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Analysis of climate change indices in relation to wine production: A case study in the Douro region (Portugal)

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Abstract. Climate change is of major relevance to wine production as most of the wine-growing regions of the world, in particular the Douro region, are located within relatively narrow latitudinal bands with average growing season temperatures limited to 13–21°C. This study focuses on the incidence of climate variables and indices that are relevant both for climate change detection and for grape production with particular emphasis on extreme events (e.g. cold waves, storms, heat waves). Dynamical downscaling of MPI-ESM-LR global data forced with RCP8.5 climatic scenario is performed with the Weather Research and Forecast (WRF) model to a regional scale including the Douro valley of Portugal for recent-past (1986–2005) and future periods (2046–2065; 2081–2100). The number, duration and intensity of events are superimposed over critical phenological phases of the vine (dormancy, bud burst, flowering, *véraison*, and maturity) in order to assess their positive or negative implications on wine production in the region. An assessment on the statistical significance of climatic indices, their differences between the recent-past and the future scenarios and the potential impact on wine production is performed. Preliminary results indicate increased climatic stress on the Douro region wine production and increased vulnerability of its vine varieties. These results will provide evidence for future strategies aimed to preserve the high-quality wines in the region and their typicality in a sustainable way.

1. Introduction

There is a general acceptance by the scientific community of the reality of climate change in relation to human activities, especially concerning greenhouse gases (GHGs) emissions. Depending on the GHGs emissions scenario, it is expected an increase in global mean surface temperature from 1°C to 3.7 °C by the end of the century when compared to the reference period 1986–2005 [1]. The influence of climate is critical in viticulture and wine production. Year-to-year meteorological variations affect the yield and the optimal environmental conditions for the grape to ripe and, therefore, whether wine typicity for a given ‘terroir’ or grapevine growing region will be correctly expressed to achieve its full potential. This is known as the “vintage effect” with climate having a greater impact on yield and quality than other environmental factors such as soil type or grapevine variety. In this sense, it is already known that an increase of temperature produces an advance in phenology, which in turn, could have advantageous effects in northern or Atlantic conditions but be detrimental under Mediterranean conditions. As the grapes are exposed to higher temperatures due both to climate change and advanced phenology, the supply of metabolites to the grape is altered, generally causing greater sugar accumulation and higher alcohol levels, lower acidity and variable effects on different aromas and secondary metabolites [2].

Most of the wine-growing regions of the world, in particular the Douro region, are located within relatively narrow latitudinal bands with average growing season temperatures limited to 13–21°C. Therefore, small changes in temperature could end affecting the typicity and style of the wine produced in them, and even produce shifts in their potential for viticulture, making it too warm or better suited to produce quality wines than before [3].

The Multicriteria Climatic Classification System (MCC System) for grape growing regions worlwide [4] along with other bioclimatic indices (e.g. Winkler index, Hydrothermic index of Branas) have been already used to assess the impact of climate change on the suitability for wine production across Europe. The indices were calculated from climate variables obtained from simulations with a grid size of about 25 km performed with the regional climate model COSMO-CLM for the recent-past climate (1960–2000) and for the 21st century (2011–2040, 2041–2070 and 2071–2100) under the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios (IPCC-SRES) B1 and A1B. The A1B scenario corresponds to a balance across all

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energy sources, whereas in the B1 scenario the emphasis is on environmental sustainability. All simulations were forced by ECHAM5/MPI-OM1 boundary conditions. The results of this study indicated an increased soil water deficit and cumulative thermal effects during the growing season in southern Europe, which could imply negative effects for wine production for these areas unless suitable adaptation measurements (e.g. rootstock and variety selection, training system, irrigation) are taken. In contrast, western and central Europe could benefit with higher quality potential for the grape and even new potential areas for wine production [5].

In another study, the atmospheric variables taken from coupled global and regional climate models (GCM-RCMs) simulations in combination with the MCC system were also used to assess present and future scenarios for the Portuguese grapevine growing regions. For present scenarios (1950–2000), the WorldClim project 1 km high resolution dataset [6], validated with E-OBS observational data [7] was used. To assess the impacts of climate change on future viticulture suitability in Portugal, the period 2014–2070 under the IPCC-SRES A1B was chosen. An ensemble of 13 RCM simulations driven by 3 different GCMs produced by the ENSEMBLES project [8] was selected. To pass from the coarse grid RCM resolution $0.22^\circ \times 0.22^\circ$ (~ 25 km) to the 1 km grid size of the WorldClim baseline dataset, a bi-cubical interpolation (pattern downscaling or ‘delta’ method) was used. The final results illustrated significant changes in the current bioclimatic viticultural Portuguese zones as they depict a lower bioclimatic diversity and a more homogenous warm and dry climate for most Portuguese wine regions [9].

