Universität Bremen
Physik Master

Seasonal climate impacts on grape harvest dates. Analysis based on historical data from several European wine areas.

Masterarbeit

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Bremen, April 29, 2014

Abstract

Historische Dokumente von Weinerntedaten enthalten wichtige Klimainformationen über vergangene Jahrhunderte, in denen keine instrumentellen Messdaten vorhanden sind. In dieser Studie werden die jahreszeitlichen Einflüsse des Klimas auf das Weinerntedatum im Burgund (Frankreich) während der instrumentelle Periode (1900 - heute) mit einem linearen Ansatz untersucht. Die Variabilität der räumlichen Korrelationsmuster auf jährlicher und dekadischer Zeitskala wird dabei ermittelt. Die Überprüfung der Resultate erfolgt mit pre-instrumentellen Daten (1500 - 1899) und mit Weinerntedatenserien von anderen Europäischen Weinanbaugebieten. Das Weinerntedatum wird vorwiegend von der Temperatur in der Vegetationszeit zwischen April und August beeinflusst (Korrelationskoeffizient: $\rho = -0.80$). Pre-instrumentelle Daten sowie Weinerntedaten von anderen Gebieten bestätigen dieses Ergebnis. Die Analyse der instrumentellen Periode deutet darauf hin, dass die dekadische Wintertemperatur ebenfalls einen Einfluss auf das Weinerntedatum hat ($\rho = -0.61$). Dieser Zusammenhang wird aus unbekannten Gründen nur teilweise durch Weinerntedaten anderer Anbaugebiete unterstützt und lässt sich für die Zeit vor 1900 gar nicht nachweisen. Für Temperaturrekonstruktionen der Vegetationszeit würde dies einen Vorteil darstellen, da kein zweiter klimatischer Einfluss den Zusammenhang mit dem Weinerntedatum verzerrt.

Abstract

Historical documents of grape harvest dates (GHD) contain important climatic information about past centuries in which no instrumental records exist. This study analyses the seasonal climatic impacts on the GHD in Burgundy (France) during the instrumental period (1900 to nowadays) by a linear approach and provides the spatial variability of the correlations on interannual and decadal time scales. The results are compared to the pre-instrumental period (1500 - 1899) and with GHD series from other European locations. The growing season temperature from April to August is found to mainly influence the GHD (correlation coefficient: $\rho = -0.80$), which is confirmed by pre-instrumental data as well as by GHD series from different locations. The analysis for the instrumental period furthermore indicates that the decadal winter temperature impacts the GHD in a second order ($\rho = -0.61$). For unknown reasons, the GHD - winter relationship is not conclusively supported by the analysis of other European GHD series and moreover, does not occur during the pre-instrumental period. For growing season temperature reconstructions this would be an advantage as the reconstruction is not biased by a second seasonal climate impact.

Contents

1 Introduction

Instrumental observations of the last 50 to 100 years indicate large interannual to multidecadal climate variability (P. D. Jones et al. 1992; Dima et al. 2007). The relative shortness of the instrumental climate record limits our understanding of the natural range of climate variability on seasonal to centennial time scales. A promising way to assess natural climate variability on these time scales is due to early instrumental and high-resolution proxy climate data (e.g., M. E. Mann et al. 1999; P. D. Jones et al. 1992; Esper et al. 2002; Rimbu et al. 2001; Lohmann et al. 2004; Luterbacher et al. 2004).

A particular proxy data set is the annually varying grape harvest date (GHD). GHDs have been documented in many European locations for several centuries (Brázdil et al. 2008; Ladurie et al. 1980; Meier et al. 2007). All major phenology stages of the grapevine strongly depend on climate conditions (G. Jones 2003). The temperature during the stages before bloom and before veraison were found to be most crucial for the GHD (Chuine et al. 2004; Garcia de Cortazar-Atauri et al. 2010). When using the GHD for climate reconstructions, several caveats have to be taken into account, e.g. plant diseases or changes in viticulture techniques, varieties, and wine types (Meier et al. 2007; Garcia de Cortazar-Atauri et al. 2010). Furthermore, missing years of observation can be a problem. Hence, the data quality differs from place to place. In some cases, the data are only sufficient for qualitative analysis like in the Czech Republic (Brázdil et al. 2008). In the case of Besançon (France), arguable dates could be identified and discarded in order to build a climatic GHD series (Garnier et al. 2011). In the case of the Burgundy region in France, several homogeneous GHD series are available and are combined to one GHD series to reduce non-climatic impacts (Chuine et al. 2004). Moreover, the varieties cultivated in the Burgundy region have been the same for the last six centuries (Garcia de Cortazar-Atauri et al. 2010).

Despite these difficulties, GHDs have been successfully used for several temperature reconstructions, mainly for the spring and summer temperature. Chuine et al. (2004) reconstructed April to August temperature (AAT) in France using a process-based phenology model. Meier et al. (2007) used linear-regression to reconstruct Swiss AAT. GHD series were applied for bi-proxy (Etien et al. 2008) and multiproxy-reconstructions (Etien et al. 2009; Guiot et al. 2005; M. Mann et al. 2008) as well as for checking other reconstructions (Brázdil et al. 2010; Masson-Delmotte et al. 2005). The GHD was also taken into account to discuss the summer heatwave in 2003 (Chuine et al. 2004; Menzel 2005; García-Herrera et al. 2010; Keenan 2007). Besides the spring and summer temperature dependence, another interpretation of the GHD was given by Souriau et al. (2001), who found a relationship to the North Atlantic Oscillation (NAO). A different approach to analyse the GHD was performed by Schleip et al. (2008), who used the Bayesian analysis to examine temperature impacts on the GHD. The June temperature was thereby found to be most important for the GHD.

However, possible changes in the GHD-climate relation and the seasonality in GHD have not been analysed in detail yet. In this study, the following research questions are addressed: Which climate signals are recorded in the GHD? What are the seasonal spatial correlation patterns of the GHD with temperature? Are the relationships stable over time, also when comparing the instrumental with the pre-instrumental period? To examine this, the analysis of the GHD-climate relation is firstly done with the Burgundy GHD series by Chuine et al. (2004) for the instrumental period. Secondly, the results are compared to the analysis of pre-instrumental climate data. The outcome of this examinations has already been published in Krieger et al. (2011). In that context, the thesis was stated that the GHD is not only influenced by the AAT but also by the winter temperature on decadal-to-multidecadal time scales. A recently published open-access data base of numerous GHD dates from different, mainly French locations by Daux et al. (2012) offers now the possibility to survey whether the findings made for the Burgundy GHD series can be affirmed by other European GHD series. Accordingly, an analysis of the GHD-climate relationship for different wine areas and a comparison to the results of the Burgundy region is performed.

2 Methods and Data

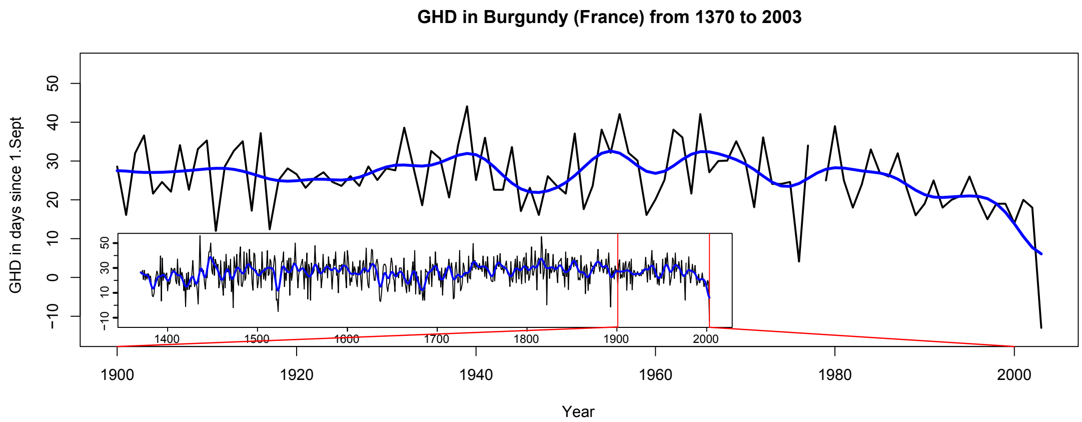

Figure 1: GHD series (Chuine et al. 2004) of the Burgundy region in France from 1370 to 2003 (in days since 1st September). The instrumental period is emphasised in the main panel as this period is of particular interest in this study. Blue line: decadal variations (low-pass filtered data using a 1/10 year cutoff).

