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Climate of the Past

Seasonal climate impacts on the grape harvest date in Burgundy (France)

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Abstract. In this study, we analyse the climatic impacts on the grape harvest date (GHD) in Burgundy (France) on interannual and decadal time scales. We affirm that the GHD is mainly influenced by the local April-to-August temperature (AAT) and provide the spatial expansion of this relationship. The spatial correlation pattern yields similar results for the instrumental and pre-instrumental period, indicating the consistency of the pre-instrumental field data with the instrumental GHD-spring/summer relationship. We find a previously undocumented second climate impact on the GHD. The winter temperature is significantly correlated with the GHD on decadal-to-multidecadal time scales and affects the GHD independently of the AAT. A multiple linear regression model, with AAT and decadal winter temperature as predictors, was found to be the best model to describe the GHD time series for the instrumental period. Stability tests of the correlations over time yield that both impacts on the GHD, AAT and decadal winter temperature, strengthen during the instrumental period. Using partial correlation analysis, we demonstrate that this is partly caused by a change in the winter–spring/summer temperature relationship. Summarising, the GHD is well suited to reconstruct interannual variations of the spring/summer temperature over large parts of Europe, even if the changing winter–spring/summer relation might affect the reconstruction in a second order. For decadal time scales, the December-to-August temperature shows the strongest relationship to the GHD and, therefore, proposes that the GHD can be used for European temperature reconstructions beyond the spring/summer season. Finally, we argue that our findings regarding the changed winter–spring/summer relation are relevant for physical and biological systems in several ways and should be analysed by other long-term proxy data and available model simulations.

1 Introduction

Instrumental observations of the last 50 to 100 years indicate large interannual to multidecadal climate variability (Jones and Briffa, 1992; Dima and Lohmann, 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., Mann et al., 1999; Jones and Briffa, 1992; Esper et al., 2002; Rimbu et al., 2001; Lohmann et al., 2004; Luterbacher et al., 2004).

A particular proxy dataset is the annually varying grape harvest date (GHD). GHDs have been documented in many European locations for several centuries (Brázdil et al., 2008; Le Roy Ladurie and Baulant, 1980; Meier et al., 2007). All major phenology stages of the grapevine strongly depend on climate conditions (Jones, 2003). The temperature during the stages before bloom and before veraison was found to be the most crucial for the GHD (Chuine et al., 2004; Garcia de Cortázar-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 Cortázar-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

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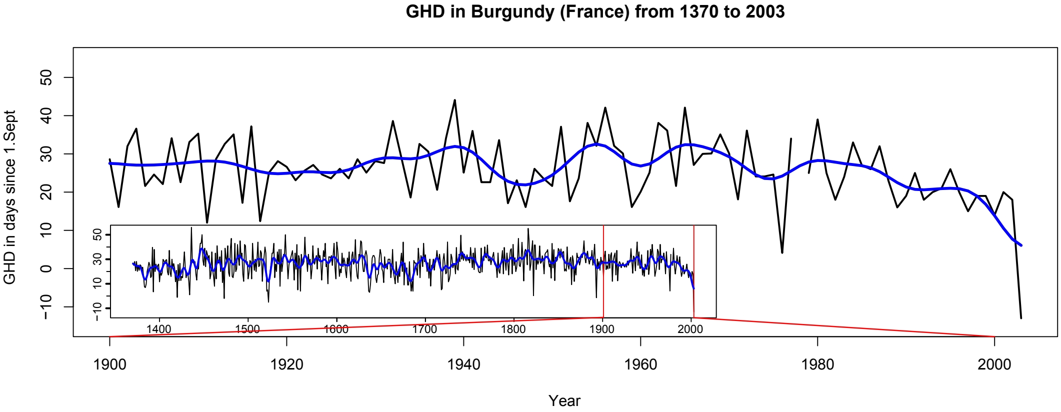

Fig. 1. GHD series (Chuine et al., 2004) of the Burgundy region in France from 1370 to 2003 (in days since 1 September). The instrumental period is emphasised in the main panel as this period is of particular interest in this study. Blue line: decadal variations (low-pass filtered data using a 1/10 year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

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., 2010). In the case of the Burgundy region in France, several homogeneous GHD series are available and are combined into 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 Cortázar-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; 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 when discussing 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 and Yiou (2001), who found a relationship to the North Atlantic Oscillation (NAO). A different approach in analysing the GHD was performed by Schleip et al. (2008), who used the Bayesian analysis to examine temperature impacts on the GHD. Thereby, the June temperature was found to be most important for the GHD.

However, possible changes in the GHD-climate relation and the seasonal dependence of the GHD have not been analysed in detail yet. Garcia de Cortázar-Atauri et al. (2010) found an increase of the GHD-AAT relation for the Paris and Burgundy GHD series during the 20th century. Independent of this, Meier et al. (2007) noted a similar trend for the Swiss GHD series. This indicates a general effect and raises the question whether there may be other than spring/summer climatic impacts on the GHD. In this study, we focus on the seasonal dependence of the GHD in Burgundy (France) and address the following research questions: 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?

2 Methods and data

The GHD series (Fig. 1) is taken from Chuine et al. (2004) and 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, and the remaining 17 series were standardised to the same average harvest date as the reference series. The final GHD series presents the median date for each year of all 18 datasets (for detailed description see Chuine et al., 2004). As the Dijon series is the reference series, we mark the location of Dijon in the resulting correlation maps.

