 1a). In the environmental conditions prevailing in recent times in the Czech Republic, the significant phenophases of vine (*Vitis vinifera*) occur on the following days on average: leaf-bud burst on 20 April–8 May, beginning of flowering on 5–15 June, end of flowering on 15–26 June, and softening of berries on 1–29 August (Hájková et al., 2012). The mean annual temperature achieves 8.7°–8.9°C and the mean annual precipitation totals are 480–540 mm (1961–2000 period) in the area studied.

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Tradition has it that the first Czech vineyard, near the town of Mělník, was established by St. Wenceslas (907–935), King of Bohemia, considered the patron saint of the Bohemian wine-growing region (Fig. 2a). In the year 1358, Emperor Charles IV (1316–1378) contributed an essential stimulus when he decreed that vineyards should be established wherever suitable. He brought Burgundy grape varieties to Bohemia and gave a twelve-year exemption from taxes to those who started vineyards (Kraus et al., 2005).

For 1845 to the present, the relevant GHDs were taken from the PHENODATA database of the Czech Hydrometeorological Institute (CHMI), which includes systematic phenological observations from several hundred sites across territory of the recent Czech Republic from 1845 onwards (Svitáková et al., 2005). For the period prior to this, GHDs were obtained from chronicles, documentary records kept by town authorities, documentary records of aristocratic origin (in particular from the Lobkowicz and Nostitz families), ecclesiastical documentary records (Archdiocese of Prague, Order of Cistercians), farming calendars, personal diaries, farming records, and reports. Among the earliest records are those from the towns of Litoměřice (Smetana, 1978) and Mělník (Böhm, 1892), and financial records kept for Bohemian viticulture (e.g. Schams, 1835; Šimáček, 1891; Honzík, 1897). For example, documentation for the year 1602 records: “Beginning of grape harvest on 14th October, harvest lasted for nine days, good wine” (Lobkowicz records); “Grape harvest on 15th October, grape-picking lasted eight days, wages paid for six men and forty-two women” (Mělník records); and “Harvest of sacramental wine on 16th October” (Archdiocese of Prague records). Each town had a wine grower’s guild that organized the beginning of the grape harvest. For example, the Mělník town guild started in 1542; numerous relics of its work survive, including written records (Fig. 2b–c).

Records of GHDs for the Bohemian wine-growing region were thus ascertained for the 1499–2012 period (Fig. 1b). In total, 5,363 harvest dates from 61 sites were collected. The majority of observations go back to 1921, whereas relatively fewer data are available before 1700. There are no temporal gaps; at least one entry was found for each year. The mean GHD time series for the 1499–2012 series was taken as a median value for all site data in the given year.

Mean monthly Czech temperature series (Brázdil et al., 2012a, 2012b), derived for the 1800–2010 period, further extended to 2012, were used as a target climatological series for temperature reconstruction. To put the Czech April–August temperature reconstruction into a wider European context, the following temperature series were selected for comparison (only those starting in the 16th century):

1) AMJJA, central Europe, documentary data (Dobrovolný et al., 2010)
2) JJA, central Europe, various proxies (Luterbacher et al., 2004)
3) JJA, Low Countries, documentary data (van Engelen et al., 2001)
4) AMJJA, Swiss Plateau, grape-harvest dates (Meier et al., 2007)
5) AMJJA, Burgundy, France, grape-harvest dates (Chuine et al., 2004)
6) MJJ, Vienna and Klosterneuburg region, Austria, grape-harvest dates (Maurer et al., 2009)
7) MJJ, Közseg, Hungary, grape-harvest dates (Kiss et al., 2011)
8) MAMJJ, northern Switzerland and south-western Germany, grain-harvest dates (Wetter and Pfister, 2011)

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9) MAMJJ, Czech Lands, winter wheat-harvest dates (Možný et al., 2012)

10) JJA, European Alps, multiproxies (Trachsel et al., 2012)

11) AMJJAS, western Europe, multiproxies (Guiot et al., 2005)

12) JJA, western and central Europe, tree-ring widths (Büntgen et al., 2011)

13) JJAS, Alps, tree-ring widths (Büntgen et al., 2006)

14) JJ, central-eastern Alps, tree-ring widths (Wilson and Topham, 2004).

3 Methods

The mean GHD series for the Bohemian wine-growing region was further used as a predictor for temperature reconstruction for the Czech Lands in the 1499–2012 period. Two approaches were taken to calibration: simple linear regression (LR) and variance scaling (VS). LR uses least squares estimation to minimize mean square error (MSE) between target data and reconstructed temperature. However, regression-based reconstructions usually underestimate the variability of reconstructed temperatures to a significant extent (Esper et al., 2005). Moreover, their capacity for capturing extreme values is limited. In contrast to regression, variance scaling (matching) re-scales proxy data to fit target measured temperatures by providing them with the same mean and variance over the calibration period (McCarroll et al., 2015). Thus VS reconstruction usually captures the full range of measured temperatures and also better reproduces extreme values. However, a higher MSE is a drawback of VS in comparison with regression.

Two statistical measures were employed herein to allow objective comparison of the two approaches above (McCarroll et al., 2015). In linear regression, squared correlation coefficient (r^2) compares MSE based on regression estimates with MSE based on the mean (climatology). Similarly, the equivalent variance explained (r^2_{vs}) compares MSE based on variance scaling with MSE based on the mean (climatology). The r^2_{vs} has a straightforward interpretation – if its value falls below zero, variance-scaled reconstruction has less skill than simply using the mean values of data over the calibration period. Moreover, differences between r^2 and r^2_{vs} measure the degree of loss in variance explained using VS-based reconstruction compared with LR-based reconstruction.

Extreme value capture employs a similar logic, comparing how many extreme years (defined, for example, as 10% of the highest and 10% of the lowest measured temperatures in the calibration period) are captured by either LR-based or VS-based reconstructions. The generally lower variability of regression-based reconstruction also means that its ability to capture the same extreme years is lower, while variance scaling may improve the ability to identify the same extreme years as occur in measured data. The extreme value capture approach tests whether the number of identified extremes in reconstruction is significantly higher than would occur by chance alone. For more details of calculation of equivalent variance and the extreme value capture, see McCarroll et al. (2015).

Final calibration was performed for the full period of overlap (1811–2010), for verification purposes divided into early (1811–1910) and late (1911–2010) sub-periods, and the two calibration/verification schemes for LR and VS deployed.

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Calibration was done on one of the sub-periods and verification undertaken on the other. The whole process was then repeated with calibration/verification sub-periods switched.