The GHD-climate relationship is particularly analysed for the instrumental period (which is defined here as the time period from 1900 to nowadays) and for the Burgundy GHD series (Fig 1) from Chuine et al. (2004) which covers the period from 1370 to 2003, except for the year 1978. It is based on the GHD series from Le Roy Ladurie (1983) and updated by Chuine et al. (2004). The GHDs were recorded in up to 18 cities and villages in the Burgundy region in France. The Dijon series is defined as reference because it is the longest series. The remaining 17 series were standardised to the average harvest date of the reference series. The final GHD series presents the median date for each year of all 18 data sets (for detailed description see Chuine et al. 2004). The harvest date is given in days since 1st September for each year. The analysis is also performed with the Burgundy GHD series from the GHD data base by Daux et al. (2012). It slightly differs from the Burgundy series by Chuine et al. (2004). Some data were revised and few series were added (Daux et al. 2012). As both series yield

Table 1: Information about the GHD series used in this study derived from Chuine et al. (2004) for the first Burgundy series and from Daux et al. (2012) for all other series. The column "Nr" specifies the number of single series included in the combined GHD series.

Location	Start	End	Mean Lat	Mean Lon	Nr	Missing Values	
						after 1750	after 1900
Burgundy (Chuine)	1370	2003	47.3	5.0	18	1	1
Burgundy (Daux)	1354	2006	47.3	5.0	20	2	2
Low Loire Valley	1801	2006	47.1	0.2	6	3	3
Champagne	1822	2006	49.0	4.0	28	3	1
Ile-de-France	1478	1977	48.9	2.2	16	2	2
Switzerland	1480	2007	46.6	6.5	15	0	0
Bordeaux	1449	2006	45.2	-0.8	14	2	0
Jura	1524	1976	46.9	5.9	16	15	8
Alsace	1700	2005	48.2	7.3	16	43	17

nearly similar outcome in all performed analyses, only the results of the Chuine et al. (2004) series are shown.

In order to survey the results of the Burgundy GHD series, grape harvest dates from other European wine areas, available in the data base from Daux et al. (2012), are analysed. The data base consists of 380 GHD series which are grouped in 27 regions. For each region, Daux et al. (2012) applied the same the procedure as Chuine et al. (2004), as described above. Eight GHD series (Burgundy, Low Loire Valley, Champagne, Ile de France, Switzerland, Bordeaux, Jura and Alsace) are chosen for the analysis as they cover the instrumental and pre-instrumental period without large gaps and contain only few missing values for the instrumental period (see Tab 1 for additional informations).

The climate impacts on the GHD are investigated by analysing the correlation of the GHD with gridded data sets of temperature, sea surface temperature (SST), sea level pressure (SLP), total cloud cover and precipitation. The analysis of temperature is done with the Berkeley temperature data set as it provides monthly gridded ($1° \times 1°$) data for the instrumental and pre-instrumental period (1750 - 2011) and is based on temperature station data from 14 data bases (Rohde et al. 2013). In the early years, only few areas contain data, but the European temperature is available for the whole period. Additionally, the seasonal European temperature data set from Luterbacher et al. (2004) covering the time from 1500 - 2002 ($0.5° \times 0.5°$) is analysed which is based on a multiproxy approach.

Monthly instrumental data ($0.5° \times 0.5°$) of precipitation and total cloud cover are taken from the Climate Research Unit (CRU) (Mitchell et al. 2003) covering the years from 1901 to 2002. A monthly historical SLP data set ($5° \times 5°$), from 1899 to 2007, is used from Trenberth et al. (1980). Furthermore, a monthly SST data set covering the period from 1870 to 2006 is taken from Kaplan et al. (1998) .

For the analysis, Pearson product-moment correlation is used as the empirical relationship of the GHD with temperature does not show any systematic deviations from linearity (Fig 2 a). However, similar results are obtained using Spearman's rank correlation: The overall correlation is equal for the AAT-GHD relation (Burgundy) during the instrumental period and both correlations simi-

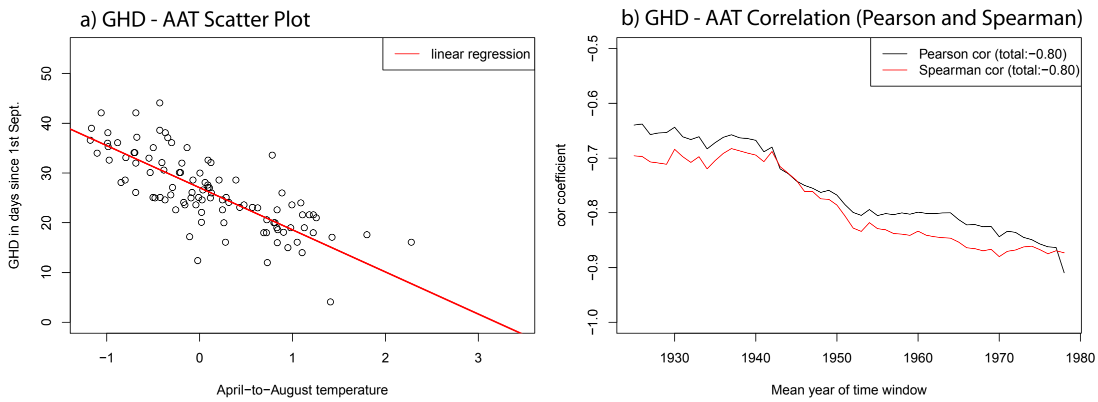

Figure 2: a) Scatter plot of the AAT and the GHD (instrumental period). The red line shows the linear regression. **b)** Comparison of running Pearson's Correlation and running Rank Correlation by Spearman for the GHD - AAT relationship (window length 50 years). In both cases, the Burgundy GHD series from Chuine et al. (2004) is used.

larly develop over time (Fig 2 b). Besides linear model approaches, process-based phenology models are typically used to investigate the GHD-climate relationship (e.g. Chuine et al. 2004). Garcia de Cortazar-Atauri et al. (2010) compared these methods and concluded that both can be accurate (Garcia de Cortazar-Atauri et al. 2010). Accordingly, it is well justified to rely on Pearson product-moment correlation. Pearson's correlation coefficient can be defined for two time series x and y as

$$\rho_{xy} = \frac{\sum_{n=1}^{N}((x_n - \mu_x)(y_n - \mu_y))}{\sigma_x \sigma_y}$$

whereas x_n is the value of the time series x at year n, μ_x is the mean value of x and σ_x is the square root of the variance of x (respectively for y). If missing values occur in one of the time series, the corresponding years are excluded from the computation of the correlation. To test the local significance of the correlations, a double-sided significance test based on a t-distribution (Storch et al. 1999) with $p = 0.05$ is applied. As the GHD series yields no memory and has a nearly white spectrum, no correction for reduced temporal degrees of freedom is necessary.

To obtain spatial correlation pattern of the GHD-climate relationship, the correlation of a single time series with each grid point of a gridded data set is computed. The correlation value of every grid point is displayed as a color in the resulting correlation maps and areas of significant correlation ($p < 0.05$) are highlighted. The location (mean latitude and mean longitude) of the wine area is represented in the correlation maps by a red dot.

As the development of grapevine is first of all influenced by local climate conditions (G. Jones 2003), the relationship of the GHD series with the local temperature is of particular interest. Therefore, local temperature indices are derived from the gridded data sets by bilinear interpolation from the closest grid points. This method is given preference compared to using local station data as (1) the stations are not necessarily at the same location as the wine area and (2) the GHD series are derived by the combination of single series of a whole region which assumably leads to compensation of local climate conditions.

To analyse relationships on decadal-to-multidecadal time scales (in the following denoted as decadal time scales), a low-pass filter is applied on the data prior to the correlation analyses. A finite response filter (cutoff frequency 1/10 year, length = 21 year) is used with the boundary constraint of minimising the first derivative (M. Mann 2004). For the analysis of filtered data, missing values of the GHD series have to be interpolated as they cannot be excluded. The values are derived by a linear model of the GHD and local AAT. As the interpolation can bias the analysis, only GHD series with few (less than 4) missing values for the time from 1750 to 2003 are used for the analyses of decadal relationships (see Tab 1). Furthermore, GHD series which do not contain data for the whole instrumental period are excluded. Hence, only Burgundy, Low Loire Valle, Champagne, Switzerland and Bordeaux are suitable for this analysis. For filtered time series, the significance of the correlation is established by using Monte Carlo experiments in which the same filter is applied on surrogate data ($N = 10000$).