We analyse the seasonal climate impacts on the GHD in Burgundy during the instrumental period, which we define as the time period 1901–2002. We have excluded the last year 2003 from our analysis, since in this extreme summer the GHD is known to be biased and to be a poor indicator of temperature (Keenan, 2007). As the Burgundy GHD series is a composite of several independent GHD series (Chuine et al., 2004) and as the vine varieties and the wine type did not change (Garcia de Cortázar-Atauri et al., 2010), it is reasonable to assume that climate variability was the main driver for the GHD variations in the instrumental period.

The climate impacts are investigated by analysing the correlation of the GHD series and gridded temperature datasets. A monthly near-surface temperature dataset is taken from the Climate Research Unit (CRU) (Mitchell et al., 2003) and covers the years from 1901 to 2002 ($0.5° \times 0.5°$). Additionally, we analyse the reconstructed temperature dataset from Luterbacher et al. (2004) covering the period 1500 to 2002 ($0.5° \times 0.5°$). Field correlation maps of the GHD time series and temperature fields are computed to investigate the spatial range of the relationships. Furthermore, several seasonal and monthly France temperature indices are derived by averaging over the area 5.5° W to 6° E and 42° N to 51.5° N. Seasonal indices are the AAT, the winter (DJF = December January February) temperature and the December-to-August temperature. In case of the Luterbacher et al. (2004) reconstruction dataset, we use the spring-summer (MAMJJA = March April May June July August) temperature instead of the AAT to take the whole period into account (monthly data are only available for 1659–2002). We also use the NAO index based on the difference of normalised sea level pressures (SLP) between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland (NAO Index Data provided by the Climate Analysis Section, NCAR, Boulder, USA; Hurrell, 1995).

In our analysis, we use the Pearson product-moment correlation, as the empirical relationship of the GHD with temperature does not show any systematic deviations from linearity (not shown). However, similar results are also obtained using Spearman's rank correlation. The missing value of the GHD for the year 1978 is excluded in the correlation process, except when using filtered data. In this case, linear interpolation is used to fill the missing year.

To test the local significance of the correlations, we apply a double-sided significance test based on a t-distribution (von Storch and Zwiers, 1999) with $p = 0.05$. As the GHD series yields no memory and has a nearly white spectrum, no correction for reduced temporal degrees of freedom has to be made. In the correlation maps, areas of locally significant correlation are coloured. To analyse the relationships on decadal-to-multidecadal time scales (in the following denoted as decadal time scales), we apply a low-pass filter on the data prior to the correlation analyses. We use a finite response filter (cutoff frequency 1/10 year, length = 21 year) with the boundary constraint of minimising the first derivative (Mann, 2004). For the 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 ($N = 10\,000$).

To analyse the stability of the correlations over time, we apply 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.

It is known that stochastic fluctuations can lead to large variations in correlations between two time series (Gershunov et al., 2001; Sterl et al., 2007). Hence, we use the Monte Carlo based stationarity test described by Sterl et al. (2007) to test the significance of the variations of the correlation through time. In this test, the observed difference between the maximum and minimum correlation is compared with the distribution of correlation differences obtained with surrogate time-series ($N = 10\,000$).

To analyse the combined influence of winter and summer temperature on the GHD, we use multiple linear regression. Hereby, 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, we use the partial correlation coefficient (Kendall and Stuart, 1979). 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 Results

3.1 Interannual relationship

We correlate the GHD series (Chuine et al., 2004) with a France temperature index (5.5° W to 6° E and 42° N to 51.5° N) derived from CRU (Mitchell et al., 2003) for single months (Table 1a). The temperature in the months from April to August is significantly negatively correlated. The temperature in September is, in turn, not significantly correlated with the GHD (Table 1a). The overall relation is dominated by interannual variability. Analysing averaged seasonal temperatures, the AAT yields the highest absolute value of correlation with $\rho = -0.73$ ($p < 0.01$). The correlation is slightly higher on interannual time scales with $\rho = -0.76$ ($p < 0.01$, high-pass filtered using a 1/10 year cutoff) and lower on decadal time scales with $\rho = -0.67$ ($p < 0.01$, low-pass filtered, 1/10 year cutoff). The field correlation of the GHD and the AAT shows that all of Western and Central Europe is significantly correlated (Fig. 2). The highest correlation is reached in central France.

Furthermore, we analyse the relation of the GHD with the spring-summer temperature based on the dataset of Luterbacher et al. (2004), covering the time from 1500 to 2002, and compare the instrumental and the pre-instrumental period. The averaged spring-summer temperature is used instead of the AAT, to take the whole period into account (monthly data are only available for 1659–2002). The correlation maps are similar for the period from 1901 to 2002 (Fig. 3a) and the period from 1500 to 1900 (Fig. 3b). In both time intervals, all of Western and Central Europe is significantly negatively correlated.

Table 1. GHD correlated with averaged monthly near-surface temperatures of France (5.5° W to 6° E and 42° N to 51.5° N) from CRU (1901–2002) (Mitchell et al., 2003). **(a)** Unfiltered data **(b)** Low-pass filtered data (1/10 year cutoff). Significant correlation values ($p < 0.05$) are bold.

