Projected impacts of climate change on viticulture over France wine-regions using downscalled CMIP6 multi-model data

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Introduction

Winegrape is a crop for which the quality and the identity of the final product depends strongly on the climatic conditions of the year. By impacting production systems and the way in which wines are developed, climate change represents a major challenge for the wine industry (Ollat et al., 2021).
Assessing major changes in the vineyard expected in the future is a highly uncertain exercise, as many factors might affect grapevine growth, cropping conditions and plant diseases. Most studies considering climate change impact focus on grapevine response to temperature and rainfall, either considering change in phenological timing (e.g. García de Cortázar-Atauri, 2017). Only few studies consider changes in phenological timing and climate conditions between key phenological stages (e.g. Sgubin et al., 2022). However, these studies do not account for each region specific training system and cultivar might be different, hence affecting grapevine phenology and water status.

Research Objectives

The purpose of this study is to estimate the current (1985-2014) and projected climate change for the middle (/early second half) of the 21st century (2040-2070) at the scale of present French wine regions integrating the response of phenological features of regional cropped varieties and water status to regional training systems using robust phenological models and water balance modeling validated in the context of viticulture. This approach makes it possible to visualize the direct impact that climate change could have on plant growth, frost risk, disease management and the potential maturity of the grapes.

Materials and methods

Observed climate data came from the SAFRAN (Système d'Analyse Fournissant des Renseignements Adaptés à la Nivologie) database produced by the French national weather service (Meteo-France). Daily minimum and maximum temperature and precipitation at an 8 km resolution grid were extracted over the French wine-growing regions. A total of 21 wine-growing regions were defined, and using an identification of the areas planted with vines provided by the Corine Land Cover (CLC) database from Copernicus land cover products (http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012). SAFRAN grid points representative of vineyard areas were selected with a 4 km buffer zone. In the following, the evolution of the different bioclimatic indices and phenological phases will be presented for a set of wine-growing regions grouped according to the dominant climatic type in these regions. Thus, three classes have been established: Mediterranean (MED), oceanic influence (OCE) and Semi-Continental Oceanic (or degraded oceanic ; SCO).
For the 2040-2070 period, climate projections came from general circulation models (GCMs) of the CMIP6 exercise (Coupled Model Intercomparison Project: Eyring et al., 2016) with the SSP5.8.5 scenario. In total, data from 20 CMGs, statistically downscaled and debiased to SAFRAN's 8 km resolution grid using the quantile mapping method. More details about the methodology of producing this data set can be found in Ollat et al. (2021).

Several bioclimatic indices were calculated. They consist either on indices calculated on fixed calendar dates (so called hereafter *agroclimatic indices*) or in indices calculated on periods relative to phenological stages (so called hereafter *ecoclimatic indices*), hence changing from year-to-year. Agroclimatic indices are calculated here on the April-September period, which seems to be more closely adjusted on the vegetative season for the French vineyards than the April-October:

- growing season average temperature (GST) ;
- growing season cumulative rainfall (GSPR) ;

Regarding the simulation of phenology phases, three phenological models were used to simulate the budburst (Smoothed-Utah: Morales-Castilla et al., 2020), flowering and veraison (GFV: Parker et al., 2011) and theoretical maturity (i.e. the date when a given sugar content in grapes is reached, GSR : Parker et al., 2020). Six grape varieties were selected according to the wine region with different concentrations of sugar for theoretical maturity (see details in Table 1).
Based on simulated phenological phases a set of seven indices were calculate:

- FrostDays : the number of days with temperature below 0°C after budburst;
- HeatDays : the number of days with temperature over 35°C from budburst to harvest;
- FRD.BB.FLO15 : the frequency of days with precipitation > 1 mm from budburst to 15 days after floraison. We assume that this is the period during which most of the mechanization, constrained by rainy days) for weeding and spraying is performed;
- CR.BB.FLO15 : the cumulative precipitations from budburst to 15 days after floraison, as rainfall favors mildews and black rot during this period during which grapevine is highly sensitive to contaminations ;
- SRD.5FLO5 : the sum of days with precipitation > 1 mm from 5 days before to 15 days after the mid-flowering stage. Rain events during this crucial period are detrimental to fertilization and fruit set.
- WE.5FLO15 : the average value of thermal effect on grapevine development using the equation of Wang and Engel, a bell-shaped curve providing a response from 0 (no effect beyond 0 and

