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An underestimated record breaking event: why summer 1540 was very likely warmer than 2003

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Abstract

This paper challenges the argument obtained from the analysis of grape harvest (GHD) and maximum latewood density (MXD) data that the 2003 heat-wave in Western Europe was the most extreme warm anomaly in the last millennium. We have evidence that the heat and drought in 1540 known from numerous contemporary narrative documentary reports is not adequately reflected in these estimates. Vines severely suffered from the extreme heat and drought which led vine-growers to postpone the harvest in hope for a rain spell. At the time of harvest many grapes had already become raisins. Likewise, many trees suffered from premature leaf fall probably as a result of a decreased net photosynthesis, as it was measured in 2003. To more realistically assess 1540's spring–summer (AMJJ) temperature we present a new Swiss series of critically evaluated GHD. Basing on three different approaches considering the drought effect on vines, temperatures were assessed between 4.3 °C and 6.3 °C (including the Standard Error of Estimate (SEE) of 0.52 °C) above the 1901–2000 mean which is significantly higher than the value of 2.9 °C measured in 2003. Considering the significance of soil moisture deficits for extreme heat-waves this result still needs to be validated with estimated seasonal precipitation from independent evidence.

1 Introduction

Future climate change will likely enhance the frequency and intensity of extreme temperature anomalies (IPCC, 2007) having a particularly severe impact on economies and societies. As such "climatic surprises" (Fuhrer et al., 2006) are by definition very rare, long records going back beyond the instrumental period are required to understand their characteristics, drivers and consequences for ecology and society (Battipaglia et al., 2010, and references therein). In addition to temperatures, parameters such as seasonality, precipitation, cloudiness, soil moisture and related feedback mechanisms should be assessed with a monthly or at least seasonal resolution in order to establish the nature and severity of societal impacts (Mauelshagen and Pfister, 2010). The summer of 2003 involving record-breaking heat-waves (Koppe et al., 2004; Marsh, 2004; Kovats and Koppe, 2005; Poumadère et al., 2005; Stéphan et al., 2005; Valleron and Boumendil, 2004; Parry et al., 2007) was such an unprecedented warm extreme in Western and Central Europe. In fact, during the first two weeks of August at least four countries experienced new all-time records of daily maximum temperature (38.1 °C in Great Britain, 40.2 °C in Germany, 41.5 °C in Switzerland and 47.5 °C in Portugal). In Spain the heat wave was characterised mostly by the persistence of very high values, but no absolute maximal values were exceeded (Diaz et al., 2006). Just the financial loss due to crop failure over Europe is estimated at $ 12.3 billion (Heck et al., 2004).

Extreme events of this kind call for longer term interpretations. According to the analysis of a long series of grape harvest dates (GHD) in Burgundy (France) by Chuine et al. (2004) the heat of spring–summer (AMJJA) 2003 in France was “probably higher than in any other year since 1370”. Luterbacher et al. (2004) considering the whole of Europe concluded that spring and summer (AMJJAS) of 2003 were the warmest of the last 500 yr. According to the very long series of maximum latewood density (MXD) in the Lötschental (Canton Valais, Switzerland), 2003 was even claimed to be the warmest summer since AD 735 (Büntgen et al., 2006).

A critical voice was raised by Keenan (2007) who blamed the authors of the Chuine et al. (2004) study for overestimating temperature in 2003 and underestimating the warmth of other years. He demonstrated that their model overestimated the measured temperature for 2003 by 2.4 °C, whilst at the same time severely underestimating temperatures in other warm summers such as 1947, 1952 and 1945. Beniston (2004) based on documentary evidence by Pfister (1984) and Glaser et al. (1999) argued that the year 1540 was warmer than 2003. The assessment of these authors is supported with the reconstruction of monthly temperature in Central Europe since 1500 (Dobrovolny et al., 2010) on the basis of documentary Pfister indices (Mauelshagen, 2010). The study by Battipaglia et al. (2010) merged three alpine MXD tree ring series in a refined statistical analysis including documentary evidence to identify extremely warm summers since the Middle-Ages. The authors still maintain their view that 2003 was the warmest summer in the last 500 yr whilst including 1540 in the list of other very warm summers. In conclusion, results of proxy data from natural archives and documentary evidence disagree with regard to the warmth of spring–summer in 1540 in comparison with 2003.

In this paper we challenge the point made by Chuine et al. (2004), Büntgen et al. (2006) and Battipaglia et al. (2010) with regard to 2003 versus 1540. Coherent narratives from chroniclers in Western Europe namely reveal that drought conditions in 1540 were so extreme that the time of grapevine harvest hinged on sufficient rainfall rather than on grape maturity, whereas many trees may have suffered from the same conditions. To reassess April to July temperatures for this outstanding year a new verified GHD series for Switzerland encompassing the period 1444 to 2011 was composed.

The study is organized as follows: the first section reviews different documentary data types, and questions the reliability of GHDs as a temperature proxy under conditions of extreme heat and drought. The steps to merge Swiss partial GHD series into a homogenised main series are presented in the second section including a high resolution focus on reported drought effect on grapes and trees in 1540. Section 3 outlines the statistical reconstruction of spring–summer (AMJJ) temperatures from this series using the calibration-verification approach (Cook et al., 1994) and presents the results. Estimated temperatures are compared with the results of other reconstructions in the fourth section taking into account concurrent studies highlighting the significance of early soil desiccation for the generation of heat waves.

2 Data

As documentary data provide the backbone of the analysis their properties are briefly reviewed. We need distinguishing between two kinds of documentary evidence, namely direct and indirect documentary proxy data (Pfister et al., 2009).

i. Direct narrative data are explicitly related to weather features with a focus on anomalies and allow distinguishing between temperature, precipitation and other meteorological parameters.

ii. Indirect data are made up of organic and non organic proxies. The former include among other things observations of plant and crop phenology. The latter give, for example, the time of freezing and opening of water-bodies or reports about the magnitude of floods.

Another important differentiation in the field of documentary evidence is made according to the agents who managed or directed the keeping of the records distinguishing between individual and institutional evidence (Pfister et al., 2009).

Individuals put an emphasis on describing and interpreting extreme events including their socio-economic impact. The more extreme an event, the more often and in detail it was usually described (Pfister et al., 2001). The heat and drought of the “hot summer” 1540 are very likely described in hundreds of chronicles in Europe of which only a small part is known. Most observers being aware that their descriptions were subjective included references to quasi objective indirect data into their narratives in the form of proxy indicators in the environment to allow comparisons over time (Pfister et al., 2006).

