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Modelling Chablis vintage quality in response to inter-annual variation in weather

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ABSTRACT

The weather during grape production affects wine quality. Changes in the weather in the Chablis region of France and in the quality of Chablis wines (vintage scores) from 1963 to 2018 were analysed. Chablis wine quality improved over this period, with no Poor vintages after 1991. Summer temperature and sunshine duration both increased progressively between 1963 to 2018 with fewer frost days but no linear change detected in precipitation. Chablis vintage score was modelled as a function of mean temperature from April to September (curvilinear relation, maximum score at 16–17 °C), mean minimum temperature in September (an index of cool nights; negative relation), and total rainfall from June to September (negative relation). This simple three-factor model distinguished between *Poor* and higher-quality Chablis vintages well, but less so between *Good* and *Excellent* vintages. Application of the model to different climate change scenarios (assuming current viticultural and oenological practices) suggests that vintage scores will decline (slightly to substantially, dependent upon emissions scenario) by the 2041 to 2070 period. This reduction in quality would, however, be minimised if the warming of cool nights is less than currently forecast. The Chablis vintage score model may help identify sites with suitable climates for premium white wine from Chardonnay grapevines in emerging cool climate viticulture regions as well as aiding Chablis producers mitigate the effects of climate change.

KEYWORDS

Chablis, Burgundy, Chardonnay, viticulture, vintage, weather, climate change

Supplementary data can be downloaded through: https://oeno-one.eu/article/view/4709

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INTRODUCTION

Considerable research has been carried out on the link between weather and wine quality. The general consensus from viticulture regions around the world is that weather is a major determinant of inter-annual variation in vintage quality (van Leeuwen and Darriet, 2016). A common finding is that vintage quality is related to growing season temperature and rainfall in the one to two months before harvest (Ashenfelter and Byron, 1995; Grifoni *et al.,* 2006; Ashenfelter, 2010; Lorenzo *et al.,* 2013; Outreville, 2018), though differences exist amongst regions and cultivars (Suter *et al.,* 2021). Global climate change, with considerable warming in recent decades (IPCC, 2014), requires greater understanding of crop quality-weather relations to support the future adaptation of crop production. This is more urgent for perennial, rather than annual, crops where planting decisions have consequences for decades.

Little research, to our knowledge, has focused specifically on the weather and the wines of Chablis in France. Chablis has been included implicitly, however, within more general studies of Burgundy (Outreville*,* 2018; Davis *et al.,* 2019). Chablis wines deserve particular attention.

i) Chablis wines are unique: the region's white wines, made exclusively from Chardonnay grapes, are distinct in aroma and flavour ("typicity") from Chardonnay wine produced elsewhere, including the rest of Burgundy (George, 2007).

ii) Chablis wine is a major commercial crop product: 34.3 million bottles of Chablis wine were sold in 2019 for an estimated 273 million Euros, with 417 companies (379 wine estates, 1 cooperative and 37 merchants) involved directly in viticulture and/or winemaking (Bureau Interprofessionnel des Vins de Bourgogne - BIVB, 2020).

iii) Chardonnay is a major grape variety for wine production: the world's second-most planted white wine variety (after Airen) and the wines, often of premium quality, from its berries are recognised by consumers worldwide (Organisation Internationale de la Vigne et du Vin - OIV, 2017).

iv) Chablis may be useful as an analogous model for Chardonnay production in emerging cool climate wine regions: Chablis is currently the most northerly region (latitude 47.8° N) for the production of high-quality single variety still Chardonnay wines at globally significant quantities (BIVB, 2020).

The single-variety Chardonnay wines of Chablis are protected by the European Union as a Geographical Indication (GI), a system set up to protect agricultural food and drink products where the quality or reputation of a product is attributable to its geographical origin (European Commission, 2016). Few other wine regions, if any, have been able to reproduce the flavours and aromas of a typical Chablis wine, which is: i) dry with "a firm backbone of acidity" (George, 2007), balanced with ii) the "mineral flavours of stony gunflint" (often referred to as "minerality") (George, 2007; Ballester *et al.,* 2013) and iii) the flavour and aroma of green apples, citrus fruit and/or white flowers. With bottle ageing, fine Chablis wine can become subtly oaky or nutty (even if never stored in oak barrels), honeyed, more elegant, and can develop greater intensity of minerality and fruit flavours (George, 2007; Biss, 2009; BIVB, 2021a).

Chablis typicity is said to come from its unique "terroir" – "[…] a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied vitivinicultural practices develop, providing distinctive characteristics for the products originating from this area […]." (OIV, 2010). The natural terroir features that are most often used to explain the typicity of Chablis wines are i) its weather, primarily a function of its relatively northerly latitude (for Chardonnay) and semi-continental position (George, 2007); ii) its Kimmeridgian geology and associated soils (Jackson, 2014) and iii) its topography and associated micro-climates (Droin, 2014).

This study investigates the effect of the first of the factors above within the region - weather and the quality of wines of Chablis typicity; specifically, whether or not inter-annual variation in weather over more than half a century (1963 to 2018) has had a detectable effect on Chablis wine quality. We test whether or not warming has occurred during the growing season in the region over this period, and how wine quality has fluctuated; develop a model of the historic effect of inter-annual variation in weather on Chablis wine quality, and, finally, apply that model to estimate the medium-term future for Chablis wine quality under various climate change scenarios.

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MATERIALS AND METHODS

1. Study area

The Chablis wine region is located in the department of Yonne, in the northern part of Burgundy, France (Figure 1). The vineyards are within a relatively compact area (approximately 16 km (North–South) by 18 km (East–West) centred around the town of Chablis (latitude 47°48′49″ N, longitude: 3°47′54″ E, 140 metres above sea level). The topography is hilly, rising to around 320 metres and the vineyards lie on both sides of the river Serein which runs broadly North–South through the town. Chablis wines are divided into four *appellations d'origine contrôlée* (AOC). In decreasing order of quality recognition, these are Grand Cru Chablis, Premier Cru Chablis, Chablis and Petit Chablis. For the purposes of this study, all four AOCs are included in the term "Chablis wine".

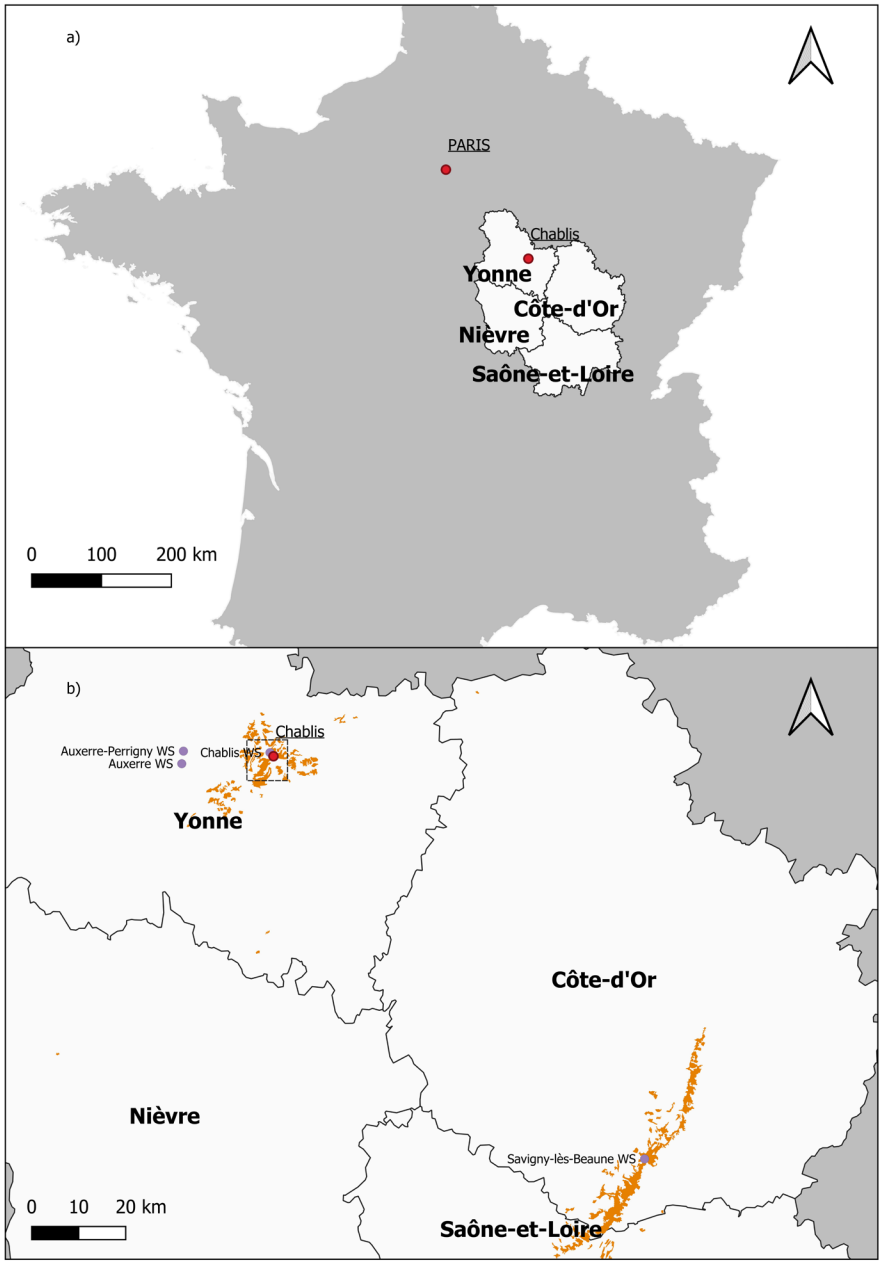

FIGURE 1. Study area: a) location of Chablis, a town in the Yonne, department of the Burgundy region, within France; b) close-up of the Yonne and Côte-d'Or departments.