With regards to specific studies for the Portuguese Douro valley region, a multivariate linear regression analysis related a long wine production series (1932–2010) collected by Porto and Douro Wines Institute (IVDP), with atmospheric variables (namely, temperature and precipitation) selected from the Vila Real station available for the period 1941–2010. Results indicated that high rainfall and cool temperatures during bud burst, shoot and inflorescence development (February-March) and warm temperatures during flowering and berry development (May) are generally favourable to high production. A logistic regression was also developed to predict three vintage yield categories (low, normal and high). Both regression approaches were then applied to climate parameters computed from the atmospheric variables provided by 16 regional climate model experiments following the SRES A1B scenario to estimate recent-past and future changes for the period 2001–2099. The datasets ranged from 25 to 18 km resolution and originated from the ENSEMBLES project [8]. Results indicated an overall positive impact under that SRES scenario with an increase of 10% in production by the end of the 21st century and an increase of high production years from 25% to over 60%. However, this study also cautions about the fact that the modelling set-up used does not take yet into account possible changes during the ripening period (e.g. rising heat stress).

There is also another pertinent statistical work relating wine production to climate in the Portuguese Douro Demarcated Region (DDR). A series of climate parameters and bioclimatic indices derived from weather stations from the Portuguese National Meteorological Service present in the Douro valley area were related with yield and quality vintage records. Temperature was introduced in the model as the successive time length periods required to reach a given threshold of heat accumulation or thermal time to pass from a given grapevine phenological phase (e.g. bud burst) to the next one (e.g. flowering). The model takes into account four key grapevine phenological phases (bud burst, flowering, ‘*véraison*’ or berry onset, and maturity). Precipitation entered the model as accumulated totals from January to March, April to June and July to September. Finally, the growing season mean temperature from March to September was taken into account as well. The results of this study illustrated that weather characteristics (e.g. growing season temperatures above the mean, warm winters, cool temperatures during ripening) are strongly associated with better quality vintages [10,11].

Most recently, a grape production model (GPM) has been developed that relates daily historic temperature and precipitation from the E-OBS observational dataset [7] with the grape production of three wineries within the Douro valley region. The model compares thermal/hydric conditions in a given year against the average conditions for high and low yield vintages. Results indicate that relatively cool pre-flowering temperatures and relatively warm conditions during berry development favour higher yields. Higher production is also associated with years with precipitation above the mean conditions before the flowering stage [12].

The present research makes use of an ensemble of Weather and Research Forecasting (WRF) model simulations driven by two forcings, namely the European Reanalysis (ERA) Interim and the Max Planck Institute Earth System - low resolution model (MPI-ESM-LR) GCM. The simulations were performed for 20-year periods as adopted by the IPCC 5th Assessment Report [13], namely 1986–2005 for the recent-past, 2046–2065 for the mid-future and 2081–2100 for the long-future climate using the Representative Concentration Pathway (RCP) 8.5 new emission scenario [14]. More details on the climatological modelling can be found in the Data and methods section.

The purpose of this study is to evaluate whether the ERA-interim driven WRF simulations for the recent-past time period (1986–2005) can be used successfully to assess the influence of climate parameters, and bioclimatic and climate change indices on vintage yield and quality records concerning the Portuguese Douro Demarcated Region (DDR). The GCM MPI-ESM-LR driven simulations are used to assess the possible impacts of the estimated climate changes under RCP8.5 for the study area in the light of the relationships found with the ERA-interim driven WRF dataset. Compared with other work previously done, this study relates regional high-resolution 9×9 km WRF simulations directly to DRR vintage yield and quality records evaluating the usefulness of computing climate parameters, and bioclimatic and climate change indices, taking into account key grapevine phenological stages (bud burst, flowering, *véraison*, maturity) based on specific heat requirements of local varieties in the region.