Institutions may be understood as bodies such as churches or municipalities who managed some source of revenue fluctuating according to climate conditions. The resulting documentation laid down in a more or less standardized form was not intended to document climate (Pfister et al., 2009). Institutional data are available over much longer periods of time than individual data which are firmly bound to the activity- or at latest to the death of the data originator. Inasmuch as they are produced by administrative routine, they have the advantage to be continuous and quasi-homogeneous over a long time period which in the best case may last up to several centuries and thus often may be calibrated against instrumental measurements (Brázdil et al., 2010).

GHD's were among the very first proxy data to be used for assessing pre-instrumental warm season temperatures (Dufour, 1870; Angot, 1883; Le Roy Ladurie, 1967). To this day, 378 series of grape harvest dates, mainly from France, were unearthed from the archives and used for climate reconstructions (Daux et al., 2011). The best known of them is the long series from Burgundy supporting the argument, that the summer 2003 was by far the warmest since 1370 (Chuine et al., 2004). However, these authors overlooked that institutional data need to be interpreted in their social and local context (Labbé and Gaveau, 2011). The two authors stress the fact that GHD series should in no case be indiscriminately put on a level with phenological observations. For example, Guerreau (1995) concluded from an extended review of the literature that the relationship between temperature and the date of grape harvests is not stationary due to risk considerations of the vine-growers (planting of mixed varieties before 1700, adverse meteorological conditions preceding the harvest leading to pre-mature harvesting), whereas Garnier et al. (2011) advanced social factors such as the passage of foreign armies and plague epidemics interfering with the harvest date. According to Labbé and Gaveau (2011) the interpretation of GHD data should be seen as a delicate task requiring a lot of endurance and accurateness, not least because in dealing with documentary evidence certain standards of source verification should be met (Brazdil et al., 2005). According to the Supplement provided by Chuine et al. (2004) (http://ebookbrowse.com/chuine-et-al-2004-suppl-data-pdf-d84187334) the relevant series is composed from an amalgam of 18 cities or villages in Burgundy with a somewhat different harvest timing being statistically converted to the series of Dijon. The data of the mean "Burgundy" series, albeit not the 18 local series, of which it is composed, were published by Chuine et al. (2005). With regard to the Dijon series being the backbone of the Chuine et al. (2004) paper, Labbé and Gaveau (2011) detected no less than 132 divergences with their corrected version. For example, the two spring–summer periods 1522 and 1523 being very warm according to Chuine et al. (2004) turned out to be rather cool in the corrected series (Labbé and Gaveau, 2011). Crucially, the point made by Chuine et al. (2004) that summer 2003 was by far the warmest since 1370 is questionable. In 1540 the area averaged GHD in "Burgundy" was on 4 October (Chuine et al., 2005), whereas the corrected GHD value for Dijon was on 3 September (Labbé and Gaveau, 2011) i.e. 31 days earlier. Moreover, we will show in the subsequent section that the onset of grape harvest under the most extreme drought conditions in 1540 depended on rainfall rather than on grape maturity.

In order to get a more reliable basis for assessing past warm season temperatures from GHD, particularly with regard to 1540, a new verified long GHD series (1444–2011) was set up for Switzerland. Admittedly, Meier et al. (2007) already presented a Swiss series, but it turned out the authors had disregarded the fact that dates prior to the introduction of the Gregorian style in 1582 need to be corrected by adding nine in the 15th, respectively ten days in the 16th and 17th Century. Likewise, they did not consider that in the protestant cantons of Switzerland the Gregorian style was only adopted in 1700 (Richards, 1998). The comparison of the Meier et al. (2007) series with the new Swiss GHD series in Fig. 1 illustrates, that their GHD prior to 1700 are too early.

The reconstruction draws on the combination of direct and indirect data from both individual and institutional agents made up of four types of documentary evidence, namely (i) Wage Payment Data- (WPD) of the Basel Hospital (ii) (Institutional) grapevine harvest dates (GHD), (iii) Historic Phenological Data- (HPD) (iv) Phenological Network Observation (PNO).

2.1 Wage Payment Data (WPD) of the Basel Hospital

The hospital was a profit orientated enterprise having the function of an old-age pension and disability insurance for the well-off in case of corresponding donations. In mid fifteenth century it already drew earnings from estates in more than 80 villages of which the accounts were maintained on a daily basis (Tscharner-Aue, 1983). Like the nobles, the hospital was not subject to the vintage ban and therefore could begin the harvest earlier without regard to other parties which had the advantage of hiring day labourers at a lower price (Lachiver, 1988). These land labourers were paid at the end of every single working day. The first appropriate entry in the account books thus represents the actual beginning of the corresponding agricultural activity. Books of expenditures were kept on a daily basis from 1444 until 1705 (Wetter and Pfister, 2011) (Fig. 2, series 1).

2.2 Institutional grape harvest dates (GHD)

The generation of this evidence is related to the provision of the vintage ban. As soon as the grapes were found to be ripe, the vineyards were “banned” by the municipality, i.e. guarded day and night. This measure was taken for several reasons, chiefly to prevent clandestine harvesting before the absentee beneficiaries (owners of vineyards and tithe) could monitor the ordinary payment of dues. Then, the large working force for gathering the grapes had to be mobilized in time. In France, the “seigneur” who was not submitted to the ban had the right to begin the harvest on his vineyards one day in advance to benefit from lower wages (Lachiver, 1988). The lifting of the ban was laid down in the municipal records, year by year, in some cases from the late Middle Ages (Labbé and Gaveau, 2011). Ten institutional GHD series have been included in the Swiss GHD series (Fig. 2, series 2–11).

2.3 Historic Phenological Data (HPD)

Prior to the establishment of national phenological observation networks, working according to standardised guidelines, historical plant and animal phenological data (HPD) were laid down by amateur observers in their sole discretion (e.g. Rutishauser et al., 2007). HPD’s are not necessarily of lower quality than Phenological Network Observations (PNO) even though lack of metadata (e.g. altitude, inclination, soil, plant varieties etc.) is a major source of uncertainty. Furthermore most historical phenological data series are rather short, scattered and hardly overlapping, so as to make the building up of a main series difficult. Two HPD series have been included in the Swiss GHD series (Fig. 2, series 12–13).