Vineyard areas in orange (European Environment Agency, 2020), study area weather stations (WS, lilac circles), and grid square (dashed square) used for climate projections (Drias, 2021).

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2. Model development

2.1. Chablis vintage scores

To gauge Chablis vintage quality between 1963 and 2018, vintage scores were taken from five sources: Berry Bros. & Rudd wine merchants (BBR) for the 1978 to 2018 vintages; Decanter magazine for 2005 to 2015; Wine Enthusiast (WE) for 1995 to 2018; Wine Scholar Guild (WSG) for 2000 to 2018; and The Wine Society (WS) for 1980 to 2018. These reputable and respected wine experts or institutions provide separate scores for Chablis (as opposed to incorporating Chablis into a more general score for 'White Burgundy'). Scores were standardised into a 10-point scale (as used by BBR and WS). This required doubling the Decanter and WSG scores (originally scored out of five) and deducting 50 and dividing by 5 for the WE scores (originally scored from 50 to 100). No quantitative scores were available for vintages prior to 1978, and only one source (BBR) for 1978 and 1979. Scores were inferred, therefore, for 1963–1979 from the qualitative vintage reports on the BIVB Chablis website (BIVB, 2021b) and Chablis specialist Rosemary George's book '*The Wines of Chablis and the Grand Auxerrois*' (George, 2007).

A consensus vintage score (Supplementary Information Table S1) was calculated as the mean of the several scores for each vintage (number of scores per vintage: mean 3, minimum 2, and maximum 5). This assumption that the scales correspond to each other was necessary because it was not practicable to use the ranking methodology described by Borges *et al.* (2012) due to the different vintage ranges covered by each source. The mean score was used in all statistical analyses, but for graphical presentation, the vintages were categorised into *Excellent* (>8), *Good* (6 to 8) and *Poor* (<6). This was based on the distribution of the data (mean = 7.1, interquartile range 6.5–8.3) and a general sense of what the scores mean (Cicchetti and Cicchetti, 2013).

2.2. Chablis weather data

Monthly weather data for Chablis were taken from the French meteorological service, Météo-France. The Chablis weather station (number 89068001) lies on the outskirts of the town of Chablis at latitude 47°49'19" N, longitude 3°47'26" E and elevation 141 m. It does not record sunshine duration, however. For this variable, the records from two weather stations in Auxerre, both approximately 19 km west of Chablis, were merged: Auxerre (latitude 47°48'05" N, longitude 3°32'43" E, elevation 207 m, from October 1962 to April 2013) and Auxerre-Perrigny (latitude 47°49'28" N, longitude 3°32'58" E, elevation 152 m, from April 2013 to October 2020).

This weather dataset comprised monthly readings from October 1962 (the earliest date available for key temperature measurements) to October 2020. The data were also used to generate climatic indices that are typically used for viticulture, including indices for growing season temperature and precipitation for the phenological phases important for wine quality. These included mean Growing Season Temperature (GST) (Jones *et al.,* 2005), the Cool Night Index (*CNI*) which in the Northern Hemisphere is the mean minimum temperature for September (Tonietto and Carbonneau, 2004), and precipitation during veraison and/or ripening (Ashenfelter, 2010; Baciocco *et al.,* 2014; Davis *et al.,* 2019).

To enable comparison between the climates of Chablis and the Côte de Beaune, data from the Savigny-lès-Beaune weather station (number 21590001, latitude 47°03'13" N, longitude 4°50'07" E, elevation 246 m), approximately 113 km southeast of the Chablis weather station, for the period 1961 to 2020 were also collated.

2.3. Modelling approach

Multiple linear regression was employed to develop a model of the impact of inter-annual variation in weather on the quality of Chablis wine (the "Chablis vintage model"). A range of regression approaches (manually based on exploratory Principal Component Analysis (PCA), best subset and forward stepwise) was used to create the model that explained the most variance in the vintage score (adjusted R-squared), but which also satisfied criteria for homoscedasticity (Breusch–Pagan test), the randomness of residual plots, normality of distribution (Shapiro–Wilk test) and leverage (Cook's distance). A more complex model (i.e., one with more predictor variables) was accepted only if it passed the F-test, achieved a lower Bayesian Information Criterion BIC score, and led to a 2 or more unit improvement in Akaike Information Criterion (AIC) (Bevans, 2020).

Eight meteorological measurements were considered as candidate independent variables in the Chablis vintage model: mean temperature, mean maximum temperature, mean minimum temperature, mean daily temperature range,

number of days equal to or exceeding 35 °C, total precipitation, number of precipitation days >1 mm, and sunshine duration. A total of 368 candidate model variables were calculated for all months singly, for periods ranging from two to nine months between February and October, and also the period November to March to cover the vines' dormancy period in the prior winter (Baciocco *et al.,* 2014).

Despite April to October being the standard period for measuring GST for Northern Hemisphere viticulture (Baciocco *et al.,* 2014; Moral *et al.,* 2016), periods that ran through to October were subsequently eliminated as candidate model variables. This was because climate change has advanced the start of harvest in Chablis since 1980 by approximately 20 days from early October to mid-September (Biss, 2020); and so including data for October would have incorporated considerable data after grapes have been harvested. This concurs with research for other wine regions of France. Neethling *et al.* (2012) used the April to September period to represent GST for the Loire Valley, a similar latitude to Chablis (47 °N), as did Ashenfelter (2010) for Bordeaux.

2.4. Model validation

Bootstrapping (10,000 resamples) was carried out with the R 'boot' package, using both case and residual resampling methods, to find 95 % confidence intervals (basic, percentile, and bias-corrected and accelerated (BCa)) for Chablis vintage model coefficients and adjusted R^2; BCa is a methodology that corrects for bias and skewness in the bootstrap distribution.

3. Predicting the quality of Chablis wine in 2041–2070

Climate projections for Chablis were taken from the French Ministère de la Transition Écologique's *Drias les futures du climat* service (Drias, 2021) for the grid square centred at latitude 47°48'27" N and longitude 3°46'42" E, approximately 1.8 km from the Chablis weather station. Data were extracted for the RCP (Representative Concentration Pathway) 2.6, 4.5 and 8.5 scenarios at the 5th, 50th (median) and 95th percentiles, using their multi-model approach, for changes in the following variables to the period 2041 to 2070: monthly mean temperature (°C), mean minimum temperature for September (°C) (*CNI*) and monthly total precipitation (mm). The reference period for these projections is 1976 to 2005, for which data was taken from the Chablis weather station. These figures were then used in conjunction with the Chablis vintage model to predict Chablis wine quality in 2041–2070. This text presents only the median percentile projections. A more complete table, including the 5th and 95th percentile projections, is available in the Supplementary Information (Table S2).

An alternative projection for *CNI* in 2041–2070 (*CNI2*) was calculated as mean *CNI* for the base period (1976 to 2005) plus 40 % of the projected change in GST. This is because the assumption that *CNI* will rise as much as the same as GST (Drias, 2021) is not supported by the recent past. Mean minimum temperature in September has so far risen far less than GST has for Chablis and nearby regions; 38 % in Chablis (1963 to 2000), 65 % in Cote de Beaune (1961 to 2020, Savigny-lès-Beaune weather station) and 39 % in the Loire Valley (1960 to 2010, using data from Neethling *et al.,* 2012).

4. Tools

R and R Studio (version 1.3.1093, www.r-project.org / www.rstudio.com) were used for statistical analysis. Boxplots and histograms showed that the vintage score and the key climate indices for Chablis were sufficiently normal in distribution for parametric statistical analysis.

RESULTS

1. Warming and vintages of Chablis typicity

The vintage score increased significantly by around 2 points to 7.1 between 1963 and 2018 in Chablis (Table 1).