		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
(a)	ρ	−0.02	0.04	−0.17	−0.15	**−0.20**	**−0.61**	**−0.55**	**−0.48**	**−0.36**	−0.16
	p-val	>0.05	>0.05	>0.05	>0.05	<0.05	<0.01	<0.01	<0.01	<0.01	>0.05
(b)	ρ	−0.34	**−0.56**	**−0.66**	**−0.64**	−0.30	**−0.70**	−0.39	**−0.45**	**−0.69**	−0.13
	p-val	>0.05	<0.01	<0.01	<0.01	>0.05	<0.01	>0.05	<0.05	<0.01	>0.05

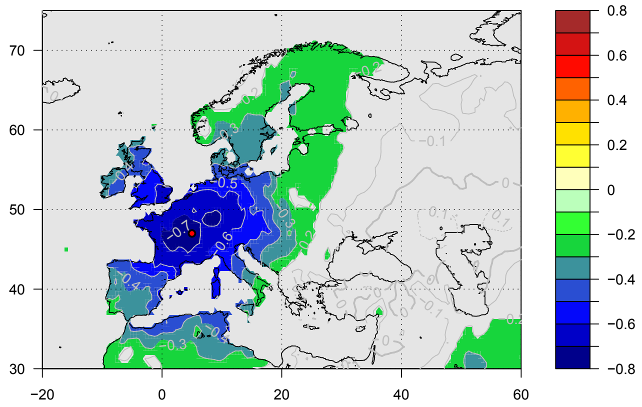

Fig. 2. Correlation of the GHD with the April-to-August near-surface temperature (AAT) from CRU (1901–2002) (Mitchell et al., 2003). Areas of significant correlation are coloured ($p < 0.05$). The red dot indicates the approximate location of Dijon (Burgundy).

3.2 Decadal relationship

For the decadal time scale, the correlations of the monthly France temperature index with the GHD are shown in Table 1b (low-pass filtered data using a 1/10 year cutoff). From December to August, the correlation coefficient is always below −0.3. The correlations of January, February, March, May, July and August are statistically significant. In contrast to the unfiltered analyses (Table 1a), the local GHD-temperature relationship shows a pronounced winter signature. This is confirmed by the field correlation of the filtered winter near-surface temperature with the filtered GHD (Fig. 4a). Western, Central and Eastern Europe are significantly negatively correlated (France index: $\rho = -0.69$). Interestingly, the correlation of the filtered AAT time series with the winter temperature (Fig. 4b) is much weaker than the GHD-winter temperature relationship. There is no significant AAT–DJF correlation in France on decadal time scales (Fig. 4b). We note that the decadal GHD-winter temperature relationship is not sensitive on the winter definition, as January-to-February temperature ($\rho = 0.68$) or December-to-March temperature ($\rho = 0.72$) give similar results.

In contrast to the spring/summer relation, the analysis of the pre-instrumental period from Luterbacher et al. (2004) does not yield the same result for the GHD-DJF temperature correlation (Fig. 5) compared to the instrumental period (Fig. 4a). The correlation value in France is nearly zero and only some Northern European areas are negatively correlated. A weak positive correlation is found in Asia Minor.

Besides the GHD-DJF relation, we have analysed several combinations of winter and summer months. The most pronounced large-scale correlation on decadal time scales is found for the December-to-August temperature with the GHD (Fig. 6). Nearly all of Europe is significantly negatively correlated with a stronger negative correlation than in winter (Fig. 4a).

As described above, the GHD is correlated with the AAT and the decadal DJF temperature. To quantify the seasonal contributions, we model the GHD 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 -7.1 ± 0.7 days/K for the AAT and -2.4 ± 0.9 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.

3.3 Stability of the correlations over time

We apply a 50-year running mean correlation to investigate the stability of the correlations over time. The relationship of the AAT and the GHD evenly increases from $\rho = -0.6$ to $\rho = -0.85$ during the instrumental period (Fig. 7a). This change in correlation is highly significant ($p < 0.01$) when applying the stability test by Sterl et al. (2007) (see Method section). If both time series are detrended prior to the analysis, the change in correlation is weaker ($\rho = -0.65$ to $\rho = -0.8$) and the change in correlation is not significant anymore. In the pre-instrumental period, the GHD-spring/summer relation varies in a similar range and shows centennial fluctuations in the running correlation (Fig. 7b). The weakest correlation is in 1919 (centred) with $\rho = -0.45$ and the strongest is in 1624 (centred) with $\rho = -0.87$. Over