2.4 Phenological Network Observation (PNO)

Compared to Germany, which has a long tradition of phenological network observations (DWD, 1991), continuous PNO in Switzerland started as late as in 1951 (Defila and Clot, 2001). The BBCH standard manual defines 39 observation categories for vines. "Begin of harvest" – is undeniably easy to be observed whereas observations about physiological stages, like e.g. maturity are more difficult to be clearly identified (Meier et al., 2009). Four PNO series, observed and recorded by MeteoSwiss, have been included in the Swiss GHD series.

None of the Swiss institutional GHD series provides a harvesting date for 1540. As the harvest date also depends on institutional factors and human decision-making, it cannot be assessed from other proxies. Instead, the time of full grape-maturity was estimated from HPD as a substitute, which is also more adequate for comparisons with the 2003 harvest date in Dijon, on which the individual vine-growers decided in place of the village community. For a better understanding of the specific context of vine maturity and harvesting in 1540 drought conditions over the months preceding the harvest need to be established. From mid March to the end of September blocking anti-cyclonic situations were quasi- persistent over Central Europe (Jacobeit et al., 1999). In Switzerland and in Southern Germany, rain only fell three or four times between early April and early August, whereby it never rained through an entire day or an entire night (Tables 1, S1). At the end of May, the level of brooks and small rivers was already so low that many mills stopped working (Glaser et al., 1999). The three contemporary chroniclers describing the situation in vine-growing areas of Switzerland and Alsace agree that it did not rain a drop between 23 June and 6 August (Table 1, S2, S3, S4). When heat and drought were probably at their maximum in early August, vine-grapes visibly suffered from the five months long persisting drought. Vine-growers in

Schaffhausen (Switzerland) were “long waiting for rain to begin the harvest”, as chronicler Oswald Huber relates (Table 1, S5). His remark suggests that rainfall had become the determinant factor for beginning the harvest after the grapes had reached full maturity. However, he writes, “because the plants wilted and withered vine-growers finally tackled the work nevertheless” (Table 1, S5). Likewise, vines in Limoges (France) were at that time already defoliated and the grapes were quasi baked (Table 1, S6). According to another French source grapes were “roasted throughout the country” (Table 1, S7). Vine-growers in the Basel region and in the Upper Alsace interrupted the vintage after picking the juicy grapes (Burmeister, 2008) because they realised that the remaining ones were quasi dried out. The vintage was only resumed just after an abundant rain spell on St. Michaels Day (8 October; Gregorian style) which brought the remaining grapes to swell somewhat (Table 1; S7, S8). The vintage ban in Dijon was officially lifted on 3 September (Labbé and Gaveau, 2011). Many grapes still hanging on the plants had already turned into raisins. They yielded a sweet sherry-like wine (Glaser et al., 1999) which made people rapidly drunk (Table 1, S9). In Würzburg (Germany) the millennium vintage of 1540 was stored in finely decorated barrels and only offered to special guests of the court. The wine became so famous that Swedish soldiers were seeking everywhere for the barrel after their conquest of the town in 1631. However, because it was hidden behind a wall, they did not find it. The last bottle of the 1540 millennium vintage containing the world’s oldest still drinkable wine is today exposed in the Würzburg citizen’s hospital (Glaser et al., 1999).

Assessing the date of grape maturity involved three approaches using independent data.

(i) The first one draws on systematic observations about both the “first sweet berries” and the beginning of grape harvest in the open vineyard in Zollikon (Canton Zürich) from 1732 to 1832 (Kohler, 1879). Both sets of observation are Pearson correlated with $r = 0.43$, the mean difference between them being 37 days (±10 days STD). In 1540 first sweet berries were reported on 5 July (Table 1, S1) in Schaffhausen and around 10 July (Table 1, S1) in Zürich. Based upon the above mentioned statistics this date suggests a maturity related harvest date between 12 and 17 August (i.e. between 2 to 27 August including the standard deviation of 10 days). These findings agree with a chronicler's report about the beginning of grape harvest by an individual in Lindau (Southern Germany) at the shore of Lake Constance on 11 August (Table 1, S10), after a first rain-spell had interrupted the terrible drought.

(ii) The starting point for the second approach is Heinrich Bullinger's narrative that he tasted grape must ("Sauser") in Zürich on 10 August (Table 1, S1). According to Werner Siegfried (personal communication, March 2012) grape must normally is obtained between one to two weeks before the main grape harvest starts which points to GHD between 17 and 24 August. This estimate coincides with a note in the chronicle of Ulm (South Germany) that new wine was served on 20 August (Table 1, S11).

(iii) The third approach uses chronicles from Besancon (Western France), Schweinfurt (Central Germany) and Cremona (Northern Italy), all relating the actual beginning of vintage around mid August (Table 1, S12, S13, S14). The three approaches are qualitatively consistent with a maturity related grape harvest in 1540 that might have started between 12 and 24 August. Both values were used in the regression to assess spring–summer (AMJJ) temperatures in that year (see Sect. 3).

3 Reconstruction of warm season temperatures in Switzerland, 1444–2011 (AMJJ)

The 17 GHD series presented in the previous section were homogenised with regard to dating style, data type and altitude following the procedure described in Wetter and Pfister (2011). Some preliminary reflections need to be made at this point on behalf of grown grape varieties. Though it is not known with certainty what variety of grape was grown up to the nineteenth or even the twentieth century in the vine growing regions of Switzerland, this issue matters for the homogenization of the data. It namely turned out that the altitude corrected mean GHD resulting from WPD of the Basel Hospital is about 17 days earlier in comparison to the Swiss series originating from other regions (see Table 2). According to Wunderlin (1986) it must be assumed that grapes in greater Basel region – even though they were labelled differently – originated from the same variety (D. Wunderlin, personal communication, September 2011).

In Canton Schaffhausen (Switzerland), an early variety of Red Burgundy grapes named Aeugstler was grown until the first decades of the twentieth century. These grapes used to be ripe on average on 10 September already, i.e. in August (Julian calendar style), from where the name Aeugstler was derived (Pfister, 1984). This author established a mean difference of 17 days with regard to the ordinary Red Burgundy grapes as well as a significant correlation of $r = 0.87$ between berry coloration and harvest date, which were both confirmed by Rothen (2009). This result supports the assumption that the early GHD grown in the Greater Basel region refer to this variety.

Figure 2 (Fig. 2, upper section) summarizes the spatial location of the Swiss GHD series from which the main series was composed including the metadata used for homogenization. The lower section of Fig. 2 (Fig. 2, lower section) shows the composition of the 17 GHD series over time.