Several weather variables (sunshine and most temperature indices) but not all (indeed, none of the precipitation indices) also showed significant trends (Table 1). Mean spring/summer temperature ($Tmean_{Apr\text{-}Sep}$) increased by almost 0.5 °C per decade between 1963 and 2020 and slightly more so than mean autumn/winter temperature cumulatively ($Tmean_{Apr\text{-}Sep}$ 2.68 °C *versus* $Tmean_{Oct\text{-}Mar}$ 2.16 °C). The mean maximum rose considerably more than the mean minimum temperature (2.33 °C *versus* 1.03 °C for September). Similarly, the number of days reaching or exceeding 35 °C between 1st April and 30 September each year has risen from close to zero to almost six days; much of this occurred between 2015 and 2020 with 12, 5, 6, 7, 10 and 8 days in successive years, indicating a non-linear trend. Mirroring the above, the number of days where minimum air temperature fell below 0 °C between April and September more than halved.

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Sunshine duration also increased, but this linear relationship was not as strong as for most temperature indices. No significant regression was detected for continentality, the difference in mean temperature between the warmest and coldest months (Skelton, 2007).

The regression line fitted over the study period (solid black line, Figure 2) explained over half of the variance in mean spring/summer temperature (Table 1). During this period, years have differed considerably in vintage rating for Chablis wine, but no *Poor*-quality vintages have been recorded since 1991 (Figure 2). Comparing temperature-year regressions amongst the three vintage classifications showed significant differences ($P < 0.005$): *Excellent* vintage rating years provided the shallowest slope, crossing the all-years temperature trend line in 1998. Hence overall, the post-2000 period provided a greater proportion of years with *Good* Chablis vintages than the 1963–1980 period (Figure 2).

TABLE 1. Descriptive statistics and parameters of linear regressions for vintage score (1963 to 2018) and key weather indices (1963 to 2020) for Chablis.

	Mean	SD	Gradient	SE	Total Trendline Change	Adj. R^2	P
Vintage Score	7.12	1.60	**0.037**	**0.012**	**2.05**	**0.13**	**0.004**
Temperature Indices							
$Tmean_{Apr\text{-}Sep}$	15.9 °C	1.03 °C	**0.047 °C yr^{-1}**	**0.005 °C**	**2.68 °C**	**0.59**	**<0.001**
$Tmean_{Oct\text{-}Mar}$	6.2 °C	1.07 °C	**0.038 °C yr^{-1}**	**0.007 °C**	**2.16 °C**	**0.35**	**<0.001**
$Tmax_{Apr\text{-}Sep}$	22.3 °C	1.43 °C	**0.061 °C yr^{-1}**	**0.008 °C**	**3.46 °C**	**0.50**	**<0.001**
$Tmin_{Apr\text{-}Sep}$	9.4 °C	0.79 °C	**0.033 °C yr^{-1}**	**0.004 °C**	**1.89 °C**	**0.49**	**<0.001**
$Tmax_{Sep}$	22.0 °C	2.06 °C	**0.041 °C yr^{-1}**	**0.015 °C**	**2.33 °C**	**0.10**	**0.010**
$Tmin_{Sep}$ *(CNI)*	9.4 °C	1.44 °C	0.018 °C yr^{-1}	0.011 °C	1.03 °C	0.03	0.110
TrangeSep	12.6 °C	1.98 °C	0.023 °C yr^{-1}	0.015 °C	1.3 °C	0.02	0.145
No. Hot Days Apr–Sep (>=35 °C)	2.5 d	3.43 d	**0.105 d yr^{-1}**	**0.023 d**	**5.97 d**	**0.25**	**<0.001**
No. Frost Days Apr–Sep	6.7 d	3.58 d	**–0.064 d yr^{-1}**	**0.027 d**	**–3.66 d**	**0.08**	**0.021**
Continentality	18.0 °C	2.36 °C	0.022 °C yr^{-1}	0.018 °C	1.23 °C	0.01	0.247
Precipitation Indices							
$P_{Apr\text{-}Sep}$	360.7 mm	83.72 mm	0.099 mm yr^{-1}	0.662 mm	5.66 mm	0.00	0.881
$P_{Jun\text{-}Sep}$	234.0 mm	62.74 mm	–0.375 mm yr^{-1}	0.494 mm	–21.36 mm	0.00	0.451
$P_{Oct\text{-}Mar}$	364.4 mm	83.27 mm	0.412 mm yr^{-1}	0.657 mm	23.5 mm	0.00	0.533
P_{Aug}	60.7 mm	35.33 mm	–0.273 mm yr^{-1}	0.277 mm	–15.53 mm	0.00	0.330
P_{Sep}	58.9 mm	34.77 mm	–0.284 mm yr^{-1}	0.273 mm	–16.19 mm	0.00	0.302
No. Rain Days Jun–Sep	34.0 d	7.38 d	–0.037 d yr^{-1}	0.058 d	–2.11 d	0.00	0.528
No. Rain Days Aug	8.4 d	3.68 d	–0.037 d yr^{-1}	0.029 d	–2.13 d	0.01	0.197
No. Rain Days Sep	8.4 d	4.07 d	–0.018 d yr^{-1}	0.032 d	–1.05 d	0.00	0.567
Monthly daily max rain Apr–Sep	107.6 mm	25.49 mm	0.214 mm yr^{-1}	0.200 mm	12.18 mm	0.00	0.289
Sunshine (Auxerre)							
Sunshine Apr–Sep	75,038.7 min	7853.0 min	**127.6 min yr^{-1}**	**59.8 min**	**7274.9 min**	**0.06**	**0.037**

Tmean = mean temperature (°C), *Tmin* = mean minimum temperature (°C), *Tmax* = mean maximum temperature (°C), *TrangeSep* = difference between the mean minimum and mean maximum temperatures for September (°C), Continentality = difference in mean temperature between the warmest and coldest months (°C) and P = total precipitation (mm), for stated multi-month periods (in subscript). Bold: significant trend ($P < 0.05$).

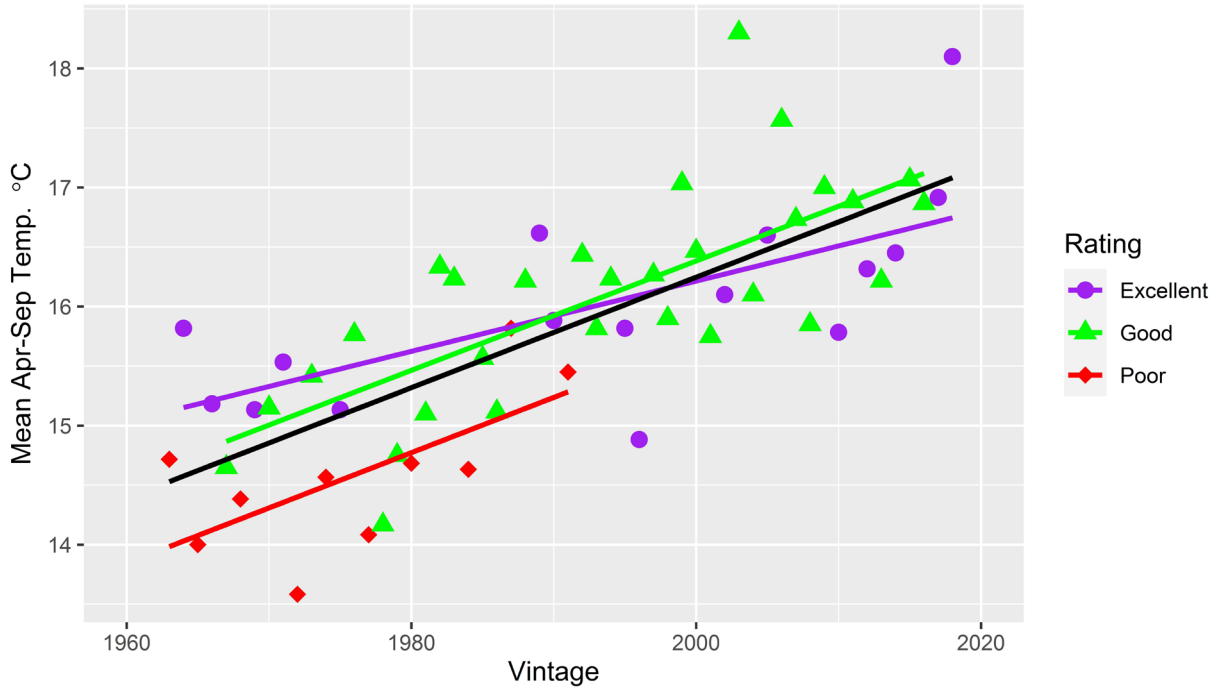

FIGURE 2. The trend of mean temperature from 1st April to 30 September ($Tmean_{Apr\text{-}Sep}$) in Chablis, France, from 1963 to 2018 (solid black line, Adjusted R-squared 0.56, $P < 0.001$).
Also shown are the years, and the respective regression of mean temperature against these years only, in which the Chablis wine vintage was rated as *Excellent* (purple line, Adjusted R-squared 0.44, $P = 0.003$), *Good* (green line, Adjusted R-squared 0.51, $P < 0.001$), or *Poor* (red line, Adjusted R-squared 0.37, $P = 0.04$).