2. The study area

The Portuguese Douro Demarcated Region (DDR) runs along both margins of the Douro River from its midcourse

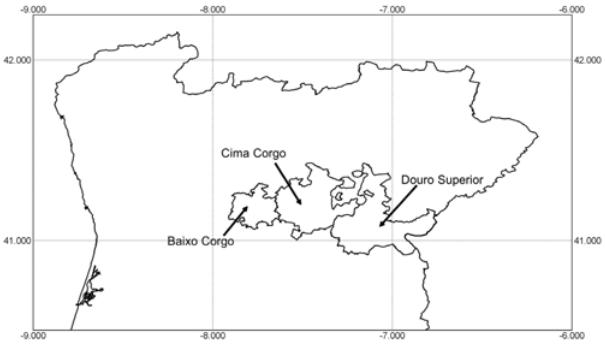

Figure 1. Demarcated Region of Douro (Portugal).

in the East up to the border with Spain in the West. The western most area of the region is located 70 km from the Atlantic Ocean. The Douro Valley extends along 90 km in the West-East direction and along 50 km in the North-South direction (Fig. 1). The landscape is characterized by mountainous terrain, rising above the Douro River and its tributaries, with moderate to steep slopes and varying exposures. The geology of the Douro Valley is dominated by schistose-layered rock, oriented nearly vertical, with some outcrops of granite. The average elevation over the entire region is 443 m, but ranges from a low near 40 m to a high of just over 1,400 m [15]. The Region covers approximately 250,000 hectares with vineyard area representing roughly 43,480 hectares, 17.4% of the total land area. The DDR is divided into three sub-regions: Baixo Corgo, Cima Corgo, and Douro Superior. The Baixo Corgo covers the smallest area (45,000 ha) with the Cima Corgo the next largest (95,000 ha) and the Douro Superior the largest sub-region (110,000 ha). The vineyard figures for these sub-regions are 13,368 ha, 20,270 ha and 9,842 ha respectively [16].

The region is characterized topographically by sloping vineyards arranged in various terraced configurations. These terraces were created and perfected throughout the centuries enabling man to cultivate vines on the steepest slopes. After the phylloxera epidemic, the devastated small terraces were abandoned and new, wider and steeper terraces were built, with or without supporting walls and allowing for a greater planting density (approximately 6,000 vines per hectare). It was then, too, that vineyards were planted according to the natural slope of the land. The introduction of mechanization to the region at the end of the 60's and early 70's, led to the appearance of a new cultivation system composed by horizontal terraces with earth supporting walls, each bearing 1–2 rows of vines and with a low planting density of some 3,000 to 3,500 vines/ha. More recently, as an alternative to the wide terraces, vines are being planted in vertical rows rising up the steeper hillsides. With a planting density similar to that of traditional vineyards (about 4,500 to 5,000 plants per/ha), this system is better adapted to small plots of land with up to 40% slopes and can be worked by mechanical means [17].

The DRR has a Mediterranean climate, with highly variable rainfall events, concentrated in winter months, and hot summers. It is sheltered from Atlantic wet and cold winds by two mountain ranges, Marão and Montemuro, located at its western border. Temperature increases and precipitation decreases from West to East. The westernmost sub-region inside the Douro Valley (Baixo Corgo) is nearer to the Atlantic Ocean and therefore more affected by the moist maritime winds. The eastern most regions within the Douro Superior sub-area are more distant from the Atlantic Ocean therefore having a more continental climate influence. The region is classified as a warm temperate climate (Köppen Csb), with average annual temperatures during 1980–2009 of 15.4°C, average daily minima temperatures (T min) in the coldest month dropping to 2.7°C, and average daily maxima temperatures (T max) in the warmest month reaching 32.1°C [10]. Mean growing season temperature (GST) from April to September for the same climatological period is 20.6 °C. Growing season precipitation (GSP) has a mean value of 193 mm, representing 30% of the annual total (624 mm). The average precipitation of the driest month (July) is just 11.2 mm. Low precipitation values along with high temperatures and high radiation exposure give rise to situations of intense summer plant-soil-water stress, particularly in the Cima Corgo and Douro Superior sub-regions [3]. The Huglin Index (HI) for the 1980–2009 period averaged 2,740 °C d^{-1} whereas the cool night index (CI) 13.6 °C and the dryness index (DI) –126 mm. In the Geoviticulture MCC System [4] the DDR climate is currently classified as HI+2/DI+2/CI+1 (Warm/Very dry/Cool nights) [18].