The reconstruction involves merging together different, partly rather short, GHD series into a continuous and homogenised long term series by correcting the evidence for dating style, data type and altitude. Location-, metadata- and composition of these GHD series are shown in Fig. 2. Pearson correlations of all series overlapping with others were calculated. Most of them do have a sufficient overlap of > 15 values and significantly correlate between $r = 0.63$ and $r = 0.92$. (Table S1 in the Supplement). Weaker correlations are clearly explained by distance (e.g. Northeastern vs. Southwestern Switzerland) and grape variety (e.g. Red Burgundy vs. Chasselas). As explained before, dates of the different GHD series needed to be homogenised from Julian- to Gregorian calendar style. GHD series from catholic sites thus only were corrected before 1582, whereas GHD from protestant sites were corrected before 1700 with +9 days in 15th and +10 days in 16th and 17th century. It was mentioned that differences in grape varieties between the Greater Basel- (inclosing the Alsace) and

Swiss Plateau region amounted at about 17 days (Table 2). The GHD series from the Basel Hospital (see Sect. 2) thus systematically was corrected by adding 17 days.

After the homogenisation of dating styles, data types and grape variety a strong and significant Pearson correlation of $r = 0.82$ ($p = 0.001$) was established between altitude and GHD (Fig. 3). In a final step all available GHD series were annually averaged.

The homogenised Swiss GHD series was then calibrated with the monthly anomalies from the 1901 to 2000 mean of the HISTALP temperature series relating to the region northwest (Auer et al., 2007; Böhm et al., 2010). Multiple stepwise linear regression revealed May temperatures to be the most important factor for the dates of grape harvest, followed by June, July and April (not shown). August was not significant in agreement with grape physiology (Mullins et al., 2007) which confirms earlier results by Legrand (1979) and Pfister (1984). Several independent calibration- and verification 50-yr sub periods of the 1774–2005 HISTALP temperature anomaly series have been tested. It was found that there were overall good calibration and verification results.

Best calibration match was found in the 1774–1824 period where HISTALP April–July mean temperatures (AMJJ) significantly correlated with Pearson $r = 0.86$ ($p = 0.001$). Best verification was found in the 1955–2005 sub period which resulted in a significant Pearson correlation of $r = 0.77$ ($p = 0.001$) (Fig. 4). Standard Error of Estimate amounts to 0.52 °C (SSE).

Figure 5 displays an 11 yr high pass filter of reconstructed temperature anomalies. The temperature reconstruction basing on GHD clearly shows that 1540 April–July mean temperature was between 4.8 °C and 5.8 °C (±0,52 °C) warmer than the mean 1901–2000 HISTALP temperature (Auer et al., 2007) depending on the assumed date of full grape maturity (12 vs. 24 August). According to this approach 1540 was by far the warmest April to July temperature anomaly in the last 566 yr, no matter which estimated GHD was used. The warmest year 1540 is followed in descending order by 1822 (+2.97 °C) and 1865 (+2.93 °C). The well known 2003 (+2.84 °C) event only is on the third place, together with 1718 and 1868 (each +2.84 °C). They are followed by 1536 (+2.75 °C) and 1945 (+2.52 °C). Coldest mean March–July temperatures appeared in 1698 (−2.84 °C) and were followed by 1542 (−2.72 °C), 1675 (−2.62 °C), 1628 (−2.53 °C), 1692 (−2.19 °C) and 1695 (−2.17 °C). All significant positive and negative temperature anomalies exceeding ±2 °C are consistent with narrative documentary evidence about warm, respectively cold seasonal conditions (Pfister, 1999).

4 Discussion

The discussion first involves a comparison of the new long Swiss grape harvest date series with those from neighbouring regions and then with the Lötschental MXD tree ring series (Büntgen et al., 2006) and the Wetter and Pfister (2011) series about the beginning of winter grain harvest (WGHD). Subsequently, a focus is put on the comparison of the estimates for 1540 in comparison with 2003.

The surplus value of this new Swiss GHD series on the one hand is given in its sheer existence because it allows reconstructing spring–summer temperatures (AMJJ) from critically verified institutional (and individual-) documentary data. Note, that the estimated values for 2003 of 2.9 °C, respective 2.8 °C according to both equations in the calibration- verification procedure agree with the anomaly of 2.9 °C measured according to the HISTALP series northwest (Auer et al., 2007).

The correlation with Meier et al. (2007) is not shown as both series share the same data basis to some extent. Overall correlations between the homogenised Swiss GHD- and other temperature proxy series show quite good results (Table 3). The Besançon GHD series (Garnier et al., 2011) correlates best (according to the independent proxy series) with 0.81, followed by the estimates based on monthly documentary Pfister temperature indices from Switzerland by Dobrovolny et al. (2010) with −0.75 and the corrrected Dijon series by Labbé and Gaveau (2011) with 0.73. With respect to the distance, far off series from Vienna and Hungary correlation is adequate as well. The low overall Pearson correlation of the uncorrected Burgundy GHD series (Chuine et al., 2004) warrants a closer inspection.

31-yr moving correlations with the uncorrected Burgundy GHD compilation series (Fig. 6, red curve) as well as 11-yr moving averages (Fig. 7), clearly reveal that the low correlation is due to the period 1516 to 1555, where the values drop to 0.14, mainly as a consequence of wrong values in 1522 and 1523 and the questionable value for 1540 (Figs. 6, 7).

Correlations between the Lötschental MXD series (Büntgen et al., 2006) and the GHD series are quasi consistently low (not shown).

A comparison with March to July temperature estimates based on Winter Grain harvest dates (WGHD) (Wetter and Pfister, 2011) shows that warm anomalies (1540, 1718, 1822 and 1868) are better represented in both series than cold anomalies, where there is only an agreement for 1542. Accordingly, the overall Pearson correlation of $r = 0.65$ m ($p = 0.01$) between the GHD and the WGHD temperature reconstruction is not too impressive though anomalies on a decadal scale move quite similarly disregarding the period 1860 to 1950 in which GHD related temperatures are substantially higher. Moreover, variance is greater in the case of the GHD related reconstructions (Fig. 8).