2. Vintage quality in response to weather

2.1. Temperature, precipitation and period

Of the eight Chablis weather variables evaluated for this study, mean temperature accounted for the most variance amongst vintage scores. A linear regression with a second-order polynomial for the period May to July ($Tmean_{May\text{-}Jul}$) explained 43 % of the variance in the vintage score (Table 2). This was the highest adjusted R-squared achieved for any single-factor model and was superior to the April to September (adjusted R-squared 0.364, $P < 0.001$) and April to October (adjusted R-squared 0.321, $P < 0.001$) periods for mean temperature.

Precipitation and sunshine duration played lesser roles in the models of the vintage score; August to September was the most important period. Total August and September precipitation in a single-factor model explained around 12 to 16 % of variance (linear or plus a second-order polynomial, $P = 0.006$, 0.004, respectively), whereas sunshine duration for these months in a single-factor model explained around 12 to 20 % of the variance (linear or plus a second-order polynomial, $P = 0.004$, 0.001, respectively). Despite the above, the August to September period of sunshine duration and precipitation (nor each month alone) did not retain significance in multiple regression models including temperature as a factor.

The importance of the May to July period was clarified by comparing vintage ratings against both temperature and rainfall for different periods within spring and summer (Figure 3). In these co-plots for temperature and rainfall in March (Figure 3a) or April (Figure 3b), there is no discrimination for the vintage rating with the *Poor*, *Good* and *Excellent* vintage ratings randomly distributed. However, as the periods examined progressed from April to May (Figure 3c) through April to June (Figure 3d), April to July (Figure 3e), until May to July (Figure 3f) the *Poor* vintage ratings separated towards the bottom of the chart. The majority of *Poor* vintages occurred when the mean temperature for May to July was below 15.5 °C (Figure 3f); the only two vintages rated higher below 15.5 °C were when total precipitation for the May to July period was less than 150 mm. These co-plots, however, showed little separation between the *Good* and *Excellent* vintage ratings.

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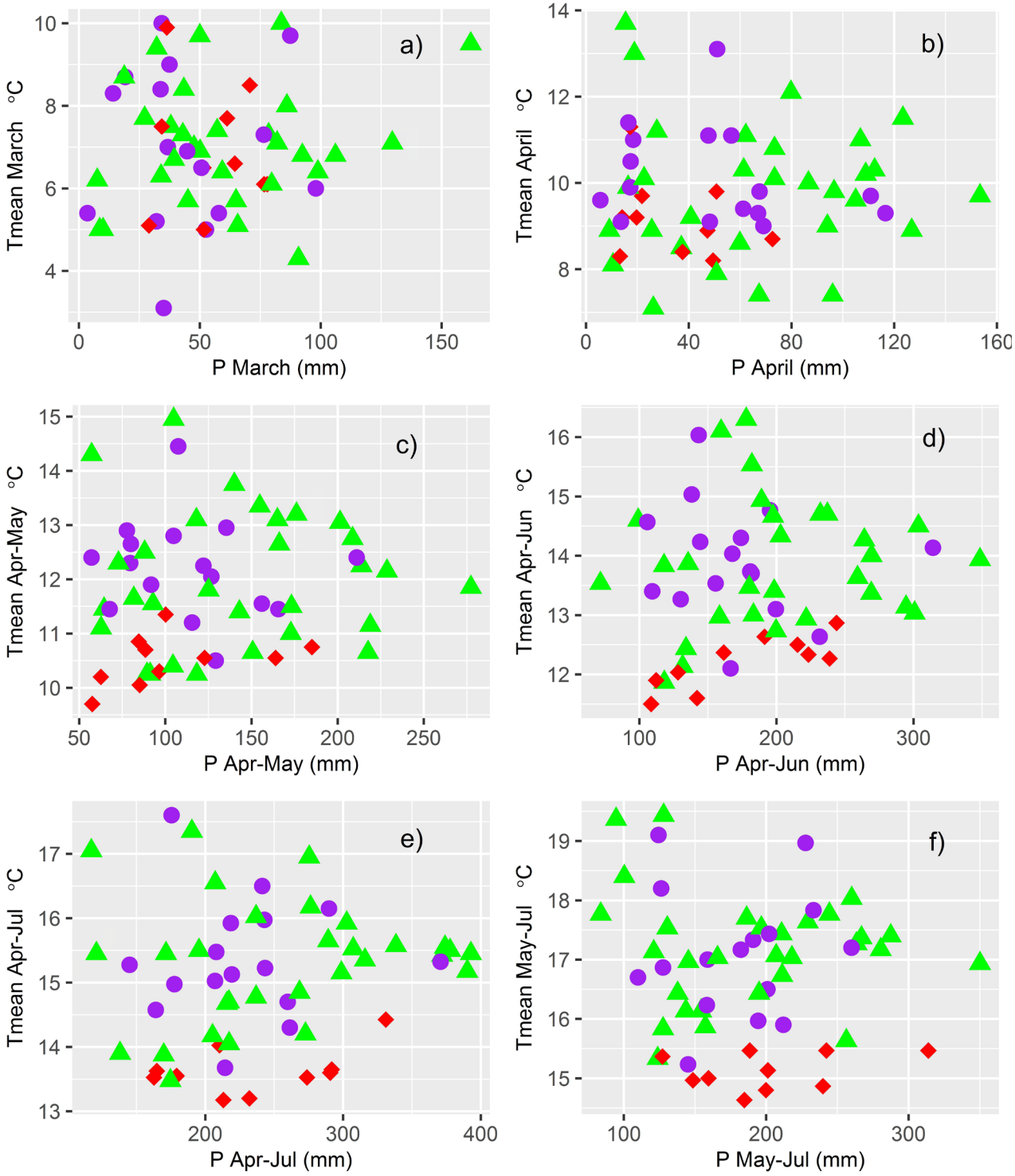

FIGURE 3. Mean temperature versus total precipitation for March (a), April (b), April–May (c), April–June (d), April–July (e) and May–July (f), and Chablis vintage rating.

The final rating classification for each vintage is marked as follows: Purple circle = *Excellent* vintage (>8 score), green triangle = *Good* vintage (6–8 score) and red diamond = *Poor* vintage (<6 score).

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TABLE 2. Parameters of the multiple linear regression Chablis vintage model selected that combines linear and quadratic temperature terms (mean temperature from 1st April to 30 September ($Tmean_{Apr\text{-}Sep}$, °C), the Cool Night Index (*CNI*; mean minimum temperature for September, °C), and total precipitation from 1st June to 30 September ($P_{Jun\text{-}Sep}$, mm) to quantify the variation amongst 56 Chablis vintage scores from 1963 to 2018. For comparison, the best single-factor model to quantify variation in the same vintage scores is also provided (linear and quadratic temperature terms for mean temperature from 1st May to 31 July, $Tmean_{May\text{-}Jul}$). The factor values provide the range of weather variables across which the model was fitted. The normality and homoscedasticity tests are the Shapiro–Wilk and Breusch–Pagan tests, respectively.

	Mean of Factor Value	Range in Factor Value	Coefficient	Standard Error	Model / Factor *P*	Model / Cumulative Adj. R^2	Normality Test (*P*)	Homoscedasticity Test (*P*)
Chablis vintage model					< 0.001	0.571	0.322	0.148
Intercept			–170.90	27.05	< 0.001			
$Tmean_{Apr\text{-}Sep}$	15.81 °C	13.58–18.30 °C	22.380	3.442	< 0.001	0.172		
$Tmean_{Apr\text{-}Sep}^2$	15.81 °C	13.58–18.30 °C	–0.6790	0.1080	< 0.001	0.364		
CNI	9.42 °C	5.80–12.80 °C	–0.4089	0.1109	< 0.001	0.510		
$P_{Jun\text{-}Sep}$	236.6 mm	119.1–354.2 mm	–0.006918	0.002392	< 0.01	0.571		
Single-factor model					< 0.001	0.425	0.118	0.219
Intercept			–129.13239	27.09245	< 0.001			
$Tmean_{May\text{-}Jul}$	16.77 °C	14.63–19.43 °C	15.61145	3.21993	< 0.001	0.204		
$Tmean_{May\text{-}Jul}^2$	16.77 °C	14.63–19.43 °C	–0.44424	0.09537	< 0.001	0.425		

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2.2. The Chablis vintage model

The best model identified and selected for the Chablis vintage model was:

$$\textit{(Equation 1) Vintage Score} =$$

$$22.38\ Tmean_{Apr\text{-}Sep} - 0.6790\ Tmean_{Apr\text{-}Sep}^{2} - 0.4089\ CNI - 0.006918\ P_{Jun\text{-}Sep} - 170.9$$

where $Tmean_{Apr\text{-}Sep}$ is mean temperature (°C) from 1st April to 30 September, *CNI* is the Cool Night Index (°C) and $P_{Jun\text{-}Sep}$ is the total precipitation (mm) from 1 June to 30 September. The model and each term were significant and explained 57 % of the variance (Table 2) with a good fit to observations from *Poor* to *Excellent* scores (Figure 4).