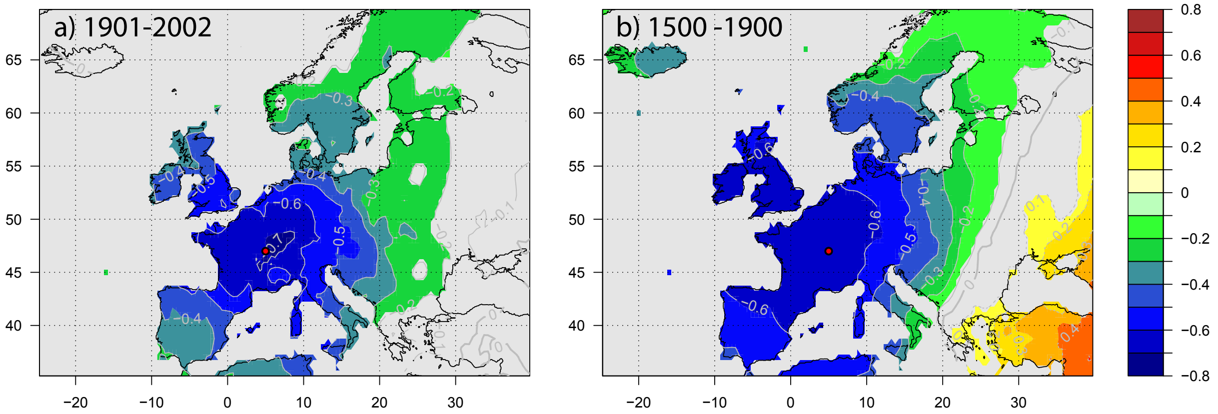

Fig. 3. Correlation of the GHD with the near-surface temperature in spring/summer (MAMJJA) from Luterbacher et al. (2004) for different periods: **(a)** 1901–2002 **(b)** 1500–1900. Areas of significant correlation are coloured ($p < 0.05$).

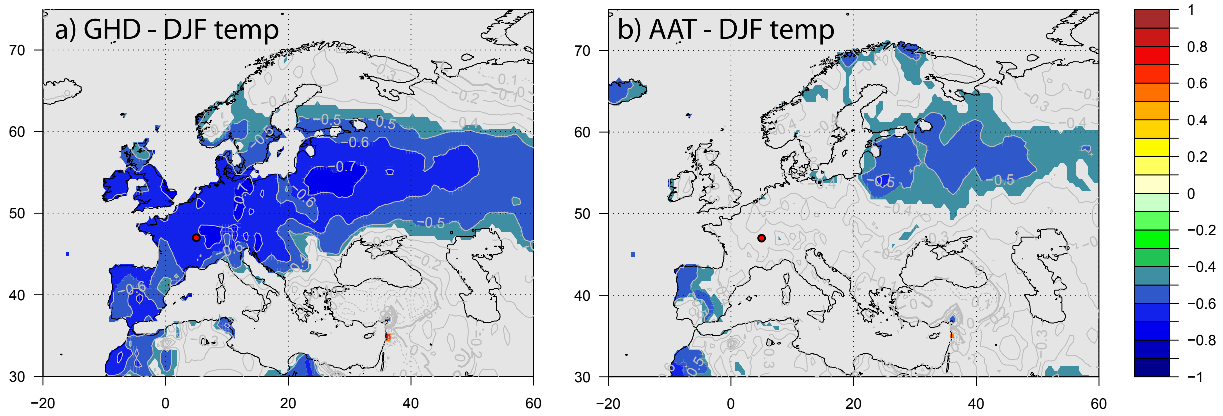

Fig. 4. Correlation of the winter (DJF) near-surface temperature from CRU with **(a)** the GHD **(b)** the France AAT time series (1901–2002). All data were low-pass filtered using a 1/10 year cutoff. Areas of significant correlation are coloured ($p < 0.05$).

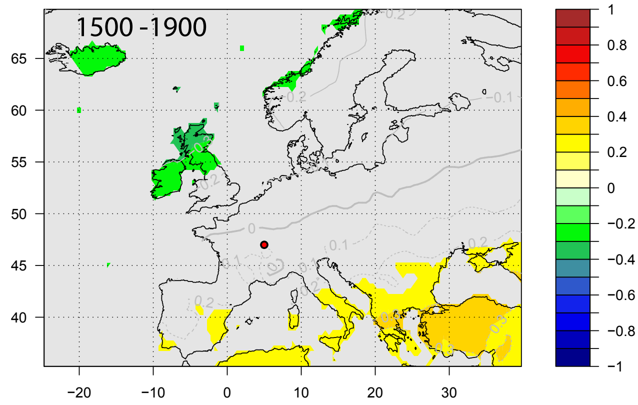

Fig. 5. Correlation of the GHD with the winter near-surface temperature from Luterbacher et al. (2004) for the period from 1500 to 1900. All data were low-pass filtered using a 1/10 year cutoff. Areas of significant correlation are coloured ($p < 0.05$).

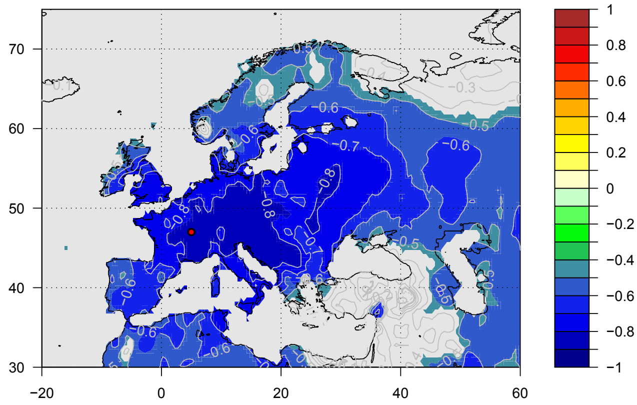

Fig. 6. Correlation of the GHD with the December-to-August near-surface temperature from CRU (1901–2002). All data were low-pass filtered using a 1/10 year cutoff. Areas of significant correlation are coloured ($p < 0.05$).