The stability of the correlations over time is analysed by calculating the correlation in a moving window (running correlation). Hereby, a 50-year time window is used and the midpoint of the window is shown in the x-axes of the figures. The local (50 year) significance limit ($p = 0.05$) is shown as a horizontal dashed line.

To analyse the combined influence of winter and summer temperature on the GHD, multiple linear regression is used. Additionally, the Bayesian information criterion (BIC) (Schwarz 1978) is calculated to compare the different regression models. The criterion accounts for the goodness of the fit and penalises models with more variables (Schwarz 1978). To separate the temperature effects of different seasons on the GHD, the partial correlation coefficient is computed (Kendall et al. 1979). It can be defined as

$$\rho_{xy\cdot z} = \frac{\rho_{xy} - \rho_{xz}\rho_{yz}}{\sqrt{1-\rho_{xz}^2}\sqrt{1-\rho_{yz}^2}}$$

whereas ρ_{xy} is the Pearson product-moment correlation of x and y (likewise for the other correlations coefficients). The partial correlation $\rho_{xy\cdot z}$ displays the statistical relationship of the variables x and y while removing the influence of a third variable z. Accordingly, the partial correlation estimates the correlation of the GHD with the temperature of one specific season while removing the effect of the other season.

3 Growing Season Relationship

Table 2: Correlation of the Burgundy GHD with local monthly near-surface temperature from Berkeley (Rohde et al. 2013) for the instrumental period (1900 - 2003). Significant correlation values ($p < 0.05$) are blue. The second row shows the significance level for each correlation.

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ρ	−0.13	0.07	−0.12	−0.23	−0.24	−0.59	−0.59	−0.46	−0.47	−0.13
p	> 0.05	> 0.05	> 0.05	< 0.05	< 0.05	< 0.01	< 0.01	< 0.01	< 0.01	> 0.05

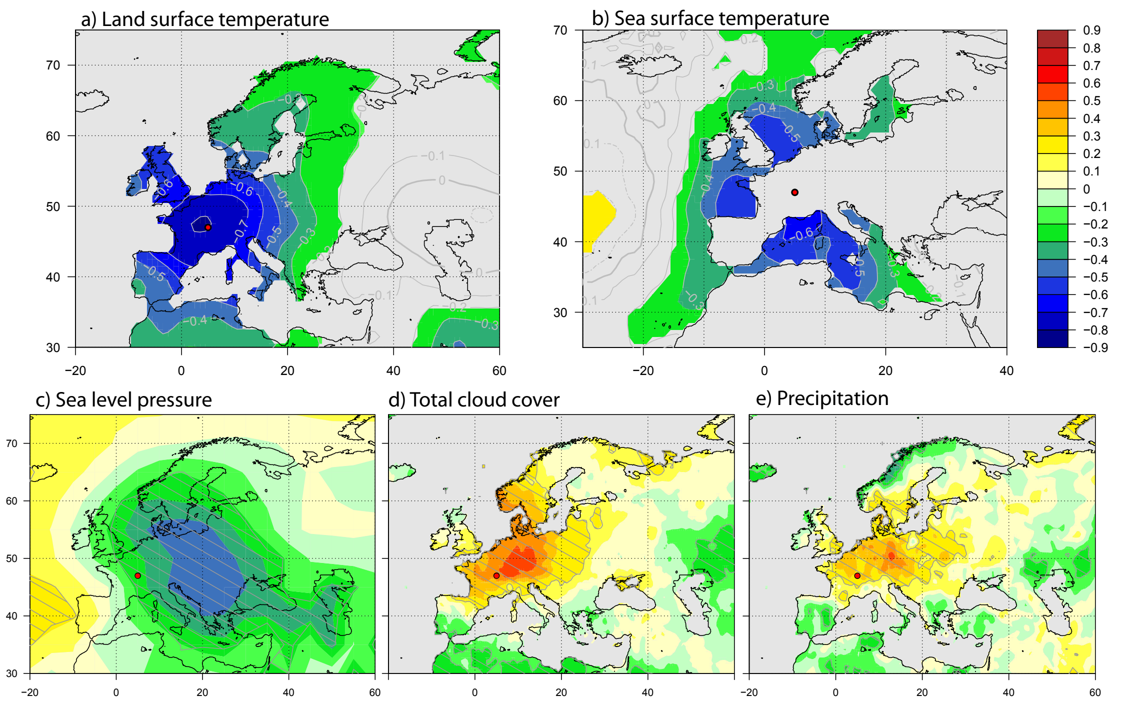

Figure 3: Correlation maps of the GHD with climate variables for the the growing season from April to August: **a)** Berkeley land surface temperature (Rohde et al. 2013), **b)** sea-surface temperature (SST) from Kaplan et al. (1998), **c)** sea level pressure (SLP) from Trenberth et al. (1980), **d)** total cloud cover and **e)** precipitation from CRU (Mitchell et al. 2003). Areas of significant correlation ($p < 0.05$) are coloured for a) and b) and shaded for c), d) and e). The red dot indicates the approximate location of Dijon (Burgundy).

3.1 Results

3.1.1 Instrumental Period

The Burgundy GHD series (Chuine et al. 2004) is correlated with a local temperature index derived from the Berkeley temperature data set (Rohde et al. 2013) for single months in the instrumental period (1900-2003) (Tab 2). The temperature in the months from March to August is significantly negatively correlated. In contrast, the temperature in September is not significantly correlated with the GHD (Table 2). Analysing mean seasonal temperatures, the AAT yields the highest absolute value of correlation with $\rho = -0.80$ ($p < 0.01$). The correlations on interannual time scales with $\rho = -0.82$ ($p < 0.01$, high-pass filtered using a 1/10 year cutoff) and on decadal time scales with $\rho = -0.79$ ($p < 0.01$, low-pass filtered, 1/10 year cutoff) are comparably high.

The field correlation of the GHD and the Berkeley AAT shows that all of Western and Central Europe is significantly correlated (Fig 3 a). The highest correlation is reached in central France close to the location of the Burgundy wine area (red dot). Also the sea surface AAT (Kaplan et al. 1998) around Europe is highly correlated with the GHD (Fig 3 b). Analogies with the temperature correlation can be found in the correlation with averaged April to August data of cloud cover (Fig 3 d) and precipitation (Fig 3 e) from CRU (Mitchell et al. 2003) as well as with SLP (Fig 3 c) according to Trenberth et al. (1980). The correlation maps of cloud cover (d) and precipitation (e) are very much alike with a local positive correlation. In contrast, SLP (c) is negatively correlated with the GHD series.

3.1.2 Pre-Instrumental Period

The pre-instrumental period is tested with the Berkeley AAT from 1750 to 2003 and with the Luterbacher spring/summer temperature back to 1500. Both data sets show the same correlation pattern (Fig 4 a and b) as in the instrumental period (Fig 3 a). While Berkeley AAT shows the same strength of correlation compared to the instrumental period (local index: $\rho = -0.81$), the Luterbacher data exhibits a weaker relationship (local index: $\rho = -0.68$). In the running correlation of the GHD - growing season relationship (Fig 4 c), Berkeley temperature is plotted for the April to August period (red) and for the spring/summer period (blue) as well as Luterbacher temperature for the spring/summer period (black). The developments of these relationships share many similarities: The relationships are stable over the whole period with continuously significant correlation values. Several periods can be distinguished. From ca. 1920 to nowadays, the correlation strengthens. Around 1920, the correlation is weaker. Before, in the 19th century, the correlation is strong and remains very stable. Especially the constancy of the Berkeley AAT correlation is remarkable. Between 1800 and 1890 it is only varying between $\rho = -0.8$ and $\rho = -0.9$. In the second half of the 18th century, the correlation weakens again, as well as before 1600 (only Luterbacher data). The developments of the spring/summer relationships from Luterbacher (black) and Berkeley (blue) are very much alike. The AAT from Berkeley (red) shows a similar development but exhibits most of the time a stronger relationship with the GHD, which is consistent with the overall correlation as shown in Fig. 4 a) and b).