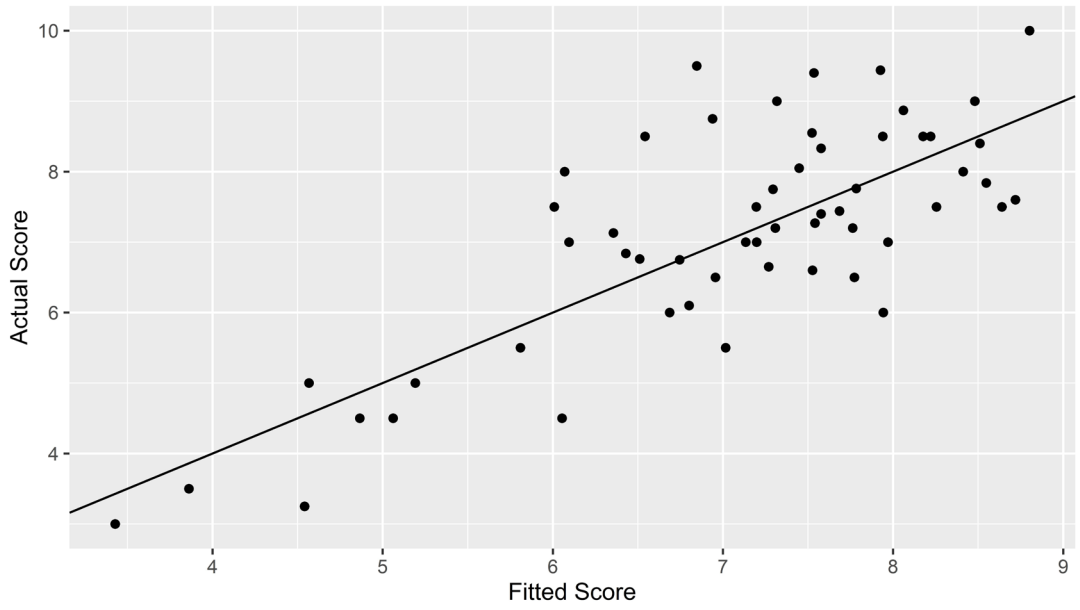

FIGURE 4. Comparison of actual Chablis vintage scores from 1963 to 2018 (●) with fitted values from the multiple regression model (Table 2). The line shown indicates perfect agreement.

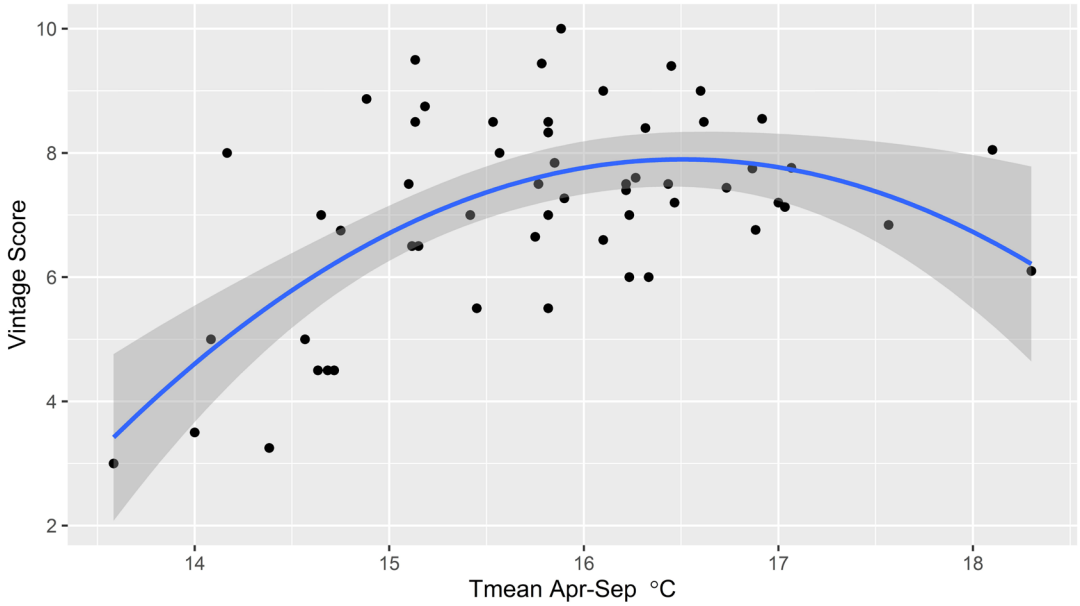

FIGURE 5. Vintage score vs. $Tmean_{Apr\text{-}Sep}$ for Chablis vintages from 1963 to 2018 (●). The grey band around the fitted regression line (in blue, Equation 1) represents the standard error.

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The relationship between vintage score and mean temperature ($Tmean_{Apr\text{-}Sep}$) was curvilinear, described well by linear and quadratic terms, with an optimum for Chablis vintage score at c. 16.5 °C for Equation 1 (Figure 5).

Whereas $Tmean_{May\text{-}Jul}$ was the best period for temperature if the fitted model comprised a single weather factor alone, in the multiple regression model with other factors (*CNI* and $P_{Jun\text{-}Sep}$) included, $Tmean_{Apr\text{-}Sep}$ was superior (adjusted R-squared increased from 0.509 to 0.571).

Replacing *CNI* with mean minimum temperature for August and September ($Tmin_{Aug\text{-}Sep}$) increased the adjusted R-squared marginally (from 0.571 to 0.584), but *CNI* was retained as it is a recognised climate index for viticulture.

Replacing June to September precipitation ($P_{Jun\text{-}Sep}$) with the August to September period ($P_{Aug\text{-}Sep}$) reduced model fit slightly (from 0.571 to 0.533) with the latter period not providing a significant term in the model ($P > 0.05$).

Replacing the regression equation with an early harvest version to the end of August ($Tmean_{Apr\text{-}Aug}$, $Tmin_{Aug}$ and $P_{Jun\text{-}Aug}$) and an advanced phenology version that brings all the factor periods forward by one month ($Tmean_{Mar\text{-}Aug}$, $Tmin_{Aug}$ and $P_{May\text{-}Aug}$) reduced adjusted R-squared, from 0.571 to 0.415 and 0.346, respectively.