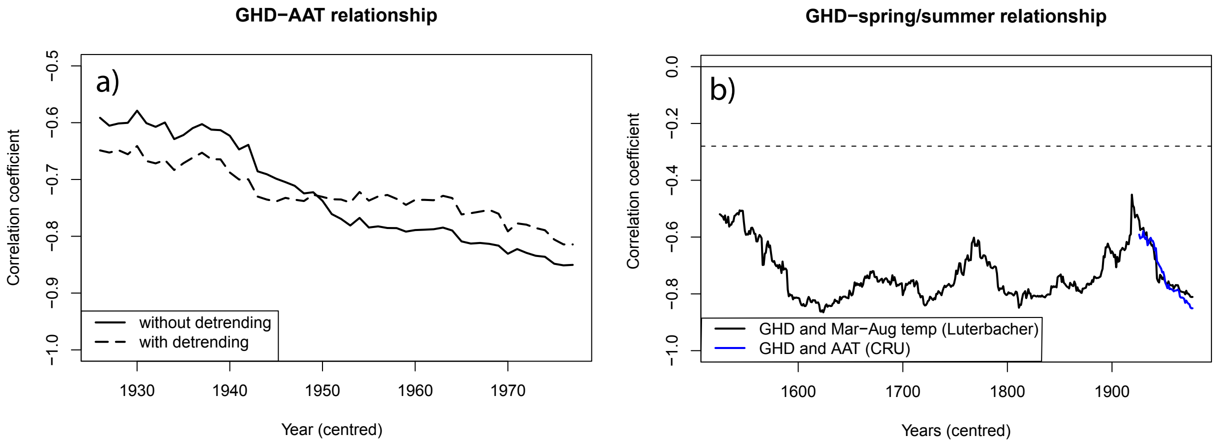

Fig. 7. **(a)** Running correlation of the GHD with the France AAT time series from CRU (1901–2002). Dashed line: correlation of detrended time series. **(b)** Running correlation of the GHD with the France spring–summer temperature from Luterbacher et al. (2004) (1500–2002). Blue line: GHD-AAT correlation (CRU). The length of the time window is 50 years. The significance level ($p = 0.05$) is at $\rho = -0.28$ – dashed line in panel **(b)**.

the whole period, the change in correlation is not significant according to the stability test by Sterl et al. (2007).

The running correlations of the decadal relationships are shown in Fig. 8. All three correlations strengthen during the instrumental period towards the end of the 20th century and the correlation values are always negative. The decadal GHD-DJF temperature relationship exhibits a correlation value of $\rho = -0.69$ for the whole period, which is highly significant ($p < 0.01$), but the running correlation is unstable (red line Fig. 8). It is rather weak from 1920 to 1960 (centred years), with the lowest amount of correlation in 1935 ($\rho = -0.1$), and then strengthens from $\rho = -0.27$ (1960 centred) to $\rho = -0.9$ (1977 centred). The total change of the running correlation is significant ($p < 0.05$) according to the stability test.

The decadal GHD-AAT relation exhibits a similar correlation coefficient of $\rho = -0.67$ ($p < 0.01$) for the whole time period, but the correlation changes over time are smaller (black line in Fig. 8) and not significant. The development of the decadal GHD-December-to-August temperature relationship is quite similar to this (green line), but the relationship is always stronger. For the total period, its correlation coefficient is $\rho = -0.82$ ($p < 0.01$). The change of the running correlation is not significant either.

The AAT-DJF temperature relationship is shown for the unfiltered data and for the decadal time scale (Fig. 9). In both cases, the correlation changes from negative to positive values during the instrumental period. Particularly in the time from 1965 to 1975 (centred), there is a strong increase in correlation. The unfiltered relationship (solid line) as well as the decadal relationship (dashed line) significantly change ($p < 0.01$) in the instrumental period according to the stability test. The development of the decadal relationship resembles the development of the decadal GHD-DJF temperature relationship (red line in Fig. 8).

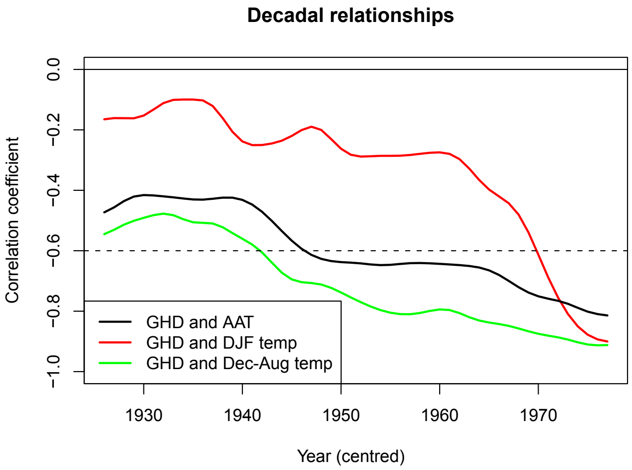

Fig. 8. Running correlation of the GHD with France AAT (black), DJF temperature (red), and December-to-August temperature (green). All data are low-pass filtered prior to the correlation (1/10 year cutoff). The length of the time window is 50 years. The horizontal dashed line shows the $p = 0.05$ significance level.