3.1.3 Comparison to other GHD series

All GHD series are significantly ($p < 0.01$) correlated with local temperature as well as with each other (Tab 3). The correlation values with local temperature are always lower than $\rho = -0.6$. The Burgundy GHD series from Chuine et al. (2004) and Daux et al. (2012) are highly correlated and exhibit similar results for all correlations. On average, Burgundy, Low Loire Valley and Champagne show the highest

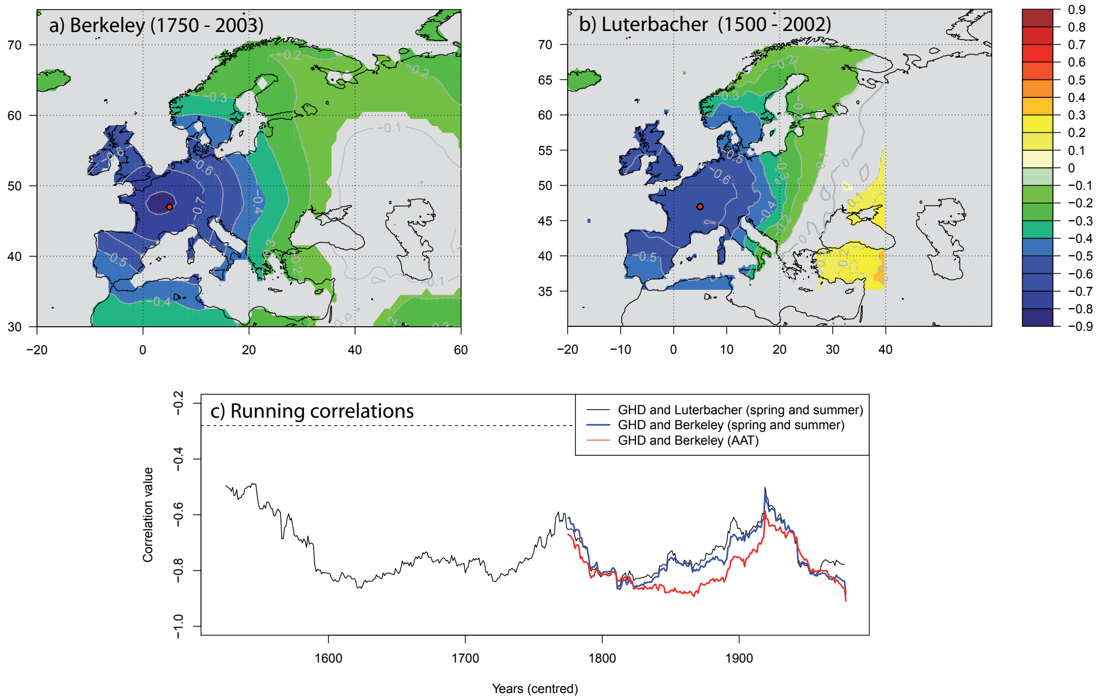

Figure 4: GHD - temperature correlation for the pre-instrumental period with **a)** Berkeley temperature (Rohde et al. 2013) (1750 - 2003) from April to August and with **b)** Luterbacher et al. (2004) spring/summer temperature (1500 - 2002). Areas of significant correlation are coloured ($p < 0.05$). The red dot indicates the approximate location of Dijon (Burgundy). **c)** Running correlation of both data sets. Berkeley temperature is displayed for the spring/summer period (blue) as well as for the April to August period (red). The length of time window is 50 years. The $p = 0.05$ significance level is at $\rho = -0.28$ (dashed line).

absolute values with the other GHD series, whereas Switzerland and Alsace exhibit considerable lower absolute values. It is important to keep in mind that the overlap of data differs from series to series. Therefore, the correlation values are not fully comparable.

According to the analysis of the developments of the AAT-GHD relationship over time (Fig 5), all GHD series basically behave similar to the Burgundy series (black line) as described above. Particularly, the weaker correlation around 1920 is pronounced in all data sets except for Switzerland, which has its weakest correlation in the second half of the 19th century. Furthermore, nearly all GHD series show an increasing correlation during the instrumental period. Two other series slightly differ compared to the other GHDs. The Alsace series generally shows a weaker relationship and the Bordeaux series is distinctly weaker correlated before 1830.

Table 3: Correlation of GHD series with local temperature and with each other over the available length of the records. All correlation values are significant with $p < 0.01$.

	Bur(Ch)	Bur(Da)	LLV	Cha	IDF	Swi	Bor	Jur	Als
Local temperature	-0.81	-0.79	-0.8	-0.76	-0.8	-0.71	-0.68	-0.79	-0.62
Burgundy (Chuine)	1	0.92	0.82	0.84	0.69	0.6	0.69	0.8	0.63
Burgundy (Daux)	0.92	1	0.81	0.83	0.72	0.58	0.66	0.78	0.6
Low-Loire-Valley	0.82	0.81	1	0.74	0.8	0.72	0.76	0.74	0.52
Champagne	0.84	0.83	0.74	1	0.83	0.6	0.72	0.7	0.68
Ile-de-France	0.69	0.72	0.8	0.83	1	0.54	0.7	0.73	0.61
Switzerland	0.6	0.58	0.72	0.6	0.54	1	0.61	0.69	0.63
Bordeaux	0.69	0.66	0.76	0.72	0.7	0.61	1	0.65	0.62
Jura	0.8	0.78	0.74	0.7	0.73	0.69	0.65	1	0.54
Alsace	0.63	0.6	0.52	0.68	0.61	0.63	0.62	0.54	1

3.2 Discussion

The near-surface temperature over France from April to August is highly correlated with the GHD (Fig 3). The time from April to August coincides with the vine phenology stages before bloom and veraison (G. Jones 2003), which are highly temperature dependent and crucial for the GHD (Chuine et al. 2004; Meier et al. 2007; Menzel 2005). In contrast, the September temperature is not significantly correlated with the GHD (Table 2), although the average GHD is at 27th September. This is consistent with the fact that the time from veraison to harvest is nearly constant and temperature independent (Chuine et al. 2004; Garcia de Cortazar-Atauri et al. 2010). The correlation pattern (Fig 3) shows that the GHD acts like a local temperature proxy as the correlation of a maximal growing season temperature time series of France (April-to-September) with European temperatures results in a similar pattern (Etien et al. 2009). This observation was also made by Daux et al. (2012).

Besides the land surface temperature relationship, other data sets are related to the GHD as well: The sea surface temperature of the offshore sea surrounding Europe shows a strong connection to the GHD (Fig 3 b). This implies that the GHD is in relationship with large-scale climate patterns. Furthermore, cloud cover and precipitation are positively correlated across France, whereas SLP, by contrast, is negatively correlated (Fig 3 c,d,e). These three results fit together with the temperature result, because high sea level pressure, slight cloud cover and slight precipitation are signs of fair weather, and are thus in connection with high temperature, and vice versa.

The analysis of the GHD-AAT relationship leads to very consistent results for the instrumental period and is furthermore confirmed by pre-instrumental data as Berkeley AAT yields a similar results for the period 1750 - 2003 (Fig 4 a) compared to the instrumental period (Fig 3 a). Luterbacher spring/summer temperature from 1500 to 2002 exhibits the same pattern but with slightly lower correlation values (Fig 4 b). The robustness of the GHD-AAT relationship is also displayed by the running correlations (Fig 4 c). Berkeley AAT (red line) and Luterbacher spring/summer temperature (black line) principally show the same behaviour. The correlation is always significant and is properly stable with correlation values lower than $\rho = -0.4$. The stronger correlation of Berke-

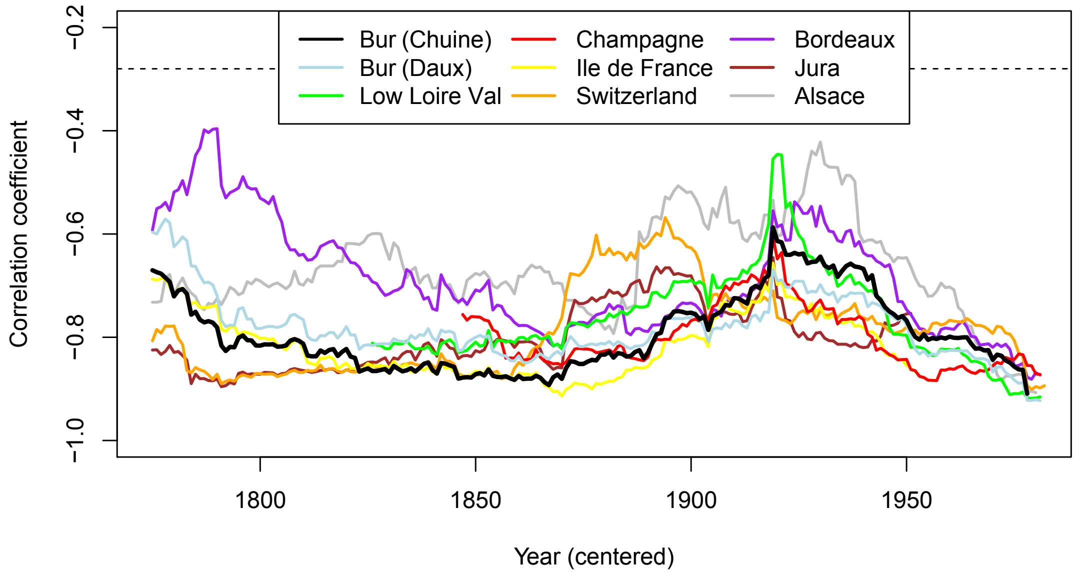

Figure 5: Running correlation of GHD series from several locations with its corresponding local AAT. The length of time window is 50 years. The $p = 0.05$ significance level is at $\rho = -0.28$ (dashed line).