40°C) to 1 (optimum, fixed at 27.6°C) following García de Cortázar-Atauri et al., (2010) optimization for cv Pinot N which is consistent with the photosynthetic optimum of grapevine.
- HydricSI : an hydric stress index from floraison to harvest. This hydric stress index corresponds to 1 - average of daily relative stomatal conductance of grapevine between flowering and maturity. Relative stomatal conductance (varying from 0 to 1) is calculated using Lebon's soil water balance model (Lebon et al., 2003), with a soil water capacity set at 150 mm for all regions and canopy parameters set to represent a common training system in each region (table 1).

For projected climate data, we used the median expressed in terms of difference between the simulation over the reference period (1985-2014) and the future period (2040-2070). The standard deviation over the 30 years period is also calculated.

Results

Bioclimatic indices
Projections for the middle of the 21st century with the SSP5.8.5 reveal a significant net increase in temperature during the growing season (Table 1). All regions would be affected in a relatively similar way by the increase in GST (+3.1°C on average). In terms of cumulative rainfall during the growing season, a significant decrease for the majority of climate models is simulated in the ouest/south-ouest of France, under oceanic influence. This decrease spreads from 40mm (Val de Loire) to 80mm (Gers ; Table 2). Other regions exhibit also a decrease in precipitation during the growing season with high variability between models.

Phenology
Higher temperatures projected in the mid 21st century have a direct impact on simulated phenological phases obtained with cumulative degree days models. Thereby, all wine-growing regions exhibit earlier simulated dates from budburst to grape maturity. This precocity is accentuated during the growing season: from -1 to -14 days for budburst, from -10 to -15 for flowering, from -16 to -23 days for veraison and from -18 to -33 days for maturity (Table 2). As recalled and observed by García de Cortázar-Atauri et al., (2017), this is still in line with other studies conducted at the French scale. Note also that for two regions (Languedoc and Pyrénnées-Orientales), the earliness of budburst is not significant for the majority of climate models used. Higher winter temperature might negatively impact the need for cold units for dormancy rise, hence delaying budbreak.

Ecoclimatic indices
The median number of frost days after budburst (FrostDays) do not change significantly in all wine regions (Table 2). It slightly decreases when considering the mean value (results not shown). However**,** only one model of budburst was used here and large differences in projected frost risk have previously been observed according to the way budburst is simulated (Sgubin et al., 2018).

The three ecoclimatic indices FRD.BB.FLO15, CR.BB.FLO15 (respectively frequency of rainy days and cumulative precipitations from budburst to 15 days after floraison) and SRD.5FLO5 (number of rainy days 5 days before to 15 days after flowering) projected do not show any significant evolution in all wine regions (Table 2). A large variance between climate models suggests that change in precipitation during spring and the flowering period is highly uncertain so that it is not possible to conclude about the impact of precipitation change on mechanization, diseases and fertilization/fruit set.

With higher temperature during the flowering period, projected thermal conditions (as expressed by the Weng and Hengel index mean value WE.5FLO15) are more favorable to photosynthesis activity. As future simulated hydric stress during this period remains very low (< 0.05 in average, i.e. no stress, results not shown) climate conditions during flowering are expected to be in favor of increased yield.

The number of heat days will significantly increase in all wine regions. The regions under MED influence would be affected by the greatest increase (+15 days against +9 and +6 days for the regions under SCO and OCE influence respectively).

The projected hydric deficit during fruit development (flowering to theoretical maturity) is expected to rise significatively in most of wine region OSC and OCE regions (Alsace Beaujolais, Bourgogne, Bugey-Savoie, Champagne, Cher, Bordelais, Cahors, Charentes, Gers, Lot et Garonne et Val de Loire) and in the northern part of Med regions with the Cotes-du-Rhone nord region.