The very high estimates of 4.8 °C and 5.8 °C (±0.5 °C SEE) for the AMJJ temperature anomaly in 1540 deserve a particular emphasis. In addition to the statistical uncertainties in the reconstruction, we need to remind that the lower and upper GHD values were assessed from observations of grape-vine development made by several vine-growers, for which, of course, uncertainties cannot be quantified. Considering the good agreement between the estimated and the measured temperature anomaly of 2.9 °C in 2003 (see Sect. 3) we may, however, conclude that spring–summer (AMJJ) temperatures were very likely higher in 1540. In interpreting this result it may also be worth noting, that the relationship between temperatures and grape maturity is non-linear. Grapes rate of net photosynthesis e.g. decreases in case of above 30 °C temperatures (significantly above 35 °C). The absolute limit of CO_2 absorption is reached if 40 °C are achieved (Currle et al., 1983). The plant in such cases temporarily stops its vegetative activity. Low water drainage soils in combination with dry periods may furthermore have the same effect on the plants growth phase if temperatures for a longer time period do not fall beyond 30 °C (personal communication with Werner Sigfried, February 2012). Trees responded like grapevines, to the extreme drought in 1540 with premature leaf fall (Table 1, S15). Leuzinger et al. (2005) found that net photosynthesis and leaf conductance decreased significantly, by 60 to 80 %, from June to August 2003 in all species of an observed forest in Basel region (Swiss lowland forest). Drought was certainly more severe in Canton Valais (Schüepp et al., 1978), which might have additionally stressed Larch trees in the Lötschental analysed by Büntgen et al. (2006).

In support of the argument that spring–summer temperatures were substantially higher in 1540 than in 2003 the train of events leading to the heat-wave in 2003 is reviewed in some detail (Fischer et al., 2007 and references therein). Heat waves are generally associated with specific large-scale anti-cyclonic atmospheric circulation patterns. The surface temperature response to such circulation anomalies is amplified by a positive feedback due to suppressed evapo-transpiration owing to the lack of soil moisture in the preceding months and a corresponding increase in sensible heat (Seneviratne et al., 2006). Through carefully validated simulations Fischer et al. (2007) found clear evidence suggesting that the dry soil conditions and ensuing soil moisture dynamics were a key in the sequence of events that led to the record-breaking heat-waves in 2003. Soil drying began early in the year with a persistent precipitation deficit and then accelerated in response to early vegetation green-up in spring. Sensitivity analyses suggest that given climatological mean soil moisture and similar continental-scale circulation, the 2003 JJA surface temperature anomalies would have been reduced by around 40 %. Thus in absence of soil moisture feedbacks, summer 2003 would still have been warm, but it would not have been such a devastating event as it turned out to be (Fischer et al., 2007).

As mentioned before, severe drought in 1540 began earlier and it was much more pronounced and persistent than in 2003 (see Sect. 2). This assessment is in line with the poor condition of the vines and some tree species (oaks) in early August (Table 1, S15) not witnessed in 2003. According to the above mentioned high significance of early soil moisture deficits for the generation of record breaking heat-waves, it might not even be fictional to assume, that spring summer (AMJJ) excess temperatures in 1540 were close to 6 °C (see Fig. 5).

Note, that summer 1540 became known for centuries as the “hot summer”. Many living in South-Eastern France, South Germany and the Swiss Plateau region complained about unbearable heat which is extremely rare. In Besançon (France) people took refuge in the cellars from 09:00 a.m. because they could not stand the heat in the streets during the day. The wheat was cut at night (Table 1, S12). In Modena (Northern Italy) the decision was taken to suspend the work at the administration of justice for a whole month because of the unbearable heat-wave during August (Table 1, S16). Note that Modena has a Mediterranean climate with hot dry summers suggesting the locals to be used to high summer temperatures. These descriptions indicate, that the area of highest temperatures in 1540 was roughly the same as in 2003 (Black et al., 2004).

5 Conclusion

Inconsistencies between biological proxies and narrative documentary about the warmest spring–summer (AMJJ) period within the last millennium were the starting point for a re-analysis of temperatures in 1540 versus 2003. As a first result, it was demonstrated, that the GHD series by Chuine et al. (2004) supporting the argument that the 2003 heat-wave in Western Europe was the most extreme warm anomaly, suffers from several flaws. It cannot be traced back to its original sources, the date postulated for 1540 is 31 days later than the corrected value for Dijon (Labbé and Gaveau, 2011) and the AMJJA temperature anomaly estimated for 2003 is 2.4 °C higher than measured temperatures in Paris (Keenan, 2007). The second result was obtained from the study of several independent narrative sources which agree that the time of grape harvest in 1540 was determined by rainfall rather than by grape maturity. There is consensus that the 1540 drought in Western and Central Europe was the longest (from mid February 1540 to early January 1541) and the most severe since 1500 (Glaser et al., 1999; Casty et al., 2005). Grapes had so much dried out in early August after five months of extreme drought that harvests were postponed or interrupted in the hope of a coming abundant rain-spell. Likewise, MXD values in the 750 yr long tree-ring-series from Lötschental (Büntgen et al., 2006) were rather low which agrees with chronicler reports about widespread defoliation of trees already in (late) summer. For these reasons a new long GHD series (1444–2011) was set up from verified Swiss sources in the light of the fact that the dating in the recent Swiss GHD series by Meier et al. (2007) was not corrected for (Julian to Gregorian) style. The statistical analysis of the new Swiss series yielded as a third result that spring–summer (AMJJ) mean temperatures in 1540 were between +4.8 °C and +5.8 °C (±0,52 °C SEE) warmer than the mean 20th century (1901–2000) in comparison to +2.9 °C (2.88 °C HISTALP) both measured (Auer et al., 2007) and estimated from the regressions in 2003. The unusually large anomaly estimated for 1540 might be plausible considering temperature feedbacks from the extreme soil moisture deficit (Fischer et al., 2007) documented for that year.

In summary, it is concluded that biological proxy data may not properly reveal record breaking heat and drought events in the pre-instrumental past. Obviously, such assessments need to be complemented with the critical study of contemporary documentary evidence being widespread in such situations and providing coherent and detailed narratives about weather patterns and climate induced impacts. The synoptic situation and the soil-atmosphere interactions reinforcing the pronounced heat and drought in 1540 are still poorly understood. Subsequent analyses should focus on assessing precipitation and drought severity to make the worst case event of 1540 and its devastating impacts more plausible and comprehensive (Wetter et al., 2012).

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/8/2695/2012/cpd-8-2695-2012-supplement.pdf.

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Table 1. Narrative documentary sources.