ley AAT (red line), particularly in the 19th century, can be explained by the different time periods used as Berkeley spring/summer temperature (blue line in Fig 4 c) similarly develops as Luterbacher spring/summer temperature (black line in Fig 4 c). This also supports the preference of the AAT over the spring/summer temperature.

Some periods of particularly weaker correlation have to be considered. For the time before 1600, flaws of the GHD series possibly lead to a weaker correlation (Daux et al. 2012). This effect could be furthermore superposed by lower quality of the temperature data. The time around 1920 shows a comparable weak correlation, which is even more pronounced on decadal time scales (black solid line in Fig 7 c). As it is very unlikely caused by low quality of the temperature data, it must be determined by flaws of the Burgundy GHD series or climate changes. The likewise occurrence in most of the other GHD series (Fig 5) indicates rather a general effect than a singular defect of the Burgundy GHD series.

A climatic explanation was given by Krieger et al. (2011) which is based on the assumption that the decadal winter temperature acts as a second climate impact on the GHD and therefore affects the GHD-AAT relationship. This assumption is elaborated and surveyed later in this thesis. In addition, there are non-climatic explanations for the weaker correlation around 1920. Firstly, the phylloxera outbreak, which started to spread in 1863, and other plant diseases greatly affected the France vineyards, significantly lowered the wine production, and lead to a disorganised wine production for many years (Daux et al. 2012). The disorganisation was secondly enhanced by law changes. The former strong municipal regulation of the harvest date disappeared in most of the French areas from 1889 until new laws were enacted in 1907 (Daux et al. 2012). Thirdly, the First World War could have biased the GHD.

GHDs from different European locations support the result of the Burgundy series, as most of them exhibit comparably high correlation values with local temperature around $\rho = -0.8$ (Tab 3) and a similar development of the running correlations (Fig 5). From all locations, Alsace yields the weakest correlation ($\rho = -0.62$) indicating a lower data quality, which is likewise reflected by the fact that Alsace shows the weakest correlations with other GHD series on average (Tab 3). This effect is also represented by other wine areas: GHD series, who are weaker correlated with local temperature, tend to have weaker correlations with other GHD series (Tab 3). Accordingly, the correlations between GHD series provide useful informations about the quality of the GHD series even if no temperature data are available. By performing running correlations between GHD series, periods of lower data quality could be identified, which would benefit temperature reconstructions based on GHDs. However, it has to be considered that the correlation between the GHD series is furthermore influenced by the locations of the vineyards. As might be expected, close wine areas like Champagne and Burgundy, Ile de France and Low Loire Valley or Jura and Burgundy show stronger correlations than wine areas with higher distance as Alsace and Bordeaux or Switzerland and Ile de France (Tab 3).

In summary, the GHD-AAT relationship is well represented by all analysed data sets and can be confirmed by the available temperature reconstructions for the pre-instrumental period. GHDs have already been used for temperature reconstruction (Chuine et al. 2004; Etien et al. 2008; Guiot et al. 2005), but only for local time series reconstructions. The recently available GHD data base (Daux et al. 2012) would furthermore allow *spatial* growing season temperature reconstruction as well as offshore SST reconstruction based on grape harvest dates. The correlation maps obtained in the instrumental period could be used to weight the contribution of a particular GHD series on every grid point.

4 Winter Relationship

4.1 Results

4.1.1 Instrumental Period

Table 4: Correlation of the Burgundy GHD with local monthly near-surface temperature from Berkeley (Rohde et al. 2013) for the instrumental period (1900 - 2003). All data are lowpass filtered using a 1/10 year cutoff. Significant correlation values (p <0.05) are blue. The second row shows the significance level for each correlation.

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ρ	-0.36	-0.46	-0.52	-0.66	-0.31	-0.67	-0.55	-0.46	-0.78	-0.11
p	> 0.05	< 0.05	< 0.05	< 0.01	> 0.05	< 0.01	< 0.01	< 0.05	< 0.01	> 0.05

For decadal time scales, correlations of the monthly France temperature index with the GHD are shown in Table 4 (low-pass filtered data using a 1/10 year cutoff). From December to August, the correlation coefficient is always below -0.3. The correlations from January to March and from May to August are statistically significant. In contrast to the unfiltered analyses (Table 2), the local GHD-temperature relationship shows a pronounced winter signature. Two winter seasons are tested. December - February (DJF) temperature exhibits a local correlation with the GHD of $\rho = -0.61$, whereas December - March (DJFM) temperature and the GHD are correlated with $\rho = -0.71$. The GHD-winter correlation, however, could be caused by the strong AAT-GHD relationship ($\rho = -0.79$ on decadal time scales) if AAT and winter temperature are highly correlated as well. This is the case for DJFM, whose correlation with the AAT is $\rho = -0.54$ (significant with $p < 0.01$). It is therefore not appropriate to discuss the GHD-winter relationship. In contrast, the DJF season only shows a weak and not significant correlation with the AAT ($\rho = -0.26$) and will be used for the further analysis.

The correlation map of GHD and DJF temperature on decadal time scales (Fig 6a) exhibits a pronounced pattern. Western, Central, and Eastern Europe are significantly negatively correlated. In contrast, the correlation of the filtered AAT time series (with reversed sign) with the winter temperature is much weaker than the GHD-winter temperature relationship (Fig 6b). There is no significant AAT-DJF correlation in France on decadal time scales (Fig 6b).

As described above, the GHD is correlated with the AAT and the decadal DJF temperature. To quantify the seasonal contributions, the GHD was modelled using a multivariate linear model with the AAT and the decadal DJF temperature as predictor variables. For the instrumental period, both variables significantly contribute ($p < 0.01$) to the GHD variations with slopes -8.1 ± 0.6 days/K for the AAT and -3.1 ± 0.8 days/K for the decadal DJF temperature, respectively. According to the Bayesian information criterion (BIC) (Schwarz 1978), this model is preferred to the univariate regression models GHD-AAT and GHD-DJF temperature.

The developments of the decadal GHD-temperature correlations over time are shown in Fig. 6 c) (solid lines). Both correlations strengthen during the instrumental period towards the end of the 20th century with continuously negative correlation values. The decadal AAT-GHD relationship exhibits