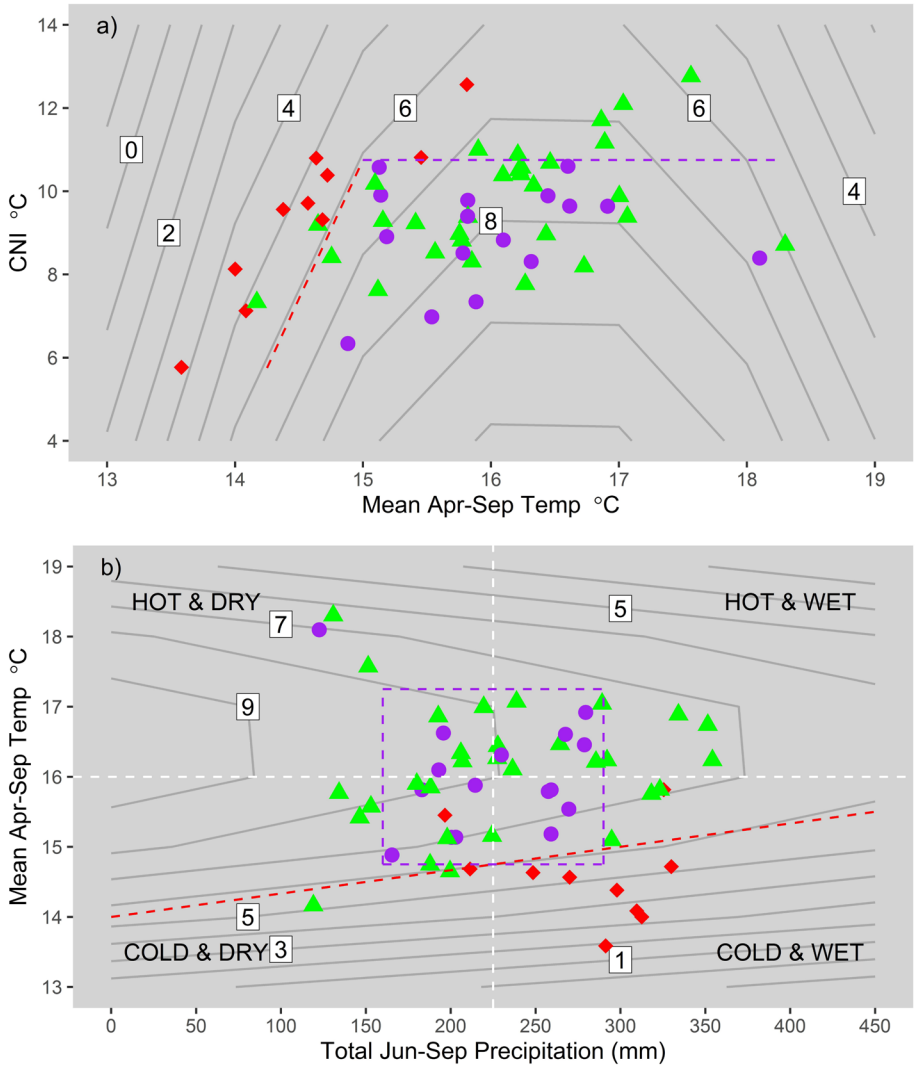

FIGURE 6. Chablis vintage ratings from 1963 to 2018.

Purple circle = *Excellent* vintage (>8 score), green triangle = *Good* vintage (6–8 score) and red diamond = *Poor* vintage (< 6 score), compared with the scores from the Chablis vintage model fitted (contour lines) in relation to weather indices: a, *CNI vs*. $Tmean_{Apr\text{-}Sep}$ where $P_{Jun\text{-}Sep}$ held constant at the long-term mean (236.6 mm); b, $Tmean_{Apr\text{-}Sep}$ *vs*. $P_{Jun\text{-}Sep}$ where *CNI* held constant at the long-term mean (9.4 °C). The broken coloured lines are described in the text.

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Model performance deteriorated further for these early harvest and advanced phenology versions when applied to only the most recent 25, 20, 15 or 10 vintages with a maximum 0.290 R-squared, maximum 0.037 adjusted R-squared and $P > 0.10$.

Comparison of contour plots from the Chablis vintage model with the actual vintage ratings from 1963 to 2018 (Figure 6) identified the following boundaries of weather indices in relation to the observed vintage ratings. In Figure 6a, the red dashed line at an angle at 14–15 °C denotes the boundary between *Poor* (on left) and *Good* or *Excellent* vintages (on right), whilst the horizontal purple dashed line (at 10.75 °C) denotes the upper *CNI* limit to *Excellent* vintages. In Figure 6b, the purple square contains all *Excellent* vintages bar one (2018), whilst the red broken line denotes the threshold of acceptability below which the cool wet weather almost always provided *Poor* vintages.

2.3. Model validation

Confidence intervals for Chablis vintage model parameter coefficients, across all bootstrapping methodologies employed here, were similar in magnitude, direction and range to those calculated parametrically from the model (Table 3). Furthermore, using the BCa confidence interval,

TABLE 3. Bootstrap confidence intervals (95 %) for Chablis vintage model parameter coefficients and adjusted R-squared.

	Parameter Coefficient (2.5 %; 97.5 %)					Adj. R^2
	Intercept	$Tmean_{Apr\text{-}Sep}$	$Tmean_{Apr\text{-}Sep}^2$	CNI	$P_{Jun\text{-}Sep}$	(2.5 %; 97.5 %)
Chablis Vintage Model	–225.1; –116.6	15.47; 29.29	–0.896; –0.462	–0.632; –0.186	–0.0117; –0.0021	N/A
Bootstrap (residuals / percentile)	–219.9; –118.8	15.71; 28.54	–0.873; –0.470	–0.621; –0.204	–0.0115; –0.0024	N/A
Bootstrap (case / basic)	–229.2; –130.0	17.19; 29.74	–0.912; –0.518	–0.605; –0.211	–0.0120; –0.0028	0.384; 0.793
Bootstrap (case / percentile)	–211.7; –112.5	15.02; 27.57	–0.840; –0.446	–0.607; –0.213	–0.0110; –0.0018	0.348; 0.758
Bootstrap (case / BCa)	–213.3; –116.0	15.50; 27.81	–0.849; –0.462	–0.596; –0.200	–0.0116; –0.0025	0.300; 0.734

Each bootstrap comprised 10,000 resamples. Bootstrap (case /) = resampling rows of observation data. Bootstrap (residuals /) = resampling regression residuals. Bootstrap (/ basic), (/ percentile) and (/ BCa) are the basic, percentile, and bias-corrected and accelerated bootstrap confidence intervals respectively.

TABLE 4. Predicted Chablis wine vintage scores (with 95 % prediction intervals) from Equation 1, with environmental data shown, for the period 2041 to 2070 for climate projections using the RCP 2.5, 4.5 and 8.5 median scenarios (Drias, 2021) for the closest grid square to Chablis (47°48'27» N, 3°46'42» E).

	Weather Data				Chablis Vintage Model	
Year and Scenario	$Tmean_{Apr\text{-}Sep}$ (°C)	*CNI* (°C)	*CNI2* (°C)	$P_{Jun\text{-}Sep}$ (mm)	Calculated Score	Calculated Score *CNI2*
1976–2005	15.8	9.4	n/a	233.6	7.7 (5.7–9.9)	n/a
2009–2018	16.8	9.8	n/a	236.0	7.8 (5.8–10.0)	n/a
			Median Projections for 2041–2070			
RCP 2.6	17.0	10.8	9.91	222.6	7.4 (5.3–9.6)	7.7 (5.7–10.0)
RCP 4.5	17.7	11.5	10.20	220.1	6.3 (4.1–8.6)	6.8 (4.6–9.1)
RCP 8.5	18.2	12.0	10.41	210.7	5.1 (2.7–7.6)	5.7 (3.4–8.2)

Two values are shown for the Cool Night Index, where *CNI2* is an alternative to *CNI* in which the increase in value from 1976–2005 to 2041–2070 was reduced to only 40 % of the projected $Tmean_{Apr\text{-}Sep}$ rise. For reference, information for the periods 1976–2005 and 2009–2018 is also presented (actual mean vintage scores were 7.1 and 8.1, respectively). A more detailed version of this table with predicted scores for the 5th, 50th and 95th percentile probabilities for each RCP scenario is provided in the Supplementary Information (Table S2).

Chablis vintage model adjusted R-squared did not fall below 0.300 in 97.5 % of bootstrap resamples (Table 3).

3. Medium-term projections for Chablis wine quality

In the intermediate RCP 4.5 emissions scenario for the period 2041–70, the Chablis vintage model (Equation 1) implies that a *Good* score would only just be achieved, markedly lower than either the 2009–2018 period or the 1976–2005 base period (Table 4). The RCP 2.6 emissions scenario provided Chablis vintage scores that are similar to the 2009–2018 period and 1976–2005 base period.

DISCUSSION

1. Chablis wine has generally benefitted from climate change to date

Chablis wine quality has improved during the study period, with no *Poor* vintages (score < 6) since 1991 (Figure 2), whilst summer temperature and sunshine duration have progressively increased with fewer frost days but no linear trend for precipitation (Table 1). This has gone hand-in-hand with a 73 % increase in vineyard area and, based on the 5-year moving average, an 86 % increase in wine production (BIVB, data by personal communication). The Chablis vintage score model (Equation 1) shows a clear historic link between recent climate change in the region, particularly warmer growing season temperature (GST; Figure 2), and better vintage scores (Figure 4). In addition to this benefit from climate change, Chablis vintage score is also likely to have risen through better vitivinicultural practices such as superior hygiene and frost protection since the 1960s (George, 2007). The effect of temperature on the vintage score quantified here (Table 2) will, in part, also have captured the improvement over time in vitivinicultural practices because of the warming over this period (Figure 2).

Providing GST is below the maximum of a cultivar's range (see below), warmer GST results in greater photosynthetic production of carbohydrates improving flowering and fruitset (Atkinson, 2011) with more reliable ripening (Jones *et al.,* 2005). In addition, phenology is advanced so that veraison and ripening occur earlier in the year when temperatures are warmer (van Leeuwen and Darriet, 2016; Leolini *et al.,* 2018). Earlier budburst does imply closer coincidence with more frost-prone months and so has the potential to reduce yield (Leolini *et al.,* 2018), as occurred throughout Europe, and specifically France, in Spring 2021.