As the GHD is connected to the AAT and to the decadal winter temperature, the partial correlations (ρ_{par}) of both seasons 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 approximately the same as the full correlations. (GHD-AAT: $\rho_{\text{par}} = -0.72$ and $\rho = -0.73$; GHD-DJF: $\rho_{\text{par}} = -0.68$ and $\rho = -0.69$). This is expected as over the whole period, DJF and AAT temperatures are only weakly correlated ($\rho = -0.14$ unfiltered; $\rho = -0.31$ filtered). The development of partial correlation and full correlation of the GHD-AAT relation slightly differs (Fig. 10a). Whereas the correlation decreases

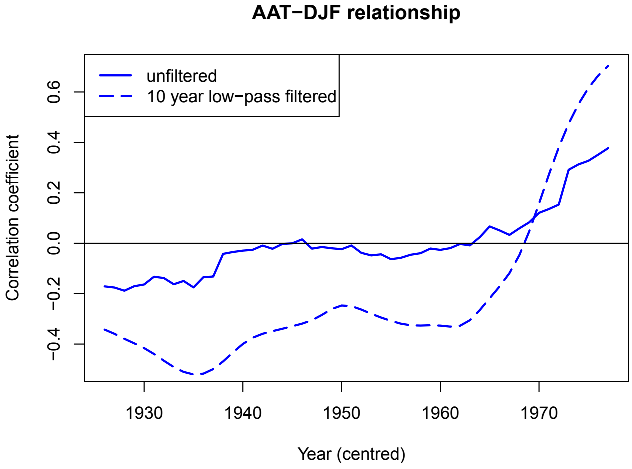

Fig. 9. Running correlation of AAT and DJF temperature. The length of the time window is 50 years. Solid line: unfiltered data; dashed line: decadal time scale (data low-pass filtered prior to the correlation using a 1/10 year cutoff). The $p = 0.05$ significance level is at $\rho = \pm 0.28$ (unfiltered data) and at $\rho = \pm 0.6$ (filtered data).

evenly, the partial correlation is stronger from 1925 to 1970 (centred) and weaker from 1970 to 1977 (centred) (Fig. 10a). In this time, the AAT-DJF temperature relation also increases (Fig. 9). The development of partial correlation and full correlation of the decadal GHD-DJF temperature relation differs as well (Fig. 10b). Whereas the correlation strongly changes from 1960 to 1977 (solid line), the partial correlation evenly decreases over the whole period and changes less (dashed line in Fig. 10b).

4 Discussion

4.1 Interannual relationship

The near-surface temperature over France from April to August is highly correlated with the GHD (Fig. 2). The time from April to August coincides with the vine phenology stages before bloom and veraison (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, although the average GHD is at 27 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 Cortázar-Atauri et al., 2010). The GHD-AAT relation is weaker on the decadal ($\rho = -0.67$) than on the interannual ($\rho = -0.76$) time scale. This also seems to be the case for the Besançon GHD series (Garnier et al., 2010). The weaker decadal relationship with spring/summer values could be due to less memory of the temperature in summer than in winter. From the correlation pattern (Fig. 2), it follows 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). Nevertheless, the Burgundy GHD series can be used as proxy for Central and Western Europe.

The GHD-AAT relationship is well established and has been used for several temperature reconstructions (e.g., Chuine et al., 2004; Etien et al., 2008, 2009; Guiot et al., 2005). Additionally, the GHD series can be used to test reconstruction datasets for the pre-instrumental period, which were derived from other sources. The Luterbacher et al. dataset exhibits nearly the same spring/summer correlation pattern for the time from 1500 to 1900 compared to the time from 1901 to 2002 (Fig. 3). This demonstrates the stability of the GHD-climate relationship and the consistency of the Luterbacher et al. dataset with the instrumental GHD-spring/summer relationship.

4.2 Decadal relationship

One remaining question is if there are other climatic impacts on the GHD. We found a significant correlation between the winter temperature and the GHD on the decadal time scale during the instrumental period (Fig. 4a, $\rho = -0.69$, $p < 0.01$). This significant correlation does not necessarily imply a direct GHD-winter relationship. It could also mean that the winter temperature influences the spring/summer season and, in this way, indirectly impacts the GHD. However, our finding that the AAT-winter temperature relationship is much weaker than the GHD-winter temperature relationship is a strong support of a direct winter influence on the GHD (cf. Fig. 4a 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, 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 spring/summer conditions and in a second order by a long-term winter impact.

One may ask whether the decadal winter relationship has 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 (Garcia de Cortázar-Atauri et al., 2009). Temperature is one of several conditions which causes the end of the dormancy state (Lavee and May, 1997). On interannual time scales, the winter temperature has no influence on the time of flowering (Williams et al., 1985; Garcia de Cortázar-Atauri et al., 2009; Nendel, 2010) and, consequently, does not impact the GHD. This is in accordance with our results, which show that there is no significant correlation on interannual time scales during the winter months (Table 1a), but this does not exclude an impact on decadal time scales. The long-term relation we found might be connected to the fact that