Sources	Originator	Title
S1	Bullinger, Heinrich (1504–1575)	Bullinger; Heinrich; Diarium (annales vitae) der Jahre 1504–1574; (Egli; E., ed.); Quellen zur Schweizer Reformationsgeschichte, 2, Basel, 1904.
S2	Haffner, Franciscus (1609–1671)	Der klein Solothurner allgemeine Schaw-Platz Historischer Geist- auch Weltlicher vornembster Geschichten und Händlen, Solothurn, 1666.
S3	Walser, Gabriel (1695–1776)	Neue Appenzeller Chronik oder Geschichte des Landes Appenzell der Innern und Äussern Rhoden; St.Gallen, Trogen; 1829.
S4	Im-Thurn, Eduard (1579–1648)	Chronik der Stadt Schaffhausen. Drittes Buch. Von Wiedererlangung der Reichsfreiheit bis zum Eintritt in den Bund der Eidgenossen 1415–1501. In: Historische Gesellschaft zu Basel, Band 223, Basel, 1844.
S5	Huber, Hans Oswald (1521–1582)	Schaffhauser Chronik, in: Festschrift zur Erinnerung an das 50jährige Jubiläum des historisch-antiquarischen Vereins des Kantons Schaffhausen, (Bächtold, C.A ed.), Meier & Cie, 196pp., Schaffhausen, 1906.
S6	De Teysseulh, Pierre (1535–1568)	Alfred LEROUX (éditeur), Extraits du Journal de Me Pierre de Teysseulh, chanoine de l'église de Limoges, 1533–1568, in: Chartes, chroniques et mémoriaux pour servir à l'histoire du Limousin, Ducourtieux, 259 pp., Tulle, Crauffon, Limoges, 1886.
S7	Gaufreteau, Jacques de	Chronique Bourdeloise, (Delpit J. ed.), Bordeaux, 1877–1878.
S8	Vanotti	Nachrichten über Witterung, Fruchtbarkeit und Preise der Naturalien vom Jahr 1138 bis 1650, in: Württembergische Jahrbücher für vaterländische Geschichte, Geographie Statistik und Topographie J.G.D. (Memminger, J.G.D.ed.), 1. Heft, 131–170, 1829.
S9	Kessler, Josua (1527–1580)	Kessler, Josua, 1527–1580, Chronologie Santgallischer Begebenheiten vom Jahr 1540 bis Ende des Jahres 1645 aufgezeichnet durch J.K., Stadtschreiber in St. Gallen, Handschriften Nr. 74.
S10		Lindauer Chronik bis 1754, Stadtarchiv Lindau, 664 pp.
S11	Fischer, Sebastian	Sebastian Fischers Chronik besonders von Ulmischen Sachen, in: Verein für Kunst & Alterthum für Ulm und Oberschwaben, (Veesenmeyer, K. G. ed.), Ulm, 1896.
S12	Froissard, Anatoile	Livre de raison de la famille de Froissard-Broissia de 1532 à 1701, in: Mémoires de la Société d'émulation du Jura, 27–105, 1886.
S13		Chronik der Stadt Schweinfurt.- Schweinfurt: UB Würzburg, Rp XXIII, 490a, 624 pp.
S14		Grandi, A.: Descrizione dello stato fisico-politico-statistico-storico-biografico della Provincia e Diocesi di Cremona, Cremona, L. Copelotti, 1856.
S15	Stolz, Hans (∼ 1510 ∼ 1540)	Die hans Stolz'sche gebweiler chronik. Zeugenbericht über den Bauernkrieg am Oberrhein, (Stolz, W.), Freiburg, 1979.
S16	De' Bianchi, Tomasino (1473–1554)	Cronaca Modenese di Tomasino De' Bianchi detto De' Lancellotti, 1538–1540, in: Monumenti di Storia Patria delle province modenesi, Serie delle Cronache, tomo VII, Parma (Borghi, C. ed.), Fiaccadori, 514 pp., 1868.

Table 2. Statistical properties of Greater Basel region GHD- (including Alsace) opposed to Swiss GHD series.

	Basel hospital (WPD)	Mulhouse (Muller, 1997)	Swiss GHD series (altitude corrected mean GHD)
altitude m a.s.l.	275	250	413–495
mean GHD (doy)	270	270	287
n	99	31	–
std.	8.89	10.41	7.59–12.08

Table 3. Overall Pearson correlations between Swiss GHD and other climate proxy series.

Type of evidence	Origin	Correlation (Pearson)	Authors
GHD	Besançon (France)	$r = 0.8$; $p = 0.001$	Garnier et al. (2011)
Documentary T Indices	Switzerland	$r = -0.75$; $p = 0.001$	Dobrovolný et al. (2010)
GHD	Dijon (France) corrected	$r = 0.73$; $p = 0.001$	Labbé and Gaveau (2011)
WGHD (winter grain harvest dates)	Swiss compilation (Switzerland)	$r = 0.65$; $p = 0.001$	Wetter and Pfister (2011)
GHD	Burgundy (France) uncorrected	$r = 0.64$; $p = 0.001$	Chuine et al. (2004)
GHD	Vienna (Austria)	$r = 0.54$; $p = 0.001$	Maurer et al. (2009)
Multi proxy (grape and grain harvest dates)	Köszeg (Hungary)	$r = 0.54$; $p = 0.001$	Kiss et al. (2011)
MXD + Documentary	Swiss and Austrian Alps	$r = -0.53$; $p = 0.001$	Battipaglia et al. (2010)
MXD	Lötschental (Switzerland)	$r = -048$; $p = 0.001$	Büntgen et al. (2006)