The quadratic relationship detected between Chablis vintage score and $Tmean_{Apr\text{-}Sep}$ (Figure 5), a pattern observed for wines in other regions (Jones *et al.,* 2005), indicates that Chablis quality may not necessarily continue to improve with further warming. The peak was at 16.5 °C (Figure 5). The 2009–2018 mean value for $Tmean_{Apr\text{-}Sep}$ (16.8 °C, Table 4) is at the warm end of the optimum plateau for the vintage score evident in Figure 5, and so further warming may reduce quality. This comment is reinforced by the different regressions of temperature with the year for each rating category where the combined and *Good* quality relations are almost identical whereas that for *Excellent* quality is shallower in slope (Figure 2); extrapolation of that relationship into the future, though unwise, would suggest a lower probability of achieving an *Excellent* vintage of Chablis typicity.

2. GST is the most important factor for vintage quality

The use of monthly weather data precluded the generation of certain temperature-based indices which accumulate above daily temperature thresholds (typically 10 °C in grape) such as Growing Degree Days (GDD), Biologically Effective Degree Days (BEDD), Huglin's Heliothermal Index (HI), or the Winkler Index (WI, based on GDD). This is, however, not considered an issue; mean Growing Season Temperature (GST) as used here and advocated by Jones *et al.* (2005) and widely used is highly correlated with the other indices for measuring growing season warmth (Moral *et al.,* 2016) and is functionally no different to GDD (Anderson *et al.,* 2012).

In our multi-factor model, temperature ($Tmean_{Apr\text{-}Sep}$) was the best weather factor explaining inter-annual variation in Chablis vintage score. This is consistent with studies on Chardonnay in Burgundy (Outreville, 2018; Davis *et al.,* 2019), in other French regions such as Bordeaux (Baciocco *et al.,* 2014; Ashenfelter, 2017), Rhone (Ashenfelter, 2017) and the Loire Valley (Neethling *et al.,* 2012) with different cultivars, and regions outside of France such as Barolo in Italy and Barossa in Australia (Ashenfelter, 2017).

It is well established that sugar concentration in grape berries is positively correlated with GST (van Leeuwen and Darriet, 2016); as is the case for Chardonnay (Gambetta *et al.,* 2016).

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Sugar concentration determines the potential alcohol content of the wine and whilst it is a prerequisite for high quality, excess heat can ultimately lead to over-alcoholic wines which, if accompanied by low concentration of organic acids, are "unbalanced" (Jones *et al.,* 2005; Neethling *et al.,* 2012; van Leeuwen and Destrac-Irvine, 2017). The reasons for greater sugar content at warmer temperatures may involve water loss from berries due to evaporation and greater concentration of the sugar (Pastore *et al.,* 2017) and/or physiological changes that may be genetically controlled and therefore cultivar specific (Suter *et al.,* 2021). Moreover, the composition of secondary metabolites that are responsible for the organoleptic properties of wine, and so affect quality, is changed in grapes ripened at high temperature (van Leeuwen and Destrac-Irvine, 2017).

3. Low peri-flowering period temperature is an early predictor of a *Poor* vintage

Mean temperature between May and July is particularly important for the subsequent quality of Chablis wine (Figure 3, Table 2). Flowering and fruitset typically occur in the first half of June for Burgundy as a whole (Davis *et al.,* 2019), though in Bordeaux, for example, can vary by around one month (Jones and Davis, 2000).

The polynomial relation for May to July mean temperature provided the best single-factor model for the vintage score (Table 2). A threshold of 15.5 °C for this period may provide a simple, easily-applied rule of thumb in advance of harvest to predict vintage quality; below this value vintage quality is likely to be *Poor* (83 % probability, Figure 3f). Warmth in this period is important for wine quality in other regions also (Real *et al.,* 2017). If it is too cool the flowering period is prolonged and can lead to uneven berry ripeness and wines with vegetal characteristics (Atkinson, 2011), or variable berry size within a bunch ("Millerandage") and/or berries that are incompletely fertilized ("Shot" berries) which hinder the production of a balanced wine (Gray and Coombe, 2009). Conversely, too high a temperature during flowering can cause premature veraison, inactivation of enzymes and incomplete biosynthesis of compounds associated with flavour (Jones *et al.,* 2005).

4. *CNI* is the second most important factor in the Chablis vintage model

The Cool Night Index (*CNI*) was the second most important weather variable, after GST ($Tmean_{Apr\text{-}Sep}$), in the Chablis vintage model (Table 2). This term in the model accounts for the effect of cool temperature during the ripening period in the 30 days until harvest (Tonietto and Carbonneau, 2004). Whilst warmth in the day is crucial for berry ripening, cool temperatures during the night result in the secondary metabolites associated with high-quality flavours and aromas (Tonietto and Carbonneau, 2004). Moreover, recent research by Aoki *et al.* (2021), albeit on an indigenous Japanese grapevine variety (*V. vinifera* cv. Koshu), suggests high night temperatures may promote downy mildew. This may also be relevant because Chardonnay vines are susceptible to downy mildew infection which can taint the wine (Skelton, 2020).

High night temperatures also increase respiration and the degradation of malic acid (Arrizabalaga-Arriazu *et al.,* 2020); and so cool nights preserve acidity in the berries. Acidity is an important aspect of Chablis typicity. Malic acid (usually converted to the smoother-tasting lactic acid by winemakers via malolactic fermentation) typically provides half of the total acidity of grapes and wine with tartaric acid (the other major acid) less prone to degradation during ripening (Jackson, 2014). Wines that lack malic acid (or lactic acid after conversion) may taste flat and are prone to microbial spoilage, although in excess wines can taste sour (Jackson, 2014).

It has been suggested that it is the difference in daily temperature range during ripening, rather than minimum temperature, produces important flavour and aroma compounds (Gladstones, 1992 cited by Jones *et al.,* 2005). However, in developing the model we found that *CNI* (i.e., mean minimum temperature in September) explained more variance in the vintage score and also the effect of the range between mean minimum and mean maximum temperatures for September was not significant ($P > 0.10$). Chablis vintage quality is more closely associated with acidity than secondary metabolites, and so the effect on night respiration rates may explain why mean minimum temperature, not the range, in September is an important factor for Chablis.

5. Precipitation from flowering to harvest is negatively related to vintage quality

Every 100 mm increase in $P_{Jun\text{-}Sep}$ reduced the vintage score by almost 0.7 in the model (Table 2). Moderate water stress is also associated with higher quality wine (van Leeuwen *et al.,* 2009; Fraga *et al.,* 2013; Alem *et al.,* 2019). Water stress increases the biosynthesis of secondary metabolites important to the development of aroma in wine, such as the carotenoid-derived C_{13}-norisoprenoids which are associated with floral and fruity odours (Alem *et al.,* 2019). Too much rain between flowering and ripening is also well known to reduce wine quality (Jones and Davis, 2000). This is because berries swell producing lower quality wine (Jones and Davis, 2000; Baciocco *et al.,* 2014) due to a reduction in the concentration of flavour- and aroma-related metabolites (VanderWeide *et al.,* 2021). In cooler climates, high rainfall may lead to sour rot infection, which increases the concentration of acetic acid in berries imparting an unwanted vinegar flavour to the wine (VanderWeide *et al.,* 2021). In this study, *Poor* vintages of Chablis with high $P_{Jun\text{-}Sep}$ (approximately > 275 mm) were associated with cool $Tmean_{Apr\text{-}Sep}$, suggesting sour rot may have been an issue in these vintages.

We also compared a model with August to September precipitation ($P_{Aug\text{-}Sep}$) rather than June to September ($P_{Jun\text{-}Sep}$). The shorter period was assessed because research for other wine regions emphasised the importance of rainfall in the few weeks leading to harvest (Ashenfelter and Byron, 1995; Davis *et al.,* 2019). In our assessment, however, the use of ($P_{Aug\text{-}Sep}$) resulted in a non-significant (P = 0.0642) rainfall term. This comparison suggests that the Chablis vintage score is reduced more consistently by greater rainfall over a longer period than just the last weeks before harvest.

6. *CNI* is a key differentiator between the Chablis vintage model and others for French wines

Several models of the influence of inter-annual variation in weather on wine quality in France have been devised since Ashenfelter, Ashmore and Lalonde (1993, cited by Ashenfelter and Byron, 1995) showed that much of the variability in the price of a Bordeaux vintage could be explained by its age, GST (growing season temperature, April to September), and rainfall both in August and September and also in the prior autumn and winter. Models which represent both the positive effect of temperature during the growing season and the negative effect of rainfall typically account for 35 to 60 % of the variance in the vintage score (Outreville, 2018) or can accurately categorise the top and bottom vintage scores (Baciocco *et al.,* 2014; Davis *et al.,* 2019). The Chablis vintage score model presented here (Table 2) is consistent with the above.