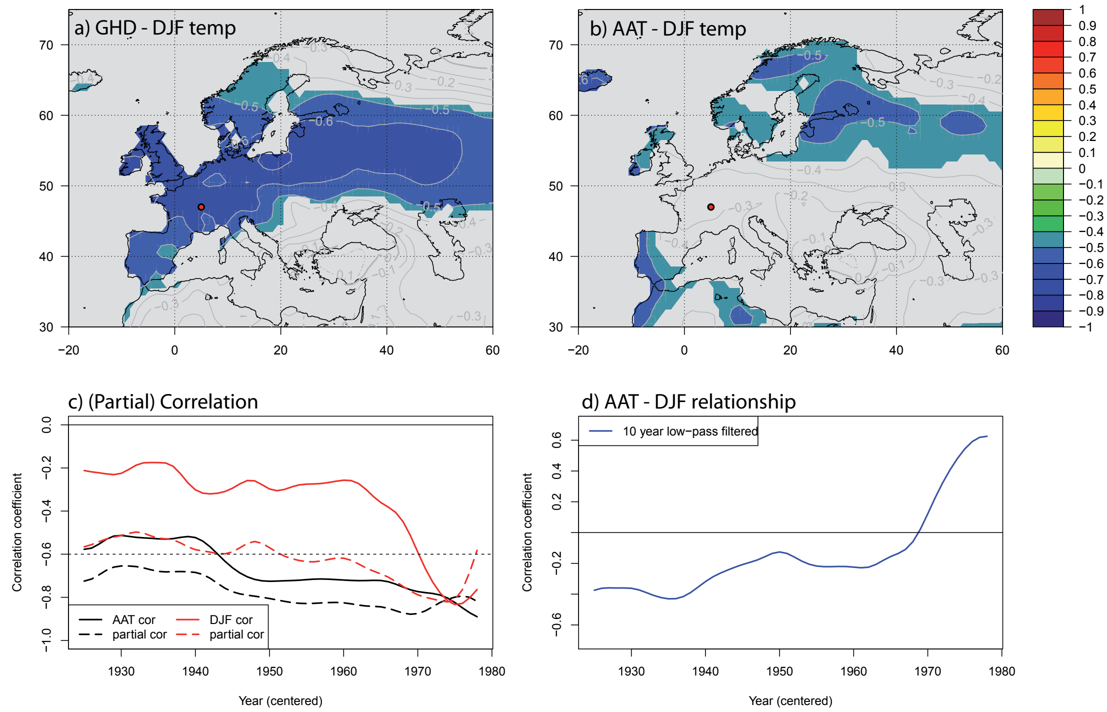

Figure 6: Correlation map of the winter (DJF) near-surface temperature with **a)** the Burgundy GHD and **b)** the local Burgundy AAT time series on decadal time scales (1900-2003). Areas of significant correlation are coloured ($p < 0.05$). **c)** Comparison of the development of the full correlation (solid lines) and the partial correlation (dashed lines) for the GHD-AAT relationship (black) and the GHD-DJF temperature relationship (red) on decadal time scales. In the partial correlation, the influence of the corresponding second variable is eliminated (see section 2 for the details). **d)** Running correlation of AAT and DJF temperature on decadal time scales. The length of the time window is 50 years. **c)** and **d)** The $p = 0.05$ significance level is at $\rho = \pm 0.6$. For all plots, the data were low-pass filtered prior to the correlation using a 1/10 year cutoff.

a significant ($p < 0.01$) correlation of $\rho = -0.76$ for the whole period, while the running correlation slightly strengthens during the instrumental period (black solid line). The DJF-GHD relationship is likewise significantly ($p < 0.01$) correlated over the whole period with $\rho = -0.61$, however, the running correlation is unstable (red solid line). It is rather weak from 1920 to 1960 (centred years), with the lowest amount of correlation in 1934 ($\rho = -0.17$), and then abruptly strengthens from 1961 ($\rho = -0.26$) to 1975 ($\rho = -0.83$).

As the GHD is connected to the AAT and to the decadal winter temperature, the partial correlations (ρ_{par}) of both seasons on decadal time scales are of interest as they show the unique contributions of one specific season to the GHD. Calculated over the whole instrumental period, the partial correlations are slightly stronger compared to the full correlations. (GHD-AAT: $\rho_{par} = -0.79$ and $\rho = -0.76$; GHD-DJF: $\rho_{par} = -0.67$ and $\rho = -0.61$). The developments of the partial correlations (dashed lines in Fig 6 c) differ from the full correlations. For both seasons, they are more stable than the full correlations. Especially the DJF-GHD partial correlation is much stronger than the full

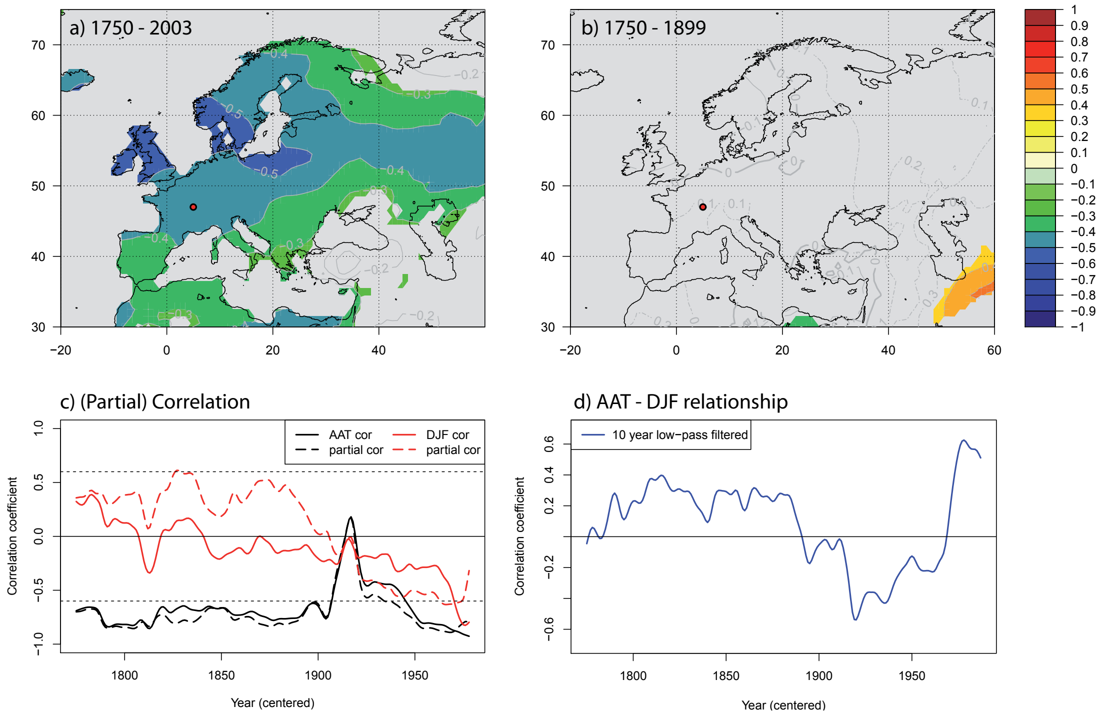

Figure 7: a) and **b)**: Correlation of the winter (DJF) near-surface temperature with the GHD for a) 1750 - 2003 and b) 1750 to 1899. Areas of significant correlation are coloured ($p < 0.05$). **c)** Comparison of the development of the full correlation (solid lines) and the partial correlation (dashed lines) for the GHD-AAT relationship (black) and the GHD-DJF temperature relationship (red) on decadal time scales for 1750 - 2003. In the partial correlation, the influence of the corresponding second variable is eliminated (see section 2 for the details). **d)** Running correlation of AAT and DJF temperature on decadal time scales for 1750 - 2003. **c)** and **d)** The length of the time window is 50 years. The $p = 0.05$ significance level is at $\rho = \pm 0.6$ (dashed lines). For all plots, the data were low-pass filtered prior to the correlation using a 1/10 year cutoff.

correlation before approximately 1974 with a difference of $\Delta\rho = 0.4$ for most of the time. After approximately 1974, both partial correlations are weaker than the full correlations.

The development of the decadal AAT-DJF relationship in Fig. 6 d) reveals that the correlation is negative before ca. 1970 and raises afterwards to high positive values. This development is linked to the relation of partial and full correlation in Fig. 6 c): When the AAT-DJF correlation is negative, both partial correlations are lower than the full correlation, which is the case before 1970. In the period of positive AAT-DJF correlation between 1970 and 1980, both partial correlations are higher than the full correlations. The AAT-DJF relationship furthermore resembles well the development of the decadal GHD-DJF temperature relationship with reversed sign (red solid line in Fig. 6 c).

4.1.2 Pre-Instrumental Period

Unlike the growing season relationship, the winter results cannot be confirmed by the pre-instrumental period (Fig 7). The overall correlation from 1750 to 2003 in a) is, although significant, much lower (local index: $\rho = -0.43$) than for the instrumental period in Fig 6 a) (local index: $\rho = -0.61$). Furthermore, there is no considerable correlation over Europe at all during the pre-instrumental period (1750 - 1899) (Fig 7 b) and the local index is even positively correlated with $\rho = 0.11$.

This is likewise reflected in the running correlation in Fig 7 c). During the pre-instrumental period (before 1900), there is no noteworthy correlation of the DJF - GHD relationship (red solid line). The partial correlation of DJF and GHD (red dashed line) is even always positive for the pre-instrumental period and considerably higher than the full correlation. The decadal AAT-GHD relationship (black full line) is, in contrast, stable, except for the time around 1920. The partial AAT-GHD correlation (black dashed line) in the pre-instrumental period only slightly differs from the full correlation.