The quality of calibration was evaluated by means of the square of Pearson's correlation coefficient (r^2), which measures the degree of common variance explained and with Durbin-Watson test statistics (DW), which diagnoses the degree of first-order autocorrelation within the regression residuals; values between 1.5 and 2.5 are generally acceptable, while those outside this range indicate problems with reconstructing multi-decadal variations.

Verification was based on r^2, reduction of error (RE) and coefficient of efficiency (CE). RE indicates whether a reconstruction provides a better estimate of temperature variability than simply using the mean value of target temperatures in the calibration period. CE is similar to RE but it tests reconstruction skill against the mean value of target temperatures in the verification period.

The formulas for RE and CE calculation may be found elsewhere (Možný et al., 2012). Both RE and CE provide values between 1 and negative infinity. Positive RE and CE values indicate that the method examined has some potential for reconstruction and the result is better than simply using the mean of a given calibration/verification period as a "reconstruction".

Final LR-based reconstruction was completed with uncertainty estimates defined as two standard errors (SE) of estimates from the corresponding regression model, approximating to 95% confidence limits. The series reconstructed were compared with other European reconstructions using Pearson correlations for the whole common period as well as with running 31-year correlations to reveal periods with significant agreement in reconstructed temperatures.

4 Results

4.1 Czech temperature reconstruction based on grape-harvest dates

Fluctuations of GHDs in the Bohemian wine-growing region during the 1499–2012 period indicate that earlier harvest dates were found in 1991–2012 (Fig. 3). On a decadal scale, the earliest harvests occurred in 2000–2009 (mean, 28 September) and the latest in 1814–1823 (29 October). The earliest GHD of all was recorded in 1540 (11 September) and the absolute latest in 1919 (2 November). GHDs as early as 30 September occurred only very rarely: in the 16th century 10 times; in the 17th century 2 times; in the 18th century 5 times; in the 19th century 2 times; in the 20th and 21st centuries 11 times. GHDs later than the second half of October occurred more often: in the 16th century 29 times; in the 17th century 49 times; in the 18th century 52 times; in the 19th century 45 times; and in the 20th and 21st centuries 43 times.

The beginning of the grape harvest depends on the weather patterns of the preceding months and the closest relationship with GHDs in the 1801–2012 period appeared for mean April–August temperatures ($r^2 = 0.64$). Based on the results of the correlation analysis (Fig. 4), GHDs were calibrated to mean AMJJA Czech temperature series (Brázdil et al., 2012a, 2012b). Summaries of the calibration/verification processes for early (1811–1910) and late (1911–2010) sub-periods and for the full calibration period (1811–2010) and for LR and VS methods of reconstruction appear in Table 1 and Figs. 5–6.

The LR statistical measures applied confirm high reconstruction skill for GHDs in both sub-periods. The AMJJA temperatures explain 51% and 76% of GHDs variability for early and late calibration respectively. Results of the Durbin–Watson test indicate no problems with autocorrelation in residuals and standard error does not differ significantly for either of the sub-periods. Validation of these calibration results shows that RE and CE are highly positive both for early and late sub-periods and indicates that GHDs have a high potential for temperature reconstruction. Full calibration with the LR model explains 64% of common variability between GHDs and AMJJA temperatures, but also indicates some problems with autocorrelation in residuals in the DW test ($p < 0.05$).

The VS method, verified by the same RE and CE metrics, also confirms high reconstruction skill for GHDs. The two metrics give lower results than those from the LR method (Table 1), but they remain highly positive. Equivalent variance explained (r^2_{vs}) for VS method and the full calibration period is 0.61 which, compared with r^2 of the LR model, indicates that the scaling (variance matching) applied to GHD data involves only 6% of lost variance explained compared with LM. This indicates that the increase in mean square error for VS is quite small and insignificant.

Much greater differences between the two reconstruction methods become evident in comparison of the overall variability of reconstructed values with those of target data in the full calibration period. AMJJA temperature anomalies varied from –2.2°C (1919) to 2.7°C (2003) in the 1811–2010 period. The corresponding values for the LR model are –1.9°C (1919) and 2.5°C (2000) respectively and they confirm a general assumption that the regression reconstruction is biased towards the mean and underestimates the true variability of the target data. According to VS reconstruction, AMJJA temperature anomalies fluctuate from –2.4°C (1919) to 3.2°C (2000). Thus the range of the VS-reconstructed temperatures exceeds those measured in the common period of overlap (1811–2010).

Finally, both reconstructions were compared in terms of their ability to capture extremely low/high temperatures (Fig. 7). The same period (1811–2010) was examined and the 10% of years with the lowest (20 years) and the highest (21 years) temperatures were defined as extreme. The maxima contain one more year than the minima because two years in the former reached equally high temperatures. The measured and reconstructed temperatures were arranged in order of rank and a comparison made to establish how many reconstructed extremes corresponded to their measured equivalents (Fig. 7). Whereas the LR reconstruction captured eight extremely cold years and nine extremely warm years, the VS reconstruction proved able to reproduce 11 cold and 17 warm extremes respectively. All the figures for the two reconstructions exceed the critical thresholds for the extreme value capture test ($p < 0.05$), after McCarroll et al. (2015). However, reconstruction based on scaling always performs far better than regression. It is noteworthy that both methods more readily indicate extremely warm years than cold ones. This finding is interesting in the light of comparison with a number of hydroclimate reconstructions (drought, precipitation) based on dendro-climatological data (Büntgen et al., 2011; Bronisz et al., 2012). The latter tend towards an enhanced ability to capture negative extremes, dry and hot conditions with circulation patterns

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favourable to warm climate during the growing season (Dobrovolný et al., 2015). Thus both types of proxy (documentary GHDs and TRW chronologies) exhibit enhanced sensitivity to warm conditions.

4.2 Fluctuations in Czech April–August temperatures

Annual and multi-decadal variations in the Czech April–August temperatures since AD 1499, reconstructed by the two methods appear in Fig. 8. Whereas certain differences at the high-frequency (annual) scale follow from the methods used and are described in the previous paragraphs, both approaches provide almost identical results at decadal and multi-decadal scales. This further confirms the high potential of GHD series for temperature reconstruction and also confirms the degree of robustness of reconstruction results.