Conclusion

This study uses 20 GCM (CMIP6 simulations) to characterize climate change impacts on viticulture conditions by 2040-2070, accounting for training systems and cultivar likely to be found in French vineyards. It is, to our knowledge, the first time such a systemic analysis is performed over all regions of a major wine producing country.
Results suggest that expected increased temperature will speed up grapevine development, favor flowering and might induce more heat damage. While precipitation during the growing season will probably decrease, the spread between models makes the changes in rainfall during the vegetative growth and flowering stages of grapevine uncertain.

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Tables and Figures

Table 1: Phenology (grape variety and maturity sugar content) and soil water balance (canopy height and width, distance between rows, row porosity and azimuth and available water capacity) models parameters selected for each wine-growing region of France.

Climate influence	Wine-growing Regions	Cultivar	Maturity sugar content [g/L]	Canopy height [m]	Canopy width [m]	Distance between rows [m]	Row porosity [%]	Row azimut [°]	Available water capacity [mm]	Comments
Oceanic and Semi-Continental	Alsace	riesling	200	1.5	0.4	2	0.25	0	150	Very high rows in alsace. Riesling is not paremetrized for sugar = 210 g/L (200 g/L is used instead), which is a bit low
	Beaujolais	pinot noir	210	0.8	0.4	1.5	0.25	0	150	No parametrization is available for gamay's budburst. Pinot noir which is cultivated in Beaujolais is used
	Bourgogne	pinot noir	210	0.8	0.4	1	0.25	0	150	Classical Burgundy cultivar (Côte de Nuits)
	Bugey-Savoie	pinot noir	210	1.2	0.4	2	0.25	0	150	Presence of pinot noir in Savoie and Bugey
	Champagne	chardonnay	170	0.8	0.4	1	0.25	0	150	Sparkling chardonnay
	Cher	pinot noir	210	0.8	0.4	1	0.25	0	150	Sancerre type
	Jura	pinot noir	210	1.5	0.4	2	0.25	0	150	chardonnay would be more adapted, but no parameter for 210 g/L
Oceanic	Bordelais	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Regular Bordeaux appellation
	Cahors	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Cabernet-sauvignon is chosen because can be cultivated there
	Charentes	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Ugni blanc values (not available) for Cognac modelling. A late variety is selected
	Dordogne	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Bergerac type
	Gaillac	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Cabernet-sauvignon is chosen because can be cultivated there
	Gers	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Not adapted, but local cultivar not represented in the phenological models
	Lot-et-Garonne	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Not adapted, but local cultivar not represented in the phenological models
	Val de Loire	cabernet-sauvignon	210	1.2	0.4	2	0.25	0	150	Cabernet-sauvignon is cultivated in Val de loire
Mediterranean	Bouches-du-Rhone	grenache	210	1.2	0.4	2	0.25	0	150	Same configuration to all mediterranean wines : grenache and 2m wide vineyard
	Cotes-du-Rhone nord	syrah	210	1	0.4	2	0.25	0	150	Typical syrah from crozes hermitage
	Cotes-du-Rhone sud	grenache	210	1.2	0.4	2	0.25	0	150	Southern Rhone appellation in VSP (no gobelet)
	Languedoc	grenache	210	1.2	0.4	2	0.25	0	150	Same configuration to all mediterranean wines : grenache and 2m wide vineyard
	Provence	grenache	210	1.2	0.4	2	0.25	0	150	Same configuration to all mediterranean wines : grenache and 2m wide vineyard
	Pyrenees-Orientales	grenache	210	1.2	0.4	2	0.25	0	150	Same configuration to all mediterranean wines : grenache and 2m wide vineyard

Table 2: Median différence of phenology phases (DEB, FLO, VER, MAT), agroclimatic (GST, GSR) and ecoclimatic (FrostRD, HeatRD, FRD.BB.FLO15, SRD.5FLO15, CR.BB.FLO15, WE.5FLO15, HydricSI) indices between the 1985-2014 period and the 2040-2070 using 20 GCMs (SSP5.8.5). Values in bold indicate the presence of a significant difference for the majority of GCMs used.