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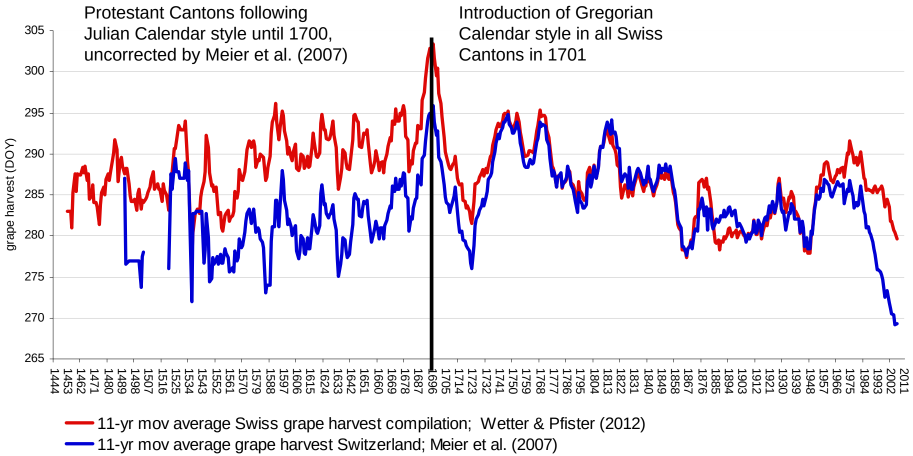
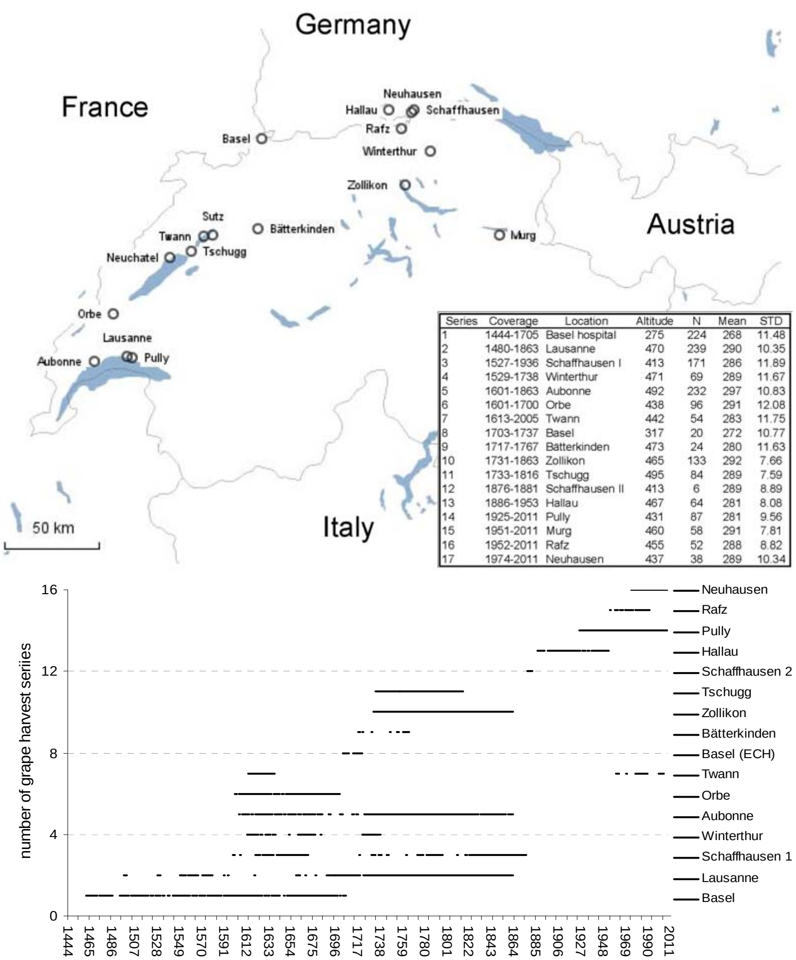


Fig. 1. Non calendar style corrected GHD by Meier et al. (2007) vs. corrected GHD by Wetter and Pfister (2012).



Series	Coverage	Location	Altitude	N	Mean	STD
1	1444-1705	Basel hospital	275	224	268	11.48
2	1480-1863	Lausanne	470	239	290	10.35
3	1527-1936	Schaffhausen I	413	171	286	11.89
4	1529-1738	Winterthur	471	69	289	11.67
5	1601-1863	Aubonne	492	232	297	10.83
6	1601-1700	Orbe	438	96	291	12.08
7	1613-2005	Twann	442	54	283	11.75
8	1703-1737	Basel	317	20	272	10.77
9	1717-1767	Bätterkinden	473	24	280	11.63
10	1731-1863	Zollikon	465	133	292	7.66
11	1733-1816	Tschugg	495	84	289	7.59
12	1876-1881	Schaffhausen II	413	6	289	8.89
13	1886-1953	Hallau	467	64	281	8.08
14	1925-2011	Pully	431	87	281	9.56
15	1951-2011	Murg	460	58	291	7.81
16	1952-2011	Rafz	455	52	288	8.82
17	1974-2011	Neuhausen	437	38	289	10.34

Fig. 2. Location-, metadata- and composition of 17 Swiss GHD series.

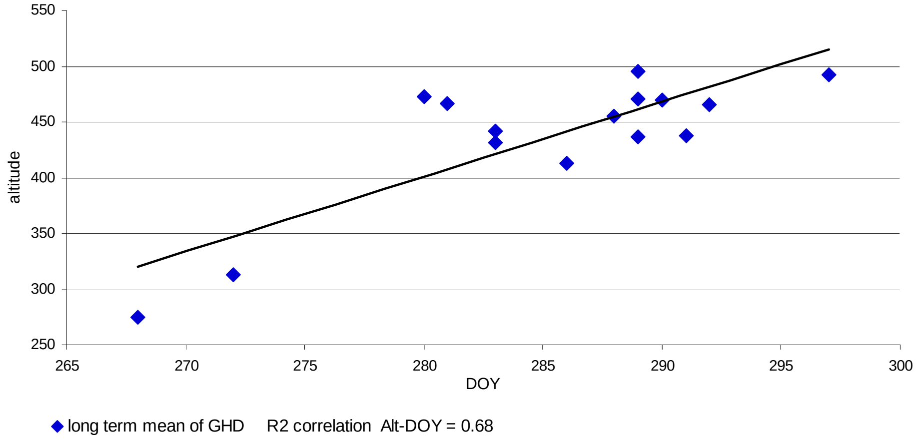


Fig. 3. Altitude – GHD (DOY) correlation of 17 homogenised GHD series.

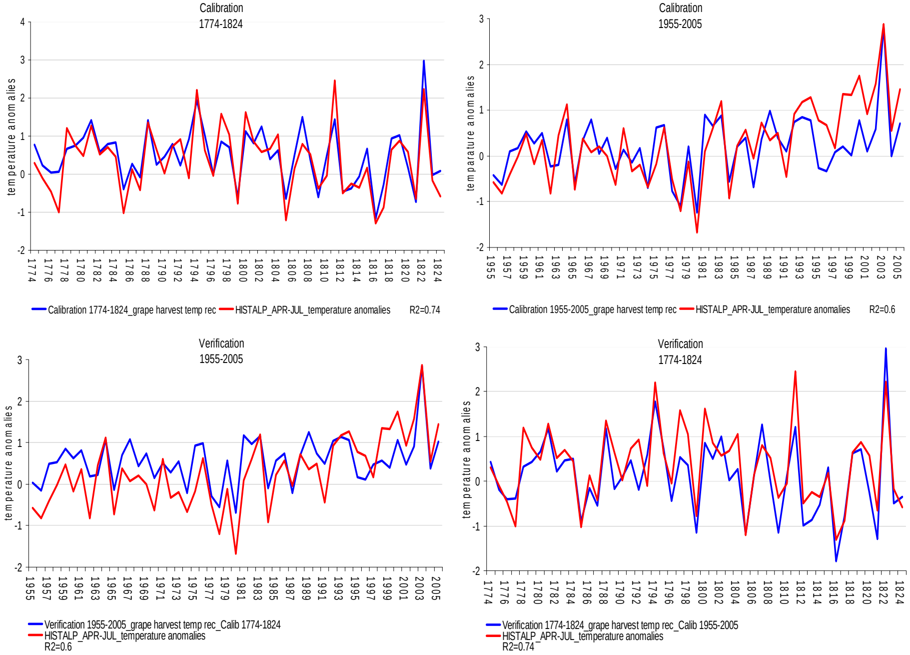


Fig. 4. Calibration and verification of homogenised Swiss Grape Harvest series with HISTALP 50-yr sub periods; 1774–1824 and 1955–2005.