Certain irregular variations in warmer and colder periods occurred during the 1499–2012 period. Significantly warmer periods (based on unsmoothed data) were found for the years 1516–1559 and 1971–2012 (Fig. 8). The first half of the 16th century was exceptionally warm, as indicated by early grape harvests. Four cycles of particularly chilly periods, beginning around 1649, 1740, 1805 and 1913, each separated by slightly warmer intervals, are detectable in reconstruction. In contrast, the coldest periods were recorded around 1820, 1840 and 1920. The warmest 30-year periods occurred in 1983–2012 (0.6°C mean) and the coldest in 1900–1929 (–0.5°C; both values based on LR reconstruction). Temperature fluctuations show great interannual and interdecadal variability and an increasing trend for the instrumental part of the series from the 19th century onwards, particularly pronounced since the 1970s.

4.3 Czech temperature reconstruction in the European context

The mean Czech April–August temperature reconstruction may be further verified by comparison with other Czech and European temperature reconstructions, as listed in Section 2. Such comparison may be influenced by the distances between regions or areas for which the reconstructions are representative; in general, correlation coefficients decrease with increasing distance (see Fig. 5 in Dobrovolný et al., 2010). Direct comparison is also complicated by variations in seasonality, i.e. the selection of months used for averaging in individual reconstructions.

Any common variability in reconstructed series was investigated by running correlations (31-year window) with 14 different series (Fig. 9). A rough categorization into five groups may be made, according to the dominant types of proxy: documentary-based, grape-harvest dates, grain-harvest dates, multiproxy, and tree-rings.

For Czech territory, GHD reconstruction may be correlated with mean Czech March–June temperatures reconstructed from winter wheat-harvest dates (WWHDs) (Možný et al., 2012), giving an overall correlation of 0.52 ($p < 0.05$). The relationship between these two Czech reconstructions becomes weaker in the light of several considerable drops in running correlation coefficients around 1600, 1675, 1730, 1770, 1900 and 1980. The earliest WWHDs occurred in 2007 (4 July), 1516 (6 July), and 1521, 1535, 1539 and 1540 (7 July). Grain-harvest days in 1516 were affected by an extremely warm winter (Pejml, 1966; Brázdil et al., 2013). It is remarkable that the grain harvest in 1540 was, like the grape harvest, extremely early.

The reconstructed Czech April–August temperatures correlated best (r = 0.71) with the central European temperature series reconstructed from documentary data in Germany, Switzerland and the Czech Lands compiled by Dobrovolný et al. (2010). These relationships become weaker in the light of several considerable drops in 30-year running correlations occurring around 1750 and 1900. Similar periods of lower coherency are also evident for the summer reconstruction based on temperature indices derived from documentary data for the more distant Low Countries (van Engelen et al., 2001) and for a gridded summer reconstruction for central Europe (Luterbacher et al., 2004) which, however, employed more types of proxy than documentary evidence alone.

Decreases in running correlations in the mid-18th century and at the end of the 19th century (slightly earlier for the tree-ring group) appear to a greater or lesser extent in all five groups of the reconstructions compared. This indicates that there may be some problems in the quality of the GHD series for these periods. Viewing the reconstruction results as a whole (Fig. 8), markedly lower variability appears in the mid-18th century than in the parts of the series before and after that period. Additionally, GHDs after 1845 were compiled from the PHENODATA database, i.e. from a qualitatively different source of data than that which preceded it, a possible reason for lower correlations with other central European reconstructions. Correlation coefficients with tree-ring based temperature reconstructions are distinctly lower; however, two of them (Wilson and Topham, 2004; Büntgen et al., 2006) represent mountain positions in the Alps.

5 Discussion

The Bohemian wine-growing area lies among the northernmost parts of the European viticulture region, and the quality of its product is thus significantly vulnerable to temperature variability between seasons and years. A cold growing season results in a below-mean vintage, with unripe and inferior grapes of low quality, while warmer growing seasons improve the quality of grapes considerably. In terms of minimum temperatures, spring frosts that damage developing shoots and frosts after bud-burst, reducing the season's overall yield, are among the extreme events that have detrimental effects. Winter frosts below –12°C may severely damage or even kill fully dormant vines; the greater frequency of hard winters in the 18th and 19th centuries adversely affected both the revenues and profitability of viticulture in the Bohemian wine-growing region (Pejml, 1966). At the beginning of the 16th century, the Bohemian vineyards covered around 5,500 hectares. With deteriorating weather conditions, this area steadily declined to 3,300 hectares in the mid-18th century, falling to 700 hectares at the end of the 19th century, a figure that holds to the present day (Kraus et al., 2005). In the context of recent climate change (global warming), conditions for growing wine in the Bohemian area are improving, with positive effects on the quality of the wine.

The main grapevine varieties (Pinot, Traminer, Gouais, Riesling) have been cultivated in the Bohemian wine-growing region for the last six centuries (Sotolář, 2009). The Pinot varieties (Pinot noir, Pinot blanc and Pinot gris) have always been dominant in the region. In the past 30 years, the Müller Thurgau and St. Laurent varieties have also expanded. The long-term prevalence of Pinot varieties in the area more or less excludes the possible influence of changing varieties on temperature reconstruction.

Comparison of Czech April–August temperatures with other proxy-based temperature reconstructions reveals possible inconsistencies in the first part of the 16th century, as well as around 1650, 1750 and 1900 (Fig. 6). The first half of the 16th century, in response to warmer climate, saw particularly consistent early starts for the grain harvest in the Czech Lands (Možný et al., 2012). This warming allowed a northward extension of the Bohemian wine- and hop-growing regions and extensive cultivation of quite thermophilic plants, such as melons and almonds (Pejml, 1966). High summer temperatures in the Czech Lands during the first half of the 16th century are further confirmed by the results of temperature reconstructions for this century using series of temperature indices (Brázdil et al., 2013).

The recent Czech reconstruction fails to reflect a critical period for wine production in the late 16th century (Brázdil et al., 2013). Starting in the mid-1580s, a number of years produced small amounts of wine, of very inferior quality. This trend also appears in Landsteiner (1999), who documents a sudden drop in wine production in central Europe. A series of bad grape yields started in 1585 in Switzerland, in 1586 in Württemberg (south-western Germany) and in 1587 in Lower Austria and western Hungary. This decline was reflected in a significant drop in revenue derived from viticulture for the Austrian state. Moreover, wine cost more at the time and tasted less sweet, leading to a shift in consumer choice from wine to beer.

GHDs in the Czech Lands around 1650 (see Fig. 3) were enormously influenced by the Thirty Years' War (1618–1648) and its subsequent hardships. The war totally devastated the Czech Lands. The population decreased by a fifth (Wilson, 2009) and some historical reports estimate population declines as catastrophic as 80% in certain regions (Balbín, 1986). Moreover, GDHs were negatively affected by an increased frequency of late spring frosts, as has been documented for the 1640s and 1660s by Brázdil et al. (2008), for example. Temperatures decreased over the second half of the 17th century and the growing season shortened all over Europe (Hudson and Keatley, 2010). This period, corresponding to the Maunder minimum of solar activity (Eddy, 1976), is recognised as the coldest phase of the Little Ice Age (Grove, 2004; Matthews and Briffa, 2005).