Climate influence	Wine-growing Regions	GST [°C]	GSR [mm]	DEB [doy]	FLO [doy]	VER [doy]	MAT [doy]	FrostRD [days]	HeatSD [days]	FRD.BB.FLO15 [%]	CR.BB.FLO15 [mm]	SRD.5FLO15 [days]	WE.5FLO15 [unitless]	HydricSI [unitless]
Oceanic and Semi-Continental	Alsace	**2.8 ± 1**	*-33 ± 74*	**-13 ± 6**	**-12 ± 6**	**-19 ± 6**	**-33 ± 7**	*0 ± 0.1*	**4 ± 4**	*-3.9 ± 0.1*	*-1.8 ± 15.5*	*-0.8 ± 1.9*	**0.051 ± 0.033**	*0.094 ± 0.079*
	Beaujolais	**3.3 ± 1.1**	*-46 ± 58*	**-11 ± 5**	**-12 ± 5**	**-19 ± 6**	**-26 ± 6**	*0 ± 0*	**9 ± 5**	*-2.9 ± 0.1*	*-5.4 ± 13.4*	*-0.6 ± 1.3*	**0.064 ± 0.032**	**0.102 ± 0.091**
	Bourgogne	**2.8 ± 0.9**	*-50 ± 68*	**-11 ± 5**	**-12 ± 7**	**-19 ± 7**	**-25 ± 6**	*0 ± 0*	**5 ± 4**	*-4.3 ± 0.1*	*-5.6 ± 11.9*	*-0.9 ± 1.6*	**0.06 ± 0.032**	**0.1 ± 0.085**
	Bugey-Savoie	**3.2 ± 1.2**	*-67 ± 77*	**-13 ± 6**	**-14 ± 5**	**-23 ± 7**	**-32 ± 8**	*0 ± 0*	**6 ± 5**	*-2.1 ± 0.1*	*-3.2 ± 19.4*	*-0.4 ± 1.4*	**0.066 ± 0.034**	**0.093 ± 0.071**
	Champagne	**2.8 ± 1.2**	*-30 ± 41*	**-12 ± 5**	**-12 ± 5**	**-23 ± 7**	**-27 ± 7**	*0 ± 0*	**3 ± 3**	*-3 ± 0*	*-2.4 ± 10*	*-0.6 ± 1*	**0.058 ± 0.03**	**0.111 ± 0.08**
	Cher	**2.7 ± 0.9**	*-47 ± 44*	**-11 ± 5**	**-12 ± 5**	**-18 ± 5**	**-24 ± 6**	*-0.1 ± 0.2*	**6 ± 5**	*-3.2 ± 0.1*	*-3.9 ± 9.9*	*-0.7 ± 1.5*	**0.05 ± 0.037**	**0.073 ± 0.089**
Oceanic	Bordelais	**2.7 ± 0.8**	**-72 ± 53**	**-14 ± 7**	**-11 ± 5**	**-17 ± 6**	**-21 ± 5**	*0 ± 0*	**8 ± 4**	*-2.9 ± 0.1*	*-1.8 ± 7.5*	*-0.6 ± 1.1*	**0.05 ± 0.023**	**0.107 ± 0.077**
	Cahors	**3.2 ± 0.9**	**-77 ± 58**	**-14 ± 5**	**-11 ± 4**	**-19 ± 5**	**-25 ± 5**	*0 ± 0*	**15 ± 7**	*-2.9 ± 0.1*	*-1.6 ± 13.4*	*-0.6 ± 1.2*	**0.059 ± 0.027**	**0.139 ± 0.088**
	Charentes	**3 ± 1.8**	**-68 ± 41**	**-13 ± 5**	**-11 ± 6**	**-18 ± 8**	**-23 ± 9**	*0 ± 0*	**7 ± 4**	*-2.6 ± 0.1*	*-1.3 ± 10.9*	*-0.6 ± 1.6*	**0.06 ± 0.045**	**0.102 ± 0.067**
	Gaillac	**3.3 ± 1**	**-66 ± 59**	**-13 ± 4**	**-11 ± 3**	**-17 ± 4**	**-23 ± 5**	*0 ± 0*	**15 ± 6**	*-3.5 ± 0.1*	*-4.5 ± 9.2*	*-0.7 ± 1.1*	**0.059 ± 0.024**	*0.113 ± 0.062*
	Gers	**2.9 ± 1**	**-80 ± 53**	**-13 ± 4**	**-11 ± 3**	**-17 ± 5**	**-23 ± 6**	*0 ± 0*	**12 ± 6**	*-2.7 ± 0.1*	*-2.6 ± 12*	*-0.6 ± 1.5*	**0.055 ± 0.025**	**0.146 ± 0.086**