3. Data and methods

3.1. High resolution 9 × 9 km WRF climate simulations

Marta-Almeida et al. [19] performed an ensemble of WRF high-resolution climate simulations driven by two forcings, namely ERA-Interim reanalysis and the Max Planck Institute Earth System - low resolution model (MPI-ESM-LR). The reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) through the ERA-Interim project, with a horizontal resolution of approximately 79 km [20]. The MPI-ESM-LR is a global Earth System Model developed by the Max-Planck Institute, with a 1.9°horizontal resolution [21] which corresponds to about 160 km horizontal resolution. This model participated in the Coupled Model Intercomparison Project Phase 5 (CMIP5), which uses new emission scenarios, namely the RCPs.

Currently there is a new set of RCPs associated to future concentrations of GHGs in the atmosphere. In this study we used the RCP8.5, defined by a radiative forcing of 8.5 W m^{-2} by 2100 and a continuous increase after this year [22]. The RCP 8.5 provides an updated and revised quantification of the original IPCC A2 SRES scenario [23].

The WRF high-resolution climate simulations were performed for 20-year periods as adopted by the IPCC 5th Assessment Report [24], namely 1986–2005 for the recent-past, 2046–2065 for the mid-future and 2081-2100 for the long-future climate. These simulations were implemented for three nested domains with increasing horizontal resolutions, namely 81, 27 and 9 km (Fig. 2). Validation of the WRF recent-past simulations driven by the two forcings with observational temperature and precipitation datasets for the Iberian Peninsula provided

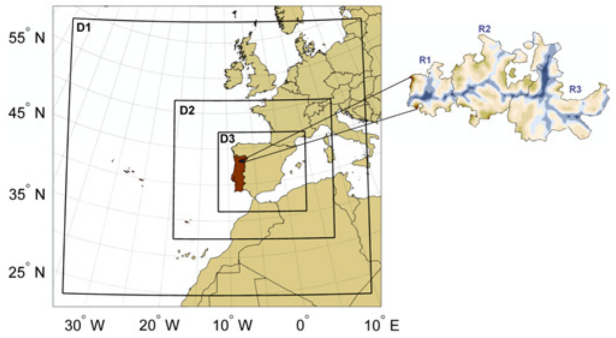

Figure 2. Nested model domains used in the regional WRF implementation with resolutions of 81 (D1), 27 (D2) and 9 (D3) km^2.

acceptable comparisons of the probability distributions of temperature and precipitation for both models, with WRF-ERA providing better results most of the times although there are occasions where WRF-MPI performed better [14].

3.2. Phenological modelling

The concept of ‘thermal time’ as the daily temperature summation above a temperature base required for a given crop to complete a specific phenological stage was established by Monteith [25]:

$$\theta = \int (T - Tb)dt \qquad (1)$$

Where θ(°C day) represents the thermic duration or thermic time for a specific phenological stage, T is the daily average temperature and Tb is a threshold above which there is plant development within that phenological stage. Models based on growing degree days (GDD, °C day) have been extensively used to model the phenology of the grapevine [26,27] or as grapevine zoning bioclimatic indices [28–30].

A specific phenological squeme partitioning the annual development cycle of the grapevine into three major phases (b – bud burst to flowering, f – flowering to *véraison*, and v – *véraison* or berry onset to maturity) has been already proposed for the study area. A.C.Real et al. [10,11] used a mixed grapevine variety arrangement as the ‘Tinta Roriz’ variety was used to define the required GDDs to reach bud burst, flowering and *véraison* and the ‘Touriga Franca’ variety was used as the set-up for the required GGDs to reach maturity in the DDR. This was done in order to simulate an intermediate varietal behaviour (neither an early nor a late grapevine variety class) for all of those phenological stages using two varieties present extensively in the Douro valley region.

This work makes use of the mixed ‘Tinta Roriz-Touriga Franca’ local grapevine varietal phenological model to compute the timings of the key grapevine phenological timings (b-bud burst, f-flowering and v-*véraison*) for the four climate modelling set-ups presented in Sect. 3.1 (WRF-ERA recent-past, WRF-MPI recent-past, WRF-MPI mid-future and WRF-MPI long-future) based on the specific varietal GDD requirements as observed at the Portuguese National Ampelographic Collection [31]. Results are contrasted with recently-made available specific phenological observations for the Douro valley region [32] in the Results section.