The period following 1740 was also characterised by intense socio-political conflicts associated with the War of the Austrian Succession (1740–1748) and the Seven Years' War (1756–1763), with many of the key field campaigns of the period taking place on Czech territory. During the war years, grapes were harvested at the earliest possible onset of maturity to preclude damage from enemy troops (Kilián, 2009). These periods of strife render the year-to-year variability of GDHs around 1650 and 1750 far less visible (Fig. 3). Although the socio-economic consequences and loss of human life were not as acute as they had been ~100 years earlier, the countryside took the brunt of the damage. Peasant farms were burdened with increasing taxes, direct war damage and army recruitment, while many owners simply left their farms. The non-sustainability of the situation was expressed in an unusually high number of peasant uprisings demanding reduction of service-based tenure (socage) and consequent violent suppression of all rebellions. This constantly deteriorating situation culminated in what became known as the "hunger years" of 1770–1772, the result of adverse weather patterns, very bad harvests and socio-economic problems, when the population of Bohemia fell by *c.* 10% (Brázdil et al., 2001; Pfister and Brázdil, 2006).

The approach to vine growing and fermenting grapes changed in the late-19th century, affecting later harvest dates (Kilián, 2012). Wine-growers experimented for several years with harvesting a few days later, since sunny weather in October may have helped augment sugar content.

Comparison of Czech April–August temperatures reconstructed from GHDs and Czech March–June temperatures reconstructed from WWHDs is also worthwhile (Možný et al., 2012). Possible inconsistencies in the two reconstructions based on biophysical series are disclosed for the years around 1600, 1675, 1730, 1770, 1900 and 1980 (Fig. 6). Explanations may be related to recorded winter and spring frosts, which affected the harvest of winter wheat and grapes in different ways (Pejml, 1966, 1974; Možný et al., 2016).

The earliest grape harvest recorded for the Bohemian wine-growing region during the 1499–2012 period occurred in 1540. The harvest may have been brought forward by very warm weather, but this could also have been a response to drought. Pfister and Brázdil (1999) identified the 1530s and 1550s as the warmest decades for summers in the 16th century in central Europe, and the 1530s to 1550s as the driest. In fact, 1540, with its very warm, dry weather, has been documented and described as probably the most outstanding of its kind in the past 500 years in central Europe, was documented and described based on many documentary data (Glaser et al., 1999; Pfister, 1999; Brázdil et al., 2013). Based on the temperature estimates for Switzerland from a great number of coherent qualitative documentary evidence, confirm exceptional heat; Wetter and Pfister (2013) considered the spring–summer temperatures for 1540 probably more extreme in neighbouring regions of western and central Europe than those of 2003 when between 22,000 and 35,000 heat-related deaths were recorded across Europe (e.g. Beniston, 2004; Schär and Jendritzky, 2004; Stott et al., 2004; Fischer et al., 2007). More recently, Wetter et al. (2014) employed the term "megadrought" to the 1540 weather patterns in Europe, a coinage that led to some discussion in the tree-ring (Büntgen et al., 2015) and documentary data (Pfister et al., 2015) communities.

6 Conclusions

Central Europe is a region very rich in the types of documentary evidence that facilitate climate reconstructions for the pre-instrumental period (Brázdil et al., 2005, 2010). Such reconstructions, applying standard paleoclimatological approaches (e.g. Cook et al., 1994; Dobrovolný et al., 2009), are based either on series of temperature indices (Glaser and Riemann, 2009; Dobrovolný et al., 2010) or biophysical series (Meier et al., 2007; Maurer et al., 2009; Kiss et al., 2011; Wetter and Pfister, 2011; Možný et al., 2012). In this context, April–August temperature reconstruction for the Czech Lands based on GHDs in the 1499–2012 period constitutes a further important contribution to the better understanding of long-term spatio-temporal temperature variability in central Europe, as well as in the broader European context.

Advantages of the Czech temperature reconstruction include the very long overlap period (1801–2012) used for calibration/verification, a very high explained variability of 64% in the instrumental period of overlap, the consistent dominance of Pinot varieties through time and stability of vineyard management throughout the period reconstructed. On the other hand, variable density of records over the past 500 years and some social bias related to long-term development of viticulture, together with the socio-political situation in the Czech Lands over time, may partly influence the reconstruction. In the context of discussions related to the exceedingly warm and dry year of 1540 (Wetter and Pfister, 2013; Wetter et al., 2014; Büntgen et al., 2015; Pfister et al., 2015), it is important that this new reconstruction confirms the year as the warmest April–August in 1499–2012 in the Czech Lands. Moreover, recent global warming (Stocker et al., 2013) finds a local reflection in the new Czech series, with 1971–2012 the warmest period in the past 514 years.

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Table 1: Summary of calibration and verification statistics used for April–August temperature reconstruction based on grape-harvest dates for the Czech Lands: r^2 – explained variance, *SE* – standard error of estimate, *DW* – Durbin-Watson test, *RE* – reduction of error, *CE* – coefficient of efficiency; RE and CE were calculated for linear regression (LR) and variance scaling (VS).

Subperiods	*Calibration statistics*				*Verification statistics*			
	r^2	*SE*	*DW*	r^2	RE_{LR}	CE_{LR}	RE_{VS}	CE_{VS}
Early calibration (1811–1910)/ late verification (1911–2010)	0.51	0.52	1.9	0.76	0.66	0.53	0.71	0.60
Early verification (1811–1910)/ late calibration (1911–2010)	0.76	0.47	1.8	0.51	0.51	0.21	0.50	0.19
Full calibration (1811–2010)	0.64	0.54	1.6	0.64	–	–	–	–