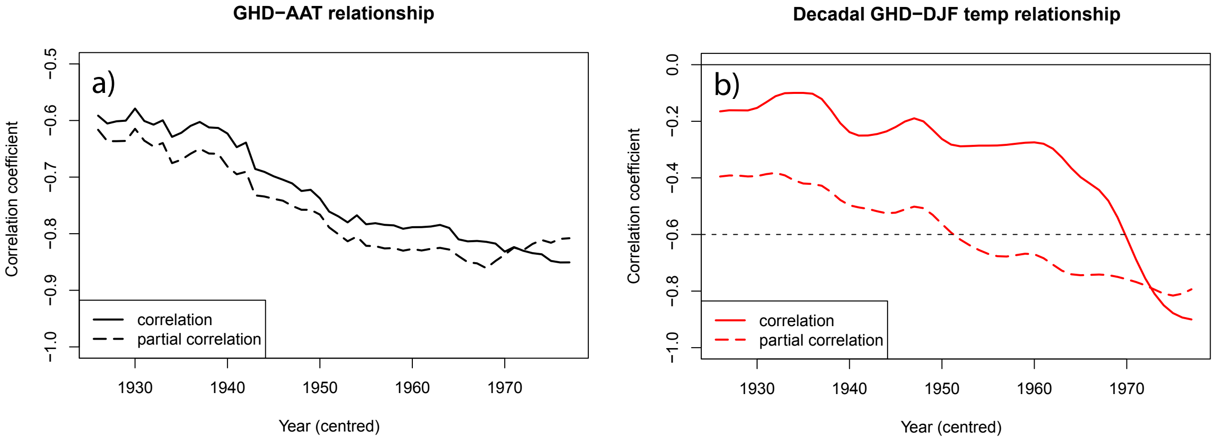

Fig. 10. Comparison of the development of the full correlation (solid lines) and the partial correlation (dashed lines). **(a)** GHD-AAT relationship **(b)** decadal GHD-DJF temperature relationship. The horizontal dashed line shows the $p = 0.05$ significance level. The length of the time window is 50 years. In the partial correlation, we eliminate the influence of the decadal DJF temperature in **(a)** and the decadal AAT in **(b)**. See text for the details.

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). Thereby, we speculate that the vine adapts to winter conditions on decadal time scales. For example, its development starts earlier after several mild winters, and vice versa. It is also conceivable that the decadal GHD-temperature link is due to vermin populations which are possibly affected by climate variations on longer time scales. Further investigations dealing with long-term biological factors of grape vine are necessary to examine this hypothesis.

This decadal connection with winter conditions is, apart from the temperature, also displayed by the winter NAO. We find a decadal GHD-NAO correlation with a slightly lower strength ($\rho = 0.5$, $p < 0.05$ for the instrumental period) than the GHD-DJF correlation. This result is consistent with Souriau and Yiou (2001).

As demonstrated above, the GHD is related to the interannual and decadal AAT and to the decadal winter temperature. Concerning only the decadal time scale, this means that the GHD is influenced by both the AAT and the winter temperature. Consequently, the correlation of the local decadal December-to-August temperature with the GHD yields even higher values (Fig. 6, $\rho = -0.81$, $p < 0.01$) than the GHD-DJF correlation alone.

Unlike the spring/summer relationship, the decadal winter relationship is not represented in the pre-instrumental Luterbacher et al. temperature dataset (Fig. 5). This could either indicate that the winter relationship only exists during the instrumental period, or that the quality of the pre-instrumental winter temperature reconstruction does not allow the detection of a relationship. The latter might be linked to seasonal differences in the reconstruction quality of European temperatures as reconstructed winter temperatures seem to be generally less accurate than reconstructed summer temperatures (Riedwyl et al., 2009). Furthermore, reconstructions which are based on regression methods substantially underestimate low-frequency temperature variations (von Storch et al., 2004). Therefore, we suspect that the pre-instrumental data does not contain the decadal winter variations in the GHD. To ascertain whether the GHD can be used as a decadal temperature proxy over Europe, the decadal relation shall be tested by using different proxies which are sensitive on decadal time scales. In case of success, the GHD-December-to-August relationship would be most capable for temperature reconstructions in Europe for the decadal time scale.

4.3 Stability of the correlations over time

During the instrumental period, all analysed GHD-temperature relations strengthen (Figs. 7a, 8). Thereby, the increase of the unfiltered GHD-AAT relation (Fig. 7a) and the increase of the decadal GHD-DJF temperature relation (Fig. 8 red line) are statistically significant according to the stability test from Sterl et al. (2007). In contrast to this, the changes of the decadal GHD-AAT (Fig. 8 black line) and GHD-December-to-August temperature relationships (Fig. 8 green line) are not significant.

As the relationship of the GHD with the AAT has been used for reconstructions, its stability over time is an important matter. Although this relationship is always significant during the instrumental period (lower than $\rho = -0.28$), the change of the correlation values is statistically significant. Similar trends were reported not only for the Burgundy GHD (Garcia de Cortázar-Atauri et al., 2010), but also for the Paris (Garcia de Cortázar-Atauri et al., 2010) and the Swiss GHD series (Meier et al., 2007). Thus, the increase is very unlikely caused by local effects or possible inconsistencies of the GHD series. We find two mechanisms which can partly explain this increase. Firstly, there is a trend in the AAT time series towards warmer temperatures (Fig. 7a), which lowers the correlation in the first half of the 20th century and raises it in the second half. Secondly, the GHD is not only influenced by the spring/summer temperature, but also by the decadal winter temperature. Thereby, the observed GHD-AAT correlation also depends on the relationship of the spring/summer 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 line in Fig. 10a). This is consistent with the changing AAT-winter relationship (cf. Figs. 9 and 10): The GHD-AAT correlation is weaker than the partial correlation when the AAT-winter relationship is negative (centred: 1925–1970), and vice versa (centred: 1970–1977). This implies that the quality of AAT reconstructions based on the GHD depends on a second order in the winter–spring/summer relationship.