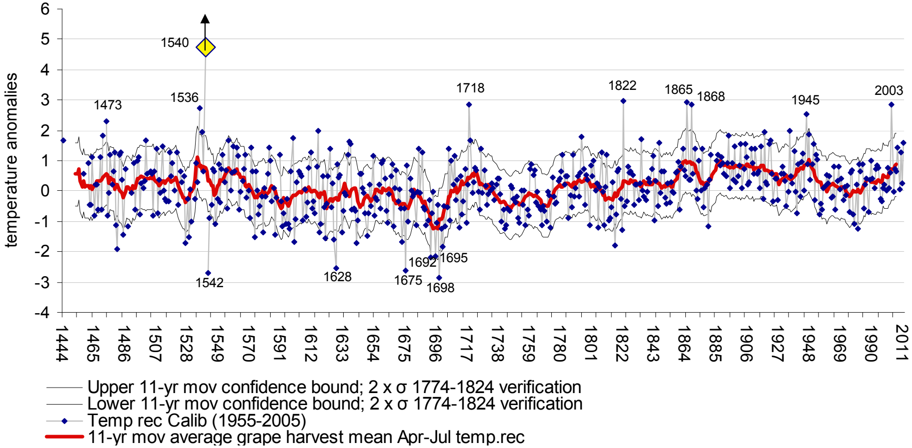


Fig. 5. Temperature reconstruction basing on the homogenised Swiss GHD series covering the period from 1444–2011.

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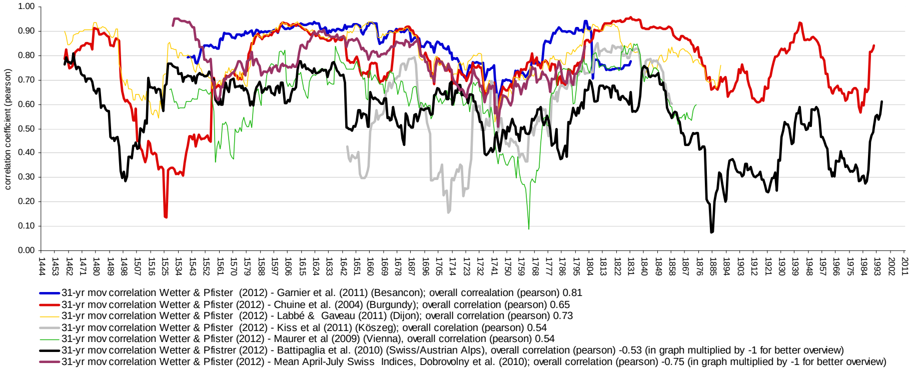
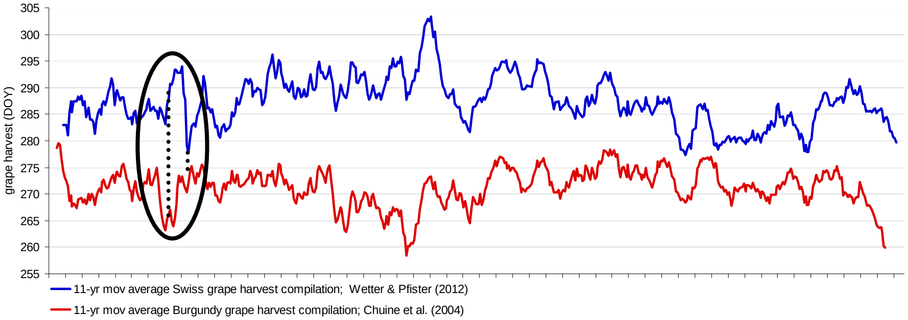


Fig. 6. 31-yr moving correlation between Swiss compiled GHD and Central European temperature proxy series.



Circle: problematic (highly differing) period between Wetter & Pfister (2012) and Chuine et al. (2004)

Dotted lines: opposite movement between Wetter & Pfister (2012) and Chuine et al. (2004)

Fig. 7. 11-yr moving averages of Swiss GHD compilation 1444–2011 and Burgundy GHD compilation 1370–2003 (Chuine et al., 2004).

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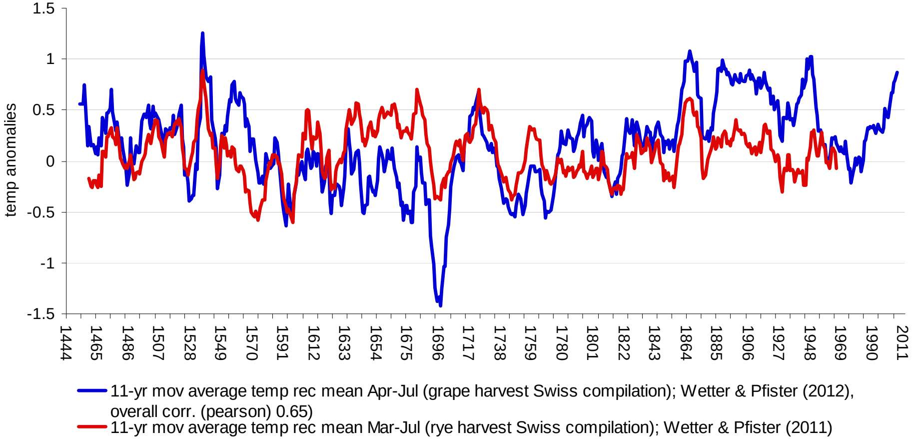

Fig. 8. 11-yr moving averages of GHD temperature reconstruction by Wetter and Pfister (2012) vs. WGHD temperature reconstruction by Wetter and Pfister (2011).