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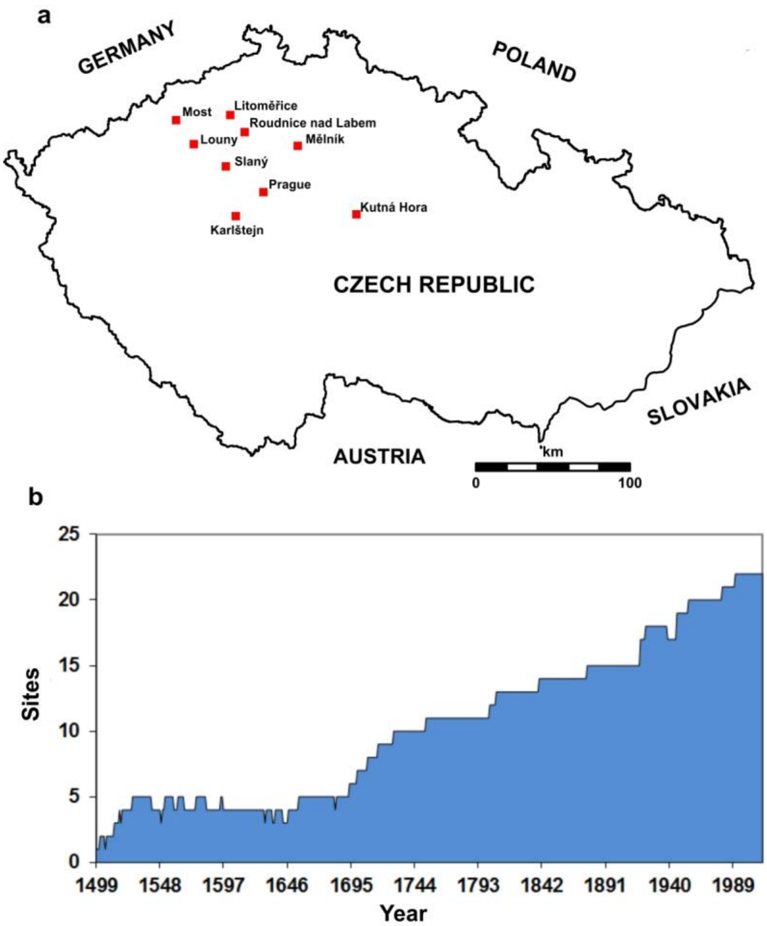

Figure 2: a) Map of the Bohemian wine-growing region, b) the number of sites of grape harvest observations for the 1499–2012 period in individual years.

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Figure 2: a) Oil painting of St. Wenceslas in a vineyard, 18th century; b) flag of the guild of wine-cultivators, 1762; c) insignia of the guild of wine-cultivators, 1676 (from the collections of the Mělník Regional Museum; photo M. Možný).

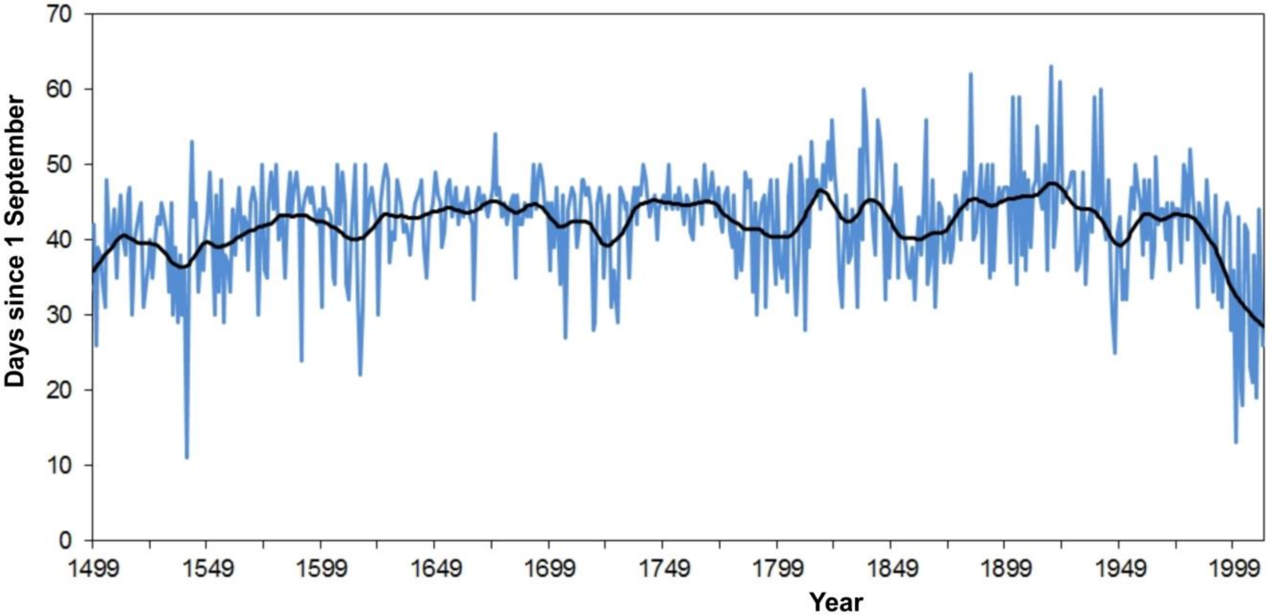

Figure 3: Fluctuations in grape-harvest days (in days after 1 September) for the Bohemian wine-growing region in the 1499–2012 period. Smoothed by Gaussian filter over 30 years.

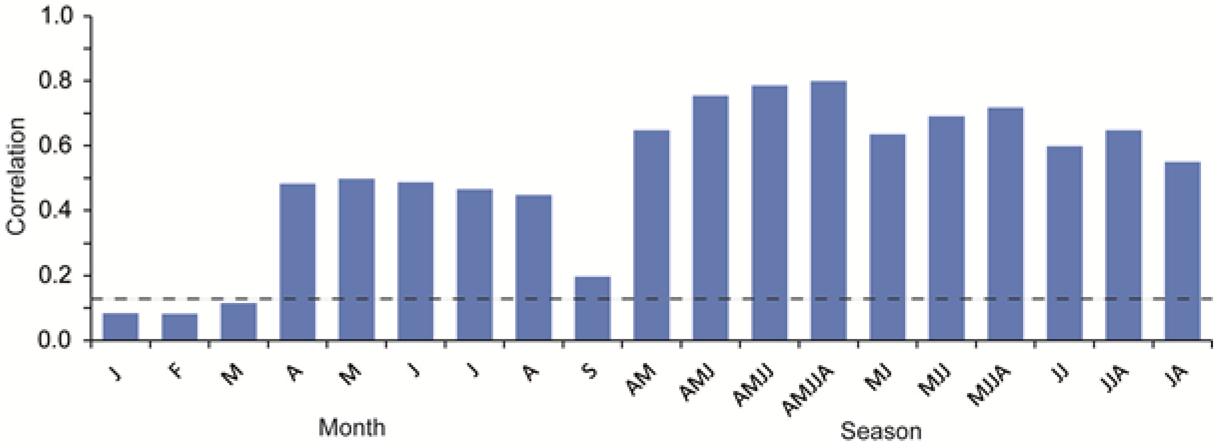

Figure 4: Pearson correlation coefficients between grape-harvest dates and Czech temperatures in the 1811–2010 period for months and seasons; broken horizontal line indicates significant correlations for one-tail test (p = 0.05, N = 200).