	Lot-et-Garonne	**2.8 ± 0.9**	**-72 ± 49**	**-13 ± 4**	**-10 ± 3**	**-16 ± 5**	**-21 ± 6**	*0 ± 0*	**11 ± 6**	*-3.5 ± 0.1*	*-3.7 ± 10.9*	*-0.7 ± 1.2*	**0.05 ± 0.023**	**0.123 ± 0.077**
	Val de Loire	**2.7 ± 1.2**	**-41 ± 35**	**-14 ± 6**	**-11 ± 5**	**-18 ± 7**	**-26 ± 8**	*0 ± 0*	**4 ± 4**	*-2 ± 0.1*	*-0.9 ± 9.8*	*-0.4 ± 1.3*	**0.062 ± 0.038**	**0.091 ± 0.058**
Mediterranean	Bouches-du-Rhone	**3.9 ± 1.1**	*-51 ± 51*	**-8 ± 3**	**-15 ± 7**	**-22 ± 7**	**-25 ± 5**	*0 ± 0*	**16 ± 6**	*-3.3 ± 0*	*-3.5 ± 7.9*	*-0.7 ± 0.7*	**0.061 ± 0.022**	*0.044 ± 0.055*
	Cotes-du-Rhone nord	**3.2 ± 1**	*-45 ± 69*	**-9 ± 5**	**-12 ± 5**	**-18 ± 5**	**-24 ± 6**	*0 ± 0*	**11 ± 5**	*-2 ± 0.1*	*-5.3 ± 12.4*	*-0.4 ± 1.2*	**0.059 ± 0.032**	**0.104 ± 0.097**
	Cotes-du-Rhone sud	**3.6 ± 1**	-49 ± 51	**-7 ± 3**	**-13 ± 7**	**-20 ± 7**	**-23 ± 5**	0 ± 0	**17 ± 6**	-2 ± 0	-2.2 ± 6.5	-0.4 ± 0.7	**0.059 ± 0.023**	0.04 ± 0.051
	Languedoc	**3.3 ± 1**	*-52 ± 55*	*-3 ± 2*	**-10 ± 4**	**-16 ± 5**	**-19 ± 5**	*0 ± 0*	**17 ± 9**	*-3.5 ± 0*	*-3.2 ± 7.6*	*-0.7 ± 0.8*	**0.059 ± 0.025**	*0.055 ± 0.067*
	Provence	**3.8 ± 1**	*-67 ± 61*	**-5 ± 3**	**-14 ± 7**	**-20 ± 7**	**-22 ± 4**	*0 ± 0*	**14 ± 6**	*-1.8 ± 0*	*-4.6 ± 7.9*	*-0.4 ± 0.6*	**0.062 ± 0.023**	*0.033 ± 0.052*
	Pyrenees-Orientales	**3.2 ± 1**	*-44 ± 46*	*-1 ± 1*	**-10 ± 4**	**-15 ± 5**	**-18 ± 5**	*0 ± 0*	**11 ± 9**	*-2.6 ± 0*	*-3.1 ± 7.4*	*-0.6 ± 0.9*	**0.061 ± 0.027**	*0.016 ± 0.087*

Columns information: growing season temperature (GST) and cumulative rainfall (GSR), simulated phenology phases (DEB: budburst, FLO: flowering, VER: veraison and MAT: maturity), frost risk days (FrostRD), heat risk day (HeatRD), the frequency of rainy days (FRD.BB.FLO15) and cumulative rainfall (CR.BB.FLO15) between budburst and 15 days after flowering, the number of rainy days 5 days before flowering to 15 days after (SRD.5FLO15), the average value of thermal effect on grapevine development using the equation of Wang and Engel 5 days before flowering to 15 days after (WE.5FLO15) and hydric stress index (HydricSI) corresponding to 1 - average of daily relative stomatal conductance of grapevine between flowering and maturity calculated using Lebon's soil water balance model (Lebon et al, 2003)