The AAT-DJF relationship (Fig 7 d) is mainly positive for the pre-instrumental period with a mean value around $\rho = 0.2$. In the instrumental period, a positive AAT-DJF correlation is linked with a higher partial than full correlation (cf. Fig 6 c and d). In the pre-instrumental period, this is only the case for the DJF-GHD relationship and not for the AAT-GHD relation. Unlike in the instrumental period, the development of AAT-DJF relationship and GHD-DJF relationship do not show any similarities before 1900. The Luterbacher data set reveals similar results for the development of winter and growing season relationship (not shown).

4.1.3 Comparison to other GHD series

The winter relationship is also tested with all suitable GHD series, which are Low Loire Valley, Switzerland, Champagne and Bordeaux. All data sets show similar results for the pre-instrumental period from 1750 - 1899 (not shown): Like for the Burgundy GHD series, there is no significant and noteworthy correlation before 1900.

In the instrumental period, results differ from series to series (Fig 8). However, all data sets share some specific features. For all correlation maps (left side), the center of strongest correlation tends to be located more in the East of Europe and not at the proxy location (red dot). For all running correlations (right side), the full correlation strengthens towards the end of the 20th century. Furthermore, the partial correlation is always lower than the full correlation before approximately 1970 and higher than the full correlation after 1970, which is consistent with the development of the AAT - DJF relationship in Fig 6 d). These similarities are shared with the Burgundy GHD series.

Beyond that, some differences between the data sets occur. Only Low Loire Valley (a_1) and Switzerland (b_1) show a pronounced winter signature where most of Europe is significantly correlated. The local correlation is $\rho = -0.44$ for Low Loire Valley and $\rho = -0.50$ for Switzerland. In contrast, Champagne (c_1) and Bordeaux (d_1) show a weaker pattern with no significant local correlation ($\rho = -0.36$ for both series). For the running correlations, only Low Loire Valley (a_2) resembles the results of the Burgundy GHD series: The partial correlation is considerable lower than the full correlation before 1970 and is more stable than the full correlation when considering the whole period. In all other cases

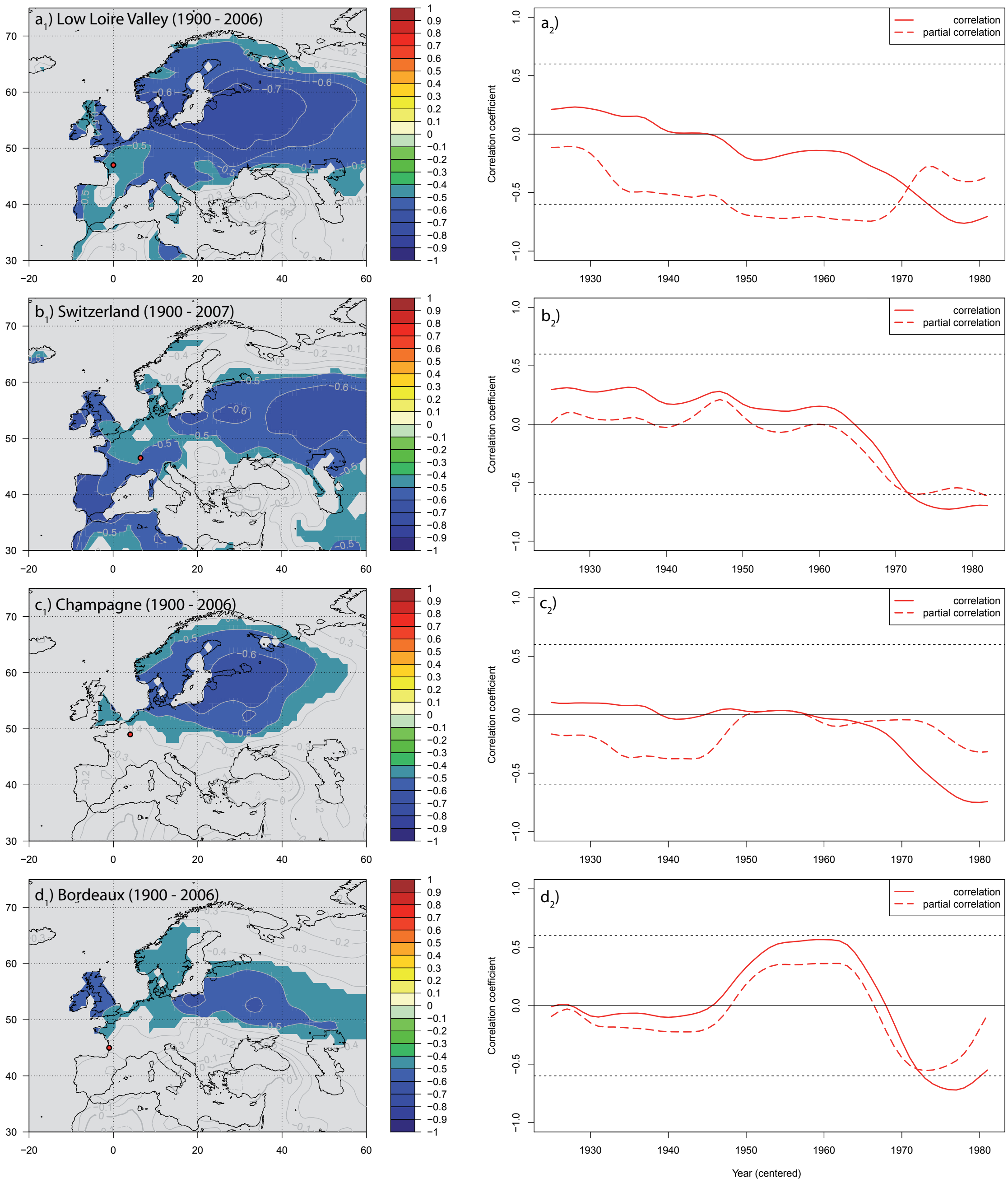

Figure 8: Correlation maps (left side) and running full and partial correlations (right side) for the GHD - DJF relationship on decadal time scales. The used GHD series are **a)** Low Loire Valley (1900 - 2006), **b)** Switzerland (1900 - 2007), **c)** Champagne (1900 - 2006), **d)**, Bordeaux (1900 - 2006). In the correlation maps, areas of significant correlation are coloured ($p < 0.05$). The red dot indicates the location of the wine area. The running correlations are computed for the full (solid lines) and the partial (dashed lines) correlation. The length of the time window is 50 years. The $p = 0.05$ significance level is at $\rho = \pm 0.6$ (dashed lines). For all plots the data were low-pass filtered prior to the correlation using a 1/10 year cutoff.

(b_2, c_2 and d_2), the partial correlation is never significant, only slightly lower than the full correlation and not more stable than the full correlation.

4.2 Discussion

As stated above, the winter temperature was suggested to impact the GHD on decadal time scales (Krieger et al. 2011). The winter impact hypothesis is indicated by the strong correlation of the Burgundy GHD with the winter temperature on decadal time scales during the instrumental period (1900 - 2003) (Fig 6 a). This significant correlation of $\rho = -0.61$ (local index) does not necessarily imply a direct GHD-winter relationship. It could also mean that the winter temperature influences the AAT and, in this way, indirectly impacts the GHD. However, the weakness of the AAT-winter temperature relationship compared to the GHD-DJF relationship suggests a direct winter influence on the GHD (cf. Fig 6 a and b).

This is also affirmed by the multivariate regression model. The prediction of the GHD is more accurate when the decadal winter temperature is taken into account. According to the Bayesian information criteria (BIC), this model is preferred to the univariate regression models. As the influence of the AAT is approximately three times larger, the GHD is first of all influenced by the AAT conditions and in a second order by a long-term winter impact.

One may ask whether the decadal winter relationship could have a biological meaning. In winter, the grape vine breaks the dormancy state, and the post-dormancy period starts, in which the development of the plant is prevented due to external conditions (Cortázar-Atauri et al. 2009). Temperature is one of several conditions which causes the end of the dormancy state (Lavee et al. 1997). On interannual time scales, the winter temperature has no influence on the time of flowering (Williams et al. 1985; Cortázar-Atauri et al. 2009; Nendel 2010) and, consequently, does not impact the GHD. This is in accordance with the fact, that there is no significant correlation on interannual time scales during the winter months (Table 2), but this does not exclude an impact on decadal time scales. The long-term winter relation might be connected to the fact that plants exhibit complex internal timing mechanisms (Rensing et al. 2001) including long-term memory (Trewavas 2003; Gális et al. 2009). Information of environmental signals are stored in various forms, e.g. by changes of molecule concentration (Gális et al. 2009) or by morphological changes (Trewavas 2003). The memory of plants exists on different time scales (Gális et al. 2009) up to genomic change due to abiotic or biotic stress (Molinier et al. 2006). Thus, it can be speculated that the vine adapts to winter conditions on decadal time scales. For example, its development starts earlier after several mild winters, and vice versa.