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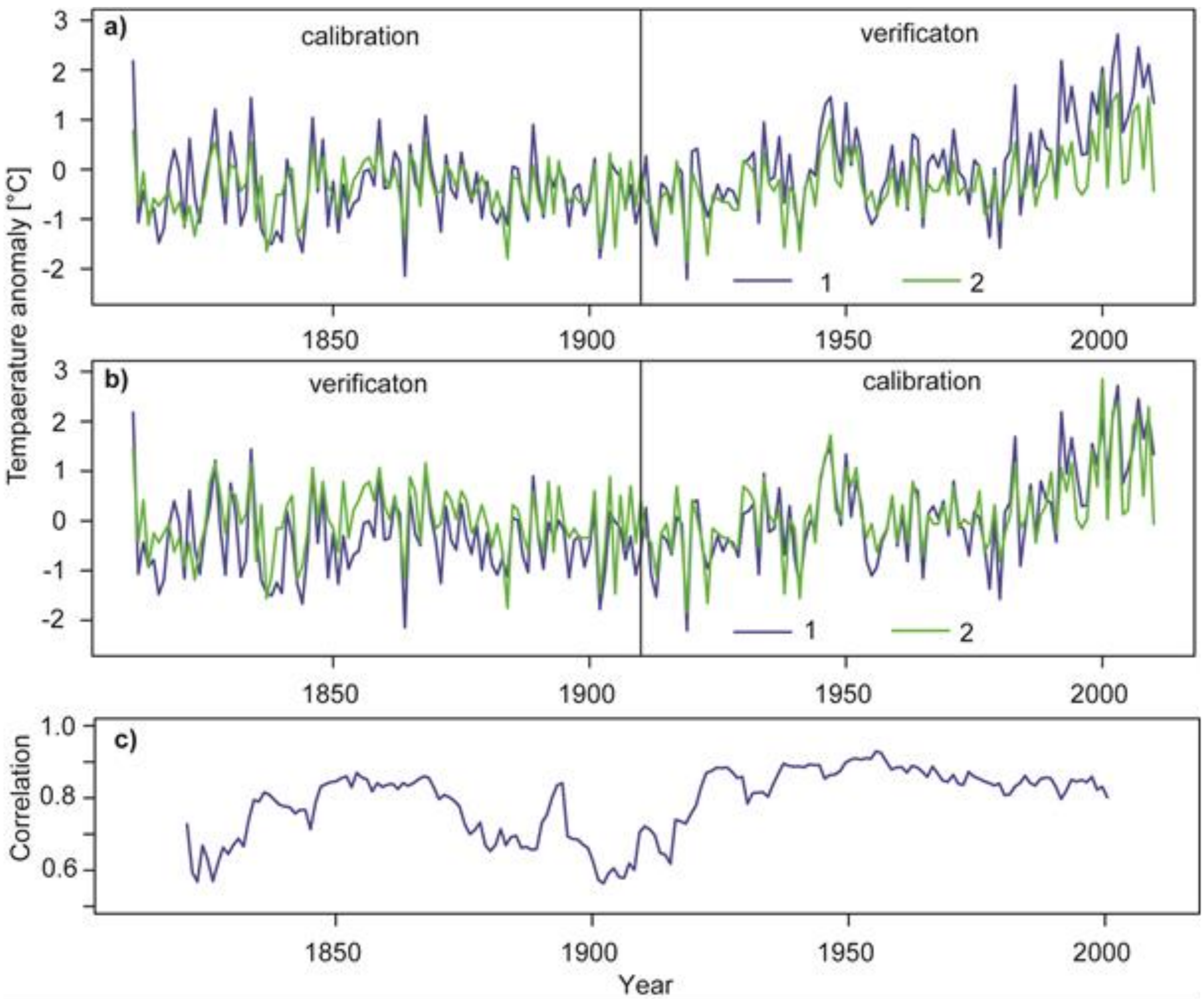

Figure 5: Comparison of measured (1) and reconstructed (2) mean Czech April–August temperatures: anomalies with respect to the 1961–1990 period. Linear regression method of reconstruction was performed for a) early (1811–1910) and b) late (1911–2010) calibration periods; c) running correlations (window 21) between mean Czech April–August temperatures and grape-harvest dates during the 1811–2010 period.

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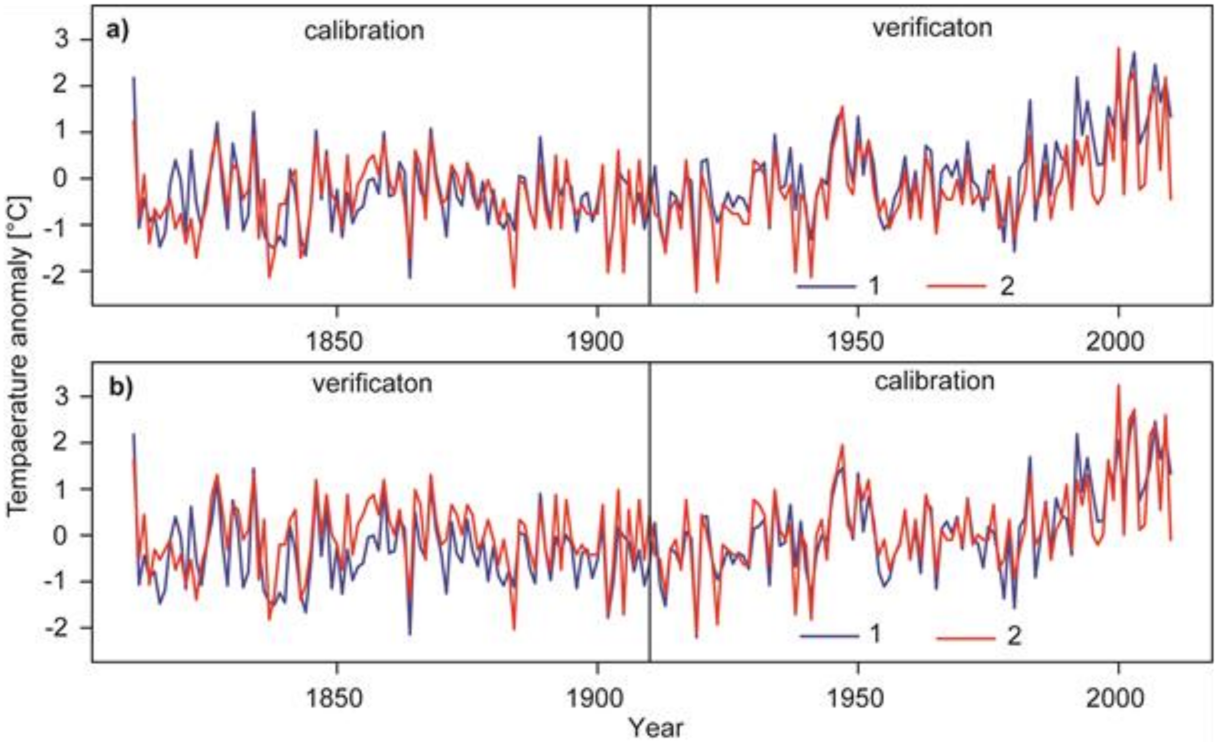