This effect is even more important for the decadal GHD-DJF temperature relationship, which also increases during the instrumental period (red line in Fig. 8). 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 winter–spring/summer relationship: its development (red line in Fig. 8) is very similar to the development of the decadal winter–spring/summer relationship (dashes line Fig. 9). Furthermore, the partial correlation independent of the decadal AAT changes only moderately (Fig. 10b). This implies that the impact of the DJF temperature on the GHD (without AAT influence) is for the most part stable and supports the robustness of the winter result.

The field correlation of the GHD with the spring/summer Luterbacher et al. temperature (Fig. 3) shows that the GHD-AAT relationship also exists during the pre-instrumental period. The running correlation (Fig. 7b) further yields that the GHD-spring/summer temperature relationship is significant at every point in time. It varies in a range from $\rho = -0.45$ to $\rho = -0.87$, which is similar to the instrumental period. In addition, this implies that the change of correlation in the instrumental period is not singular. It has been suggested that variations of the temperature relation with GHDs are linked to non-climatic factors (Garcia de Cortázar-Atauri et al., 2010; Meier et al., 2007; Garnier et al., 2010). We further suggest that some changes might be related to changes in the winter–spring/summer relation as described above, which has to be verified by other proxy data.

5 Conclusions

In this study, we analysed the seasonal climatic impacts on the GHD in Burgundy (France) (Chuine et al., 2004) during the instrumental period and established the spatial pattern for interannual and decadal variability. We compared the instrumental with the pre-instrumental period and examined whether the relationships are stable over time. We affirm that the GHD is mainly influenced by the local AAT (Chuine et al., 2004; Meier et al., 2007; Menzel, 2005) and provide the spatial expansion of this relationship. Furthermore, we evaluated the relation for the pre-instrumental period by using the Luterbacher et al. (2004) temperature dataset. The spatial correlation pattern yields similar results for the instrumental and pre-instrumental period, indicating the consistency of the pre-instrumental Luterbacher et al. data with the instrumental GHD-spring/summer relationship.

We found a previously undocumented second climate impact on the GHD. The winter temperature is significantly correlated with the GHD 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 GHD. One may speculate that the decadal winter relation is caused by a long-term influence of the winter temperature on the vine during the dormancy and post-dormancy state, which could effect the vine's adaption to climatic conditions on decadal time scales. This is possible as plants can store information from environmental signals to optimise their fitness in nature (Gális et al., 2009). Memory in plants can have a short-time character or can last for years or even for generations (Gális et al., 2009). Furthermore, Trewavas (2003) stated that many aspects of dormancy show analogies to nervous memory as there are short- and long-term versions, and a complex interplay of environmental factors modifies dormancy. Even the molecular basis may be similar to animal memory (Trewavas, 2003). For unknown reasons, the winter relationship is not confirmed by the pre-instrumental period. It will be subject to further investigation whether this is caused by instabilities of the winter relationship (a breakdown of decadal correlations for the pre-instrumental period) or by inconsistencies of the reconstruction in the pre-instrumental period on decadal time scales. The latter might be caused by the fact that low-frequency temperature variations are underestimated by the regression model used (von Storch et al., 2004), or due to seasonal differences in reconstruction skill, as winter temperature reconstructions are less accurate than summer temperature reconstructions (Riedwyl et al., 2009). Techniques that preserve low frequency variability are necessary for climate reconstructions (von Storch et al., 2004; Mann et al., 2007; Riedwyl et al., 2009).

The running correlations of the GHD with the AAT and decadal winter temperature indicate a significant increase of both correlations during the instrumental period. This is partly caused due to changing climate. The winter–spring/summer temperature relationship strengthens during this period and, therefore, affects the GHD-climate relationships. Using partial correlation analysis, we demonstrate: (1) the changing winter–spring/summer relation modulates the observed GHD-winter relationship, and the underlying decadal winter influence on the GHD is more stable than the observed correlation. (2) The GHD-AAT relation is also slightly influenced over time by the changing winter–spring/summer relationship.

Summarising, the GHD is well suited to reconstruct interannual variations of the AAT over large parts of Europe, even if the changing winter–spring/summer relation might affect the reconstruction in a second order. For decadal-to-multidecadal time scales, the December-to-August temperature shows the strongest relationship to the GHD and, therefore, proposes that the GHD can be used for European temperature reconstructions beyond the spring/summer season. It will be interesting to see how the GHDs will develop in the future due to a noticeable change in the growing season. The growing season length, based on exceedance of local temperature thresholds, has a rate of increase of about 1.5 days per decade during the second half of the 20th century and will probably increase in the twenty-first century by more than a month (Christidis et al., 2007; Stine et al., 2009). Such major changes in seasonality will affect viticulture due to longer growing seasons (Jones et al., 2005). Finally, we argue that our findings related to the changed winter–summer relation are relevant for physical and biological systems, beyond the GHD. As a logical next step, we will evaluate the winter-to-summer relation for long-term temperature trends covering past, present and future scenarios.

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