Focusing on Burgundy, Outreville (2018) found that temperature in July and August provided the best (positive) association and rainfall in August and September the best (negative) association with white wine quality. Davis *et al.* (2019) found that the impact of rainfall on white Burgundy wine quality varied with phenology, but the Chablis vintage model developed here, with monthly data, detected only the negative relation for June to September rainfall reported in Table 2.

TABLE 5. Comparison of the means of three climate indices, relevant to the Chablis vintage model, for Chablis and Savigny-lès-Beaune weather stations from 1963 to 2018 and 2009 to 2018.

Climate Indices	Chablis	Savigny-lès-Beaune
	1963–2018	
GST ($Tmean_{Apr\text{-}Sep}$) (°C)	15.8	16.75
CNI (°C)	9.40	11.24
$P_{Jun\text{-}Sep}$ (mm)	236.6	244.6
	2009–2018	
GST ($Tmean_{Apr\text{-}Sep}$) (°C)	16.8	17.6
CNI (°C)	9.8	11.8
$P_{Jun\text{-}Sep}$ (mm)	236.0	268.8

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The main difference between our Chablis vintage model and one for white Burgundy (Davis *et al.,* 2019) is the inclusion of *CNI*, which we found to be a more important factor than rainfall.

This difference may be because acidity is more important for Chablis than other white wines from Burgundy (George, 2007). This would tally with the observation that while GST is around 1 °C lower in Chablis compared to Savigny-lès-Beaune, *CNI* is proportionally far cooler during the ripening period (Table 5) – important to the acid content of the berries. Moreover, minerality, another characteristic of Chablis wine, may be positively correlated with acidity (Ballester *et al.,* 2013). Hence, *CNI* could be a key variable in the difference in typicities between Chablis and the white wines of the Côte de Beaune, and elsewhere.

7. Model factor periods are affected by advancing phenology

The mean minimum temperature in September (*CNI*) was an inappropriate factor for the 2003 vintage because the harvest started on 25 August (George, 2007). This was also partly the case for the 2007, 2011, 2015, 2017 and 2018 vintages for which harvest began in early September (Biss, 2020). In both cases, since harvest typically takes around two weeks to complete, August or mid-August to mid-September might be a more relevant period to consider for the *CNI* in future developments of the model, as suggested by the slight improvement in model performance achieved by using August and September instead of just September. Omazić *et al.* (2020) found the same problem with *CNI* for wine regions in Croatia due to earlier harvests.

A similar issue arises for GST and precipitation from flowering to harvest, with climate change advancing the beginning and endpoints for these indices. However, no model improvement was observed by advancing these weather factor periods by one month for the most recent 25, 20, 15 or 10 vintages. Indeed, the advancement to phenology versions of the model performed poorly, but this may have been because there were no *Poor*-quality wines in these recent periods (Figure 2) and so a narrower range of vintage scores available for analysis. A larger model incorporating the effects of weather on the timing of crop development, soil water balance (such as the Dryness Index (Tonietto and Carbonneau, 2004)), or one with greater temporal resolution and more precise data for wine quality, might be an improvement. All models are simplifications of the real world, however, and our current model has the virtues of simplicity and ease of application.

8. Model limitations

We have developed, and validated, a simple model here to describe the historic effect of inter-annual variation in weather on Chablis vintage score quality. Bonada and Sadras (2015) point out that such approaches are "bound to be inconclusive" because numerous factors are either confounded or analysed insufficiently. Such factors include wind, previous years' weather and vine development, water deficit, vapour pressure deficit, viticultural and oenological practices, and extreme weather events. Neither has the increase in atmospheric CO_2 concentration since 1963 been accounted for. This may affect wine quality with, for example, faster berry development leading to reduced malic and tartaric acid concentrations (Leibar *et al.,* 2017; Arrizabalaga-Arriazu *et al.,* 2020).

There is also the subjective basis of vintage scores (Hodgson, 2008; Cicchetti and Cicchetti, 2013; Jackson, 2014). Other issues include variation in phenology from year to year and the limitation of weather data from only one station given that inter- and intra-vineyard variation in temperature and bioclimatic indices can be as great as at larger scales (Bonnefoy *et al.,* 2013). The above may help to explain why the Chablis vintage model accounted for only 57 % of the variance in the vintage score. We also acknowledge that the model was far better in distinguishing between the *Poor* and the two better vintages than between the *Good* and the *Excellent* (Figures 4 and 6). Nonetheless, the model provides a first approximation of the weather typically associated with high-quality Chablis wine production, compares well with similar models for other regions and/or cultivars, and, we argue, has utility in the comparative ease of application to different scenarios.

9. Climate change and Chablis typicity

Poor Chablis vintages appear to have been avoided in recent years due to warming (Figure 2). Looking ahead, the median probability of the intermediate RCP 4.5 scenario in combination with the Chablis vintage model suggests that Chablis producers will struggle to maintain the high quality of their wine by 2041 to 2070 (predicted score 6.3, Table 4). However, if minimum temperatures in September (*CNI*) continue to rise more slowly than maximum temperatures the decline may be reduced (*CNI2* predicted score 6.8, Table 4).

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On the other hand, warming is likely to hasten ripening (van Leeuwen and Destrac-Irvine, 2017) further into August which would further increase the effective *CNI*. Representative Concentration Pathway 2.6 is the only scenario that has a chance (> 66 %) of meeting the Paris Agreement (OECD, 2017); we predict that achieving that target would provide Chablis vintage score only marginally below that of recent years (7.4–7.7 *versus* 7.8 for 2009–2018).

Vintage scores assess whether wines are of typicity. A *Good* rating, for example, indicates the wine is not an *Excellent* example of a Chablis but it may well be very pleasurable to drink (Martin, 2020). Similarly, vintages with the same score may not be identical in all regards. The 2003 and 2018 vintages were noteworthy for being unusually hot ($Tmean_{Apr\text{-}Sep}$ > 18 °C) and dry ($P_{Jun\text{-}Sep}$ < 135 mm). Their ratings were "*Good*" (score 6.1) and "*Excellent*" (score 8.1), respectively, but they were not like typical Chablis wines lacking acidity (Robinson, 2019) and minerality (Martin, 2020). This consideration is relevant to future vintages. Tables 4 and 5 show that the Chablis region's climate in 2041 to 2070, especially with the RCP 4.5 emissions scenario, may approach that of today's Côte de Beaune, a region world-renowned for its premium quality Chardonnay wines such as Corton-Charlemagne, Chassagne-Montrachet, Meursault and Puligny-Montrachet. Hence, although climate change may reduce Chablis vintage score in future (Table 4), Chardonnay grapes grown in the Chablis region are likely to continue to produce premium quality wines.

These predictions must be approached with caution. In addition to errors in the Chablis vintage model, there are uncertainties associated with emissions scenarios and climate modelling (Jacob *et al.,* 2014; OECD, 2017), including the possibility of decadal-scale cold waves (Sgubin *et al.,* 2019). It is also the case that short-term extreme weather events, such as hail and intense rain – the frequency and strength of which will increase with climate change (van Leeuwen and Darriet, 2016) – are not accounted for in the above.

Moreover, it is expected that wine producers will adapt to and/or mitigate the effects of climate change through crop management (van Leeuwen *et al.,* 2019; Santos *et al.,* 2020). The Chablis vintage model presented here may support producers in that task. A further aim is for the model to be applied to identify sites with suitable climates for premium white wine from Chardonnay grapevines in emerging cool climate viticulture regions, such as the UK, an approach to site selection advocated by Ashenfelter (2017).

CONCLUSIONS

This study has shown that both the weather in the region and Chablis vintage wine scores have changed over the period 1963 to 2018. The key findings are:

- Summer temperature has warmed progressively over this period whilst the proportions of *Poor* and *Good* vintage years have diminished and increased, respectively.
- There is a curvilinear relationship between Chablis wine quality and mean temperature during the growing season (April to September). This is the most significant factor in the Chablis vintage score model.
- *CNI* (mean minimum temperature during the period of ripening, with September used in this study) is the second most important factor in distinguishing between vintage scores.
- High rainfall from flowering (June) to harvest (September) reduces Chablis wine quality.
- Cool mean temperatures from 1st May to 31 July (peri-flowering, mean ≤ 15.5 °C) may signal a vintage of *Poor* quality.
- Whilst most climate change scenarios imply a decline in Chablis quality by 2041–2070, the decline would be small if the Paris Agreement were to be met.
- Under these scenarios, especially RCP 4.5, the climate of Chablis in 2041–2070 (and so the typicity of Chablis wine, if managed as now) may approach that of the Côte de Beaune today.

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