Figure 6: Comparison of measured (1) and reconstructed (2) mean Czech April–August temperatures: anomalies with respect to the 1961–1990 period. Variance scaling method of reconstruction was performed for a) early (1811–1910) and b) late (1911–2010) calibration periods.

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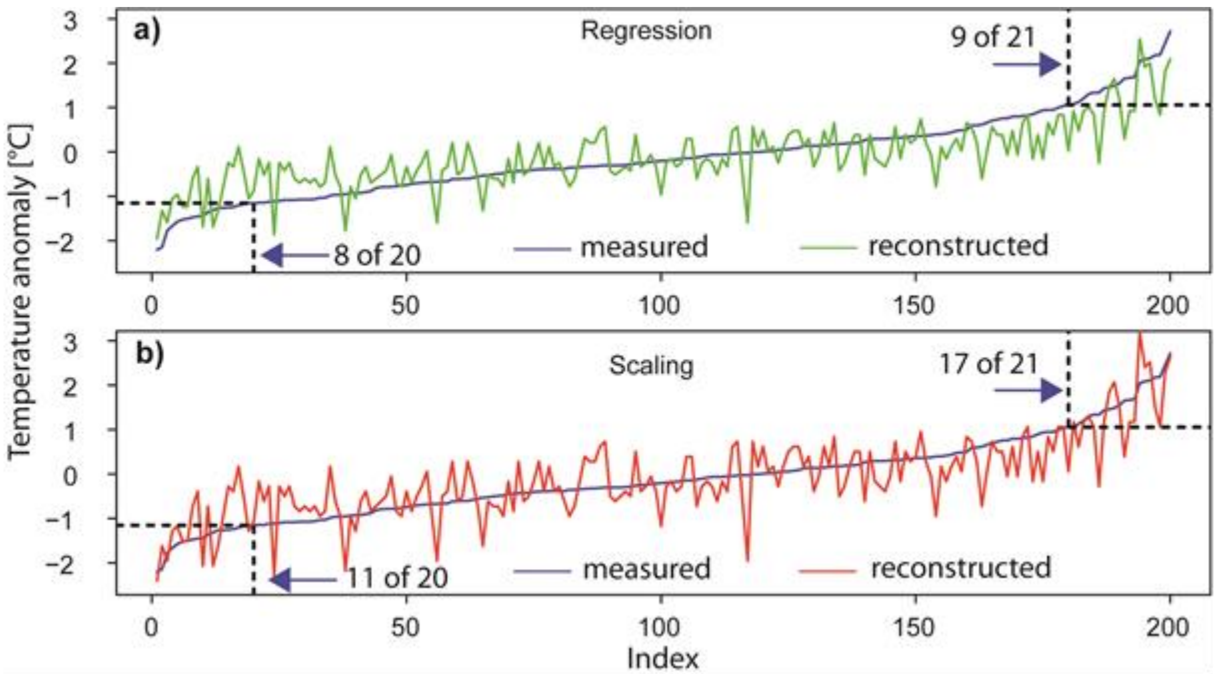

Figure 7: Comparison of measured (continuous blue line) and reconstructed temperatures using regression (a – green line) and scaling (b – red line) presented in rank order; dashed boxes indicate the upper and lower 10% portions of measured temperatures and numbers of these extremes reproduced in reconstructions.

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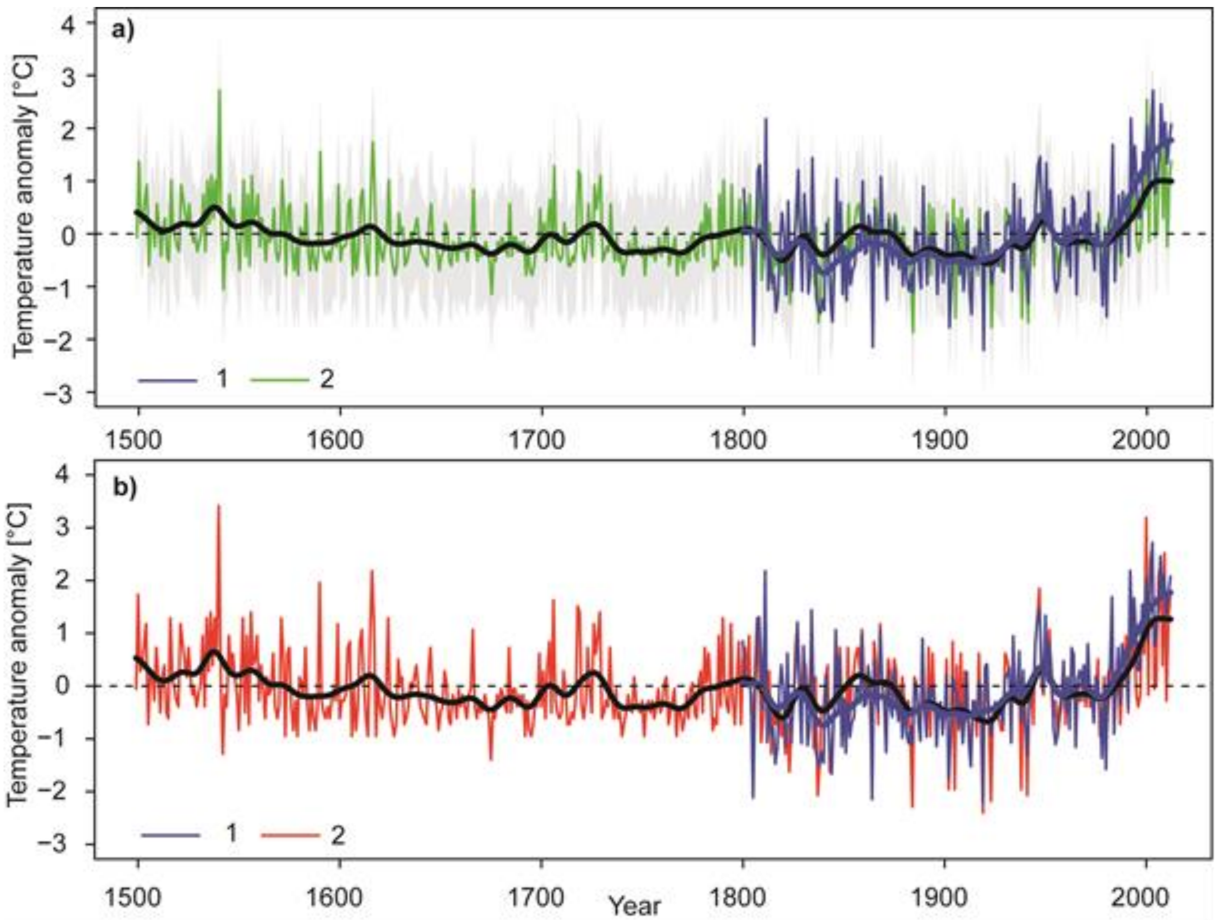