The assumption of a winter impact on the GHD furthermore gives an explanation for the change in correlation during the 20th century for both AAT-GHD and DJF-GHD relationship. If the GHD is not only influenced by the AAT but also by the decadal winter temperature, the observed GHD-AAT correlation additionally depends on the relationship of the growing season temperature to the winter temperature: A negative AAT-DJF relation would weaken the observed GHD-AAT correlation and a positive AAT-DJF relation would strengthen the observed GHD-AAT correlation. This is demonstrated by the partial correlation analysis, which estimates the GHD-AAT correlation while removing the effect of the winter temperature. The change of the partial correlation is less pronounced than the full correlation (dashed and solid black line in Fig 6 c). This is consistent with the changing AAT-winter relationship (cf. Fig 6 c and d): The GHD-AAT correlation is weaker than the partial correlation when the AAT-winter relationship is negative (centred: 1925-1970), and vice versa (centred: 1970-1980).

This effect is even more pronounced for the decadal GHD-DJF temperature relationship, which also increases during the instrumental period (red line in Fig 6 c). As the decadal DJF temperature has a much lower influence on the GHD compared to the AAT, the GHD-DJF temperature relationship is more sensitive to changes in the DJF-AAT relationship: Its development (red line in Fig 6) is very similar to the development of the decadal DJF-AAT relationship (Fig 6 d). Furthermore, the partial correlation, independent of the decadal AAT, changes only moderately (dashed red line in Fig 6c). This implies that the impact of the DJF temperature on the GHD (without AAT influence) is for the most part stable and would support the robustness of the winter result.

To sum up, the assumption that the winter temperature impacts the GHD is very consistent for the instrumental period and the Burgundy GHD series. In addition, it partly explains the changes of the correlations during the instrumental period. For the pre-instrumental period, however, the winter impact hypothesis cannot be confirmed for three main reasons:

(1) Even though there is a significant correlation pattern for the whole period (1750 - 2003) (Fig 7 a), it is only caused by the last period (1900 - 2003), as the pre-instrumental period (before 1900) does not exhibit any correlation at all (Fig 7 b). This is also displayed by the running correlation. In the pre-instrumental period, the DJF-GHD relationship fluctuates around $\rho = 0$ (red solid line Fig 7 c).

(2) For the instrumental period it was argued that the winter relationship is strong when AAT and DJF temperature are positively correlated, which is the case for the time after ca. 1970 (cf. red solid line in Fig 7 c and Fig 7 d). This does not hold true for the pre-instrumental period. While AAT and DJF temperature are slightly positive correlated before ca. 1900, the winter temperature and GHD are not correlated at all. The partial correlation is even positive (red dashed line).

(3) In contrast to the instrumental period, the decadal AAT-GHD relationship (black line in Fig 7 c) is always very stable during the pre-instrumental period independently of the DJF-AAT relationship, which contradicts the winter impact hypothesis.

The Luterbacher data set exhibits the same behaviour for the pre-instrumental period (not shown). Several reasons can be mentioned to be careful with the interpretation of pre-instrumental reconstruction data. According to Riedwyl et al. (2009), reconstructed winter temperatures generally seem to be less accurate than reconstructed summer temperatures. Furthermore, reconstructions which are based on regression methods substantially underestimate low-frequency temperature variations (Storch et al. 2004). Thus, it can be suspected that the pre-instrumental reconstructions are limited to display the decadal variations of the winter temperature. Even by taking this into account, it is questionable why the pre-instrumental period does not show any winter correlation at all. Moreover, all analysed GHD series from other locations show the same behaviour for the pre-instrumental period. None of them yield any considerable correlation before 1900.

If only the instrumental period is considered, the analysis of other GHD series does not exhibit such a clear result like for the pre-instrumental period. Low Loire Valley shows a quite similar behaviour compared to the Burgundy GHD series. The winter temperature is significantly correlated (Fig 8 a_1), the partial correlation is more stable than the full correlation and the developments of partial and full correlation are similar to the Burgundy series (Fig 8 a_2). The only difference is that the Burgundy GHD is stronger correlated with the winter temperature. The Switzerland GHD series exhibits a significant negative correlation (Fig 8 b_1) but not a conclusive running correlation as the partial correlation is not particularly more stable than the full correlation (Fig 8 b_2). In contrast to the Burgundy GHD series, Champagne and Bordeaux show neither a significant local correlation nor a similar development of the running correlations (Fig 8 c and d). Switzerland, Champagne and Bordeaux have in common that the winter relationship only occurs after 1970.

To sum up, the other GHD series do not conclusively support the result of the Burgundy GHD for the instrumental period and no data set shows any sign of a winter impact during the pre-instrumental period. Despite extensive analysis, no comprehensive reason could be found to explain why Burgundy and partly Low Loire Valley indicate a winter temperature impact during the instrumental period. It can be only suspected that the strong GHD-DJF relationship after 1970, which is shared by all GHD series, occurred statistically by chance. This is at least possible, as the GHDs are highly correlated between each other as well as the local temperature indices (more than $\rho = 0.9$ for the instrumental period).

5 Conclusion

This study analyses the seasonal climatic impacts on the GHD in Burgundy (France) (Chuine et al. 2004) during the instrumental period (1900 to nowadays) and establishes the spatial pattern for interannual and decadal variability. The April to August temperature (AAT) and the decadal winter temperature are found to possibly influence the GHD. Whereas the AAT impact is well established (Chuine et al. 2004; Meier et al. 2007; Menzel 2005), the winter impact was not documented before. The results for both seasons are compared with the pre-instrumental period (1500 - 1899) and with GHD series from other European locations.

As to the AAT impact, it can be affirmed that the GHD is mainly influenced by the local growing season temperature from April to August. This relation is furthermore reflected by other variables like SST, SLP, total cloud cover and precipitation. The GHD - AAT relationship is also confirmed by pre-instrumental data. Berkeley temperature (1750 - 2003) as well as Luterbacher temperature (1500 - 2002) exhibit correlation pattern similar to the instrumental period. The robustness of the result indicates the reliability of both the GHD and the pre-instrumental data sets. GHD series from other European regions support the outcome of the Burgundy GHD series as most of them yield comparably high correlation values with the AAT. Thus, the open-access data-base of different GHD series by Daux et al. (2012) bears the potential for more reliable growing season temperature reconstructions in the future as they can base on documentary GHD records from several wine areas. The comparison of running correlations between different GHD series would therefore allow to detect flawed periods of particular GHD series. Furthermore, the data base offers the possibility for spatial temperature reconstruction in Western Europe.

The GHD - winter temperature relationship is indicated by the analysis of decadal relationships for the Burgundy GHD series during the instrumental period. The winter temperature is significantly correlated on decadal-to-multidecadal time scales and affects the GHD independently of the AAT. Consequently, a multivariate regression model with AAT and decadal winter temperature as predictors was found to be the best model to describe the Burgundy GHD for the instrumental period. As plants can store information on different time scales from environmental signals to optimise their fitness in nature (Gális et al. 2009), the winter impact could be a sign for a long-term adaptation of the vine plant to climatic winter conditions. However, other GHD series only partly represent the winter relationship for the instrumental period and some of them do not show any winter signature at all. Moreover, none of the GHD series confirms the winter relationship for the pre-instrumental period. Even though the reliability of pre-instrumental winter temperature on decadal-to-multidecadal time scales is questionable, it cannot explain the complete breakdown of the correlation before 1900. In summary, arguments are predominating that the GHD-DJF relationship cannot be interpreted as second climate impact on the GHD. Accordingly, the winter hypothesis presented in this study is to be dismissed. For reconstruction matters this is an advantage as the reconstruction of the growing season temperature is not biased by a second climate impact. It remains an open question whether the instrumental GHD-DJF relationship occurred statistically by chance or can be explained by other theories. Analysis of high quality GHD series outside Europe would help to clarify this.

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Hiermit bestätige ich, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe.

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Bremen, April 29, 2014