Figure 8: Measured (1) and reconstructed (2) mean Czech April–August temperatures in the 1499–2012 period using linear regression (a) and variance scaling (b); temperatures indicate anomalies with respect to the 1961–1990 period. Thick blue and black lines represent measured and reconstructed temperatures smoothed by Gaussian filter for 30 years; grey area approximates 95% confidence interval constructed as two units of standard error (SE) of the estimate from the linear regression.

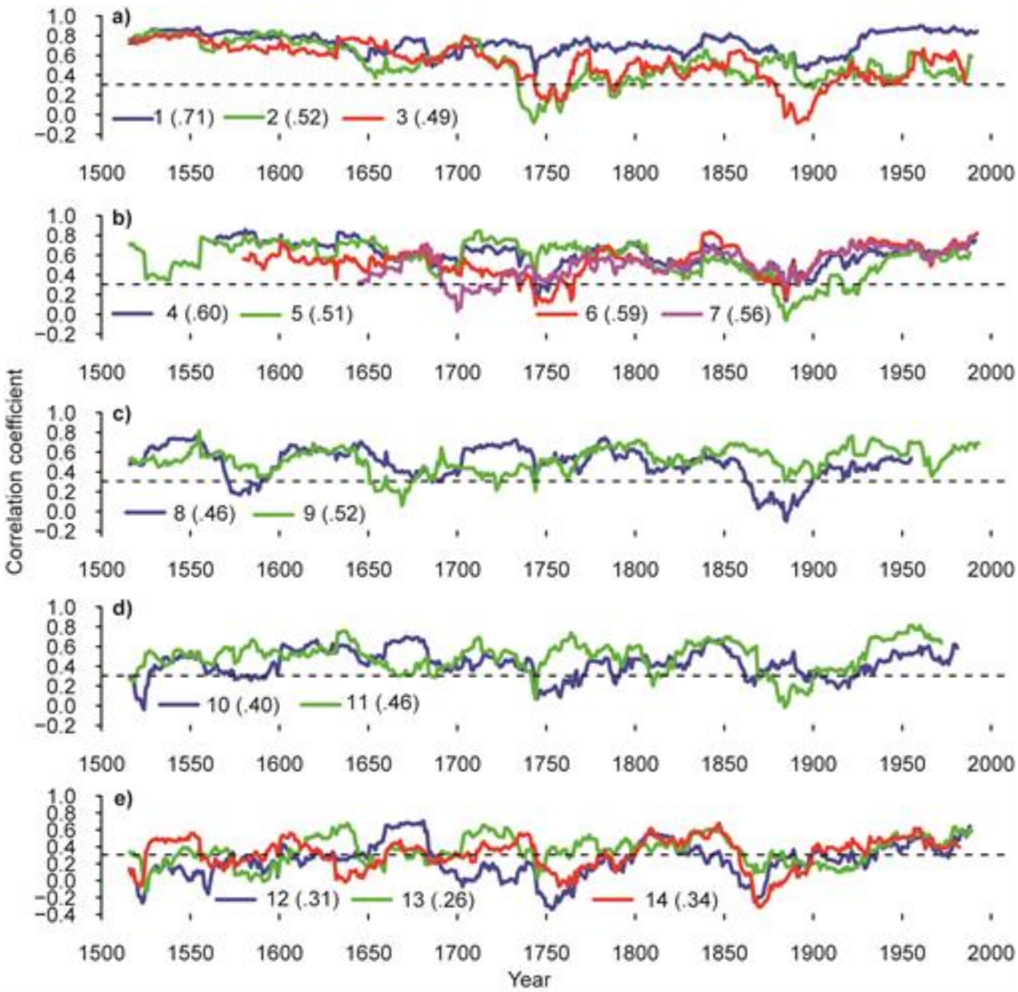

Figure 9: Running 31-year correlation coefficients between GHD-based reconstructed Czech AMJJA temperatures and selected European proxy reconstructions: (a) documentary: (1) AMJJA Central Europe (Dobrovolný et al., 2010); (2) JJA central Europe (Luterbacher et al., 2004); (3) summer Low Countries (van Engelen et al., 2001); (b) grape-harvest dates: (4) AMJJA Swiss Plateau (Meier et al., 2007); (5) AMJJA Burgundy (Chuine et al., 2004); (6) MJJ Vienna and Klosterneuburg region (Maurer et al., 2009); (7) MJJ Közseg, Hungary (Kiss et al., 2011); (c) grain-harvest dates: (8) MAMJJ northern Switzerland and south-western Germany (Wetter and Pfister, 2011); (9) MAMJJ Czech Lands (Možný et al., 2012); (d) multiproxies: (10) JJA European Alps (Trachsel et al., 2012); (11) AMJJAS western Europe (Guiot et al., 2005); (e) tree rings: (12) JJA western and central Europe (Büntgen et al., 2011); (13) JJAS Alps (Büntgen et al., 2006); (14) JJ central-eastern Alps (Wilson and Topham, 2004). Numbers in brackets are overall correlations for the common period in question and broken horizontal lines represent critical values of correlation coefficient for α = 0.05 for one-tailed t-test, assuming no autocorrelation.