3.3. Climate parameters and indices

Using the daily maximum and minimum temperatures and the daily total precipitation from the four different regional WRF modelling set-ups (WRF-ERA recent-past, WRF-MPI recent-past, WRF-MPI mid-future and WRF-MPI long future), a total of 26 climatic parameters, 4 grapevine bioclimatic indices, and 28 climate change indices were calculated.

3.3.1. Climate parameters

The climatic parameters consisted of computing the average of daily maximum temperatures, daily minimum temperatures and daily mean temperatures (as T max + T min / 2) and the total precipitation (P) for each one of the yearly phenological stages based on the conventional monthly scheme for the northern hemisphere (bud burst usually occurs between April and May, flowering relates more often with June and July and *véraison* usually happens between August and September). Therefore, a set of twelve climatic parameters was calculated following the conventional scheme (e.g. T max Apr-May, T min Apr-May, T avg Apr-May, P Apr-May etc.). Another set of twelve climatic parameters was computed taking into account the yearly dates according to the phenological modelling arrangement (T max-b, T min-b, T avg-b, P-b etc.). Finally, two other climatic parameters were computed following the conventional scheme (months from April to September) to summarize information for intercomparison purposes: growing season average temperature (GST) and growing season total precipitation (GSP).

3.3.2. Bioclimatic indices

Four specific grapevine bioclimatic indices were selected: Winkler index (WI), the Heliothermal index of Huglin (HI), the cool night index (CI) and the dryness index (DI). These indices are commonly used to characterize grapevine growing areas worldwide in an standardized way and as an agronomic zoning tool [4], [33].

The Winkler index is the sum of the daily average temperatures above a threshold temperature of 10 °C considered the active grapevine temperature (the temperature above which it activates its vegetative cycle) along the growing season. The index is usually calculated from monthly data:

$$\begin{aligned} WI &= \textstyle\sum_{April1st}^{October31st} (Tavg - 10^\circ C), Tavg \geq 10^\circ C \\ Tavg &= \frac{T\max + T\min}{2} \end{aligned} \qquad (2)$$

The HI provides information regarding heliothermal and sugar potential. It is very much correlated with the Thermal Index of Winkler ($r^2 = 0.98$ over 97 grape-growing regions worldwide) but, according to Tonietto et al. [4], is more pertinent to the qualitative factors (e.g. berry sugar potential):

$$\begin{aligned} HI &= \textstyle\sum_{April1st}^{September30th} \frac{(T\max - 10^\circ C)+(Tavg - 10^\circ C)}{2} d \\ Tavg &= \frac{T\max + T\min}{2} \end{aligned} \qquad (3)$$

Where again, Tavg is the mean air temperature (°C), Tmax is the maximum air temperature (°C), d is length of day coefficient ranging from 1.02 to 1.06 between 40° and 50° of latitude. A value of 1.02 was assumed for a latitude between 40°01′ and 42°00′. This index is usually also calculated from monthly climatic means.

The purpose of CI is to improve the assessment on the grape qualitative potentials, notably in relation to secondary metabolites (polyphenols, aromas) in grapes [4]:

$$CI = \sum_{September1st}^{September30st} \frac{T\ \mathrm{min}}{30} \tag{4}$$

Finally, DI indicates the potential water availability in the soil, related to the level of dryness in a region. It is also related with the level of grape ripening and wine quality [4].

$$W = W_0 - P - T_v - E_s \tag{5}$$

For intercomparison reasons, it is also calculated on a monthly basis during the same period used for HI (April 1st to September 30th), which is acceptable for most of grape growing regions in the northern hemisphere. W is the estimate of soil water reserve at the end of the April 1st–September 30th modelled growing season period, W_0 is the initial soil water reserve, which can be accessed by the vine roots, P total monthly precipitation, T_v the potential transpiration of the vineyard and E_s the direct evaporation from the soil. To compute T_v and E_s is also necessary to compute the monthly total potential evapotranspiration. This is usually done by the Penman-Monteith method but as we only worked with temperature and precipitation records, it was approximated by the Hargreaves method which produces comparable results in arid and semiarid environments and requires temperature data only [34]. The result is mm of water in the soil. The initial W_0 is usually taken as 200 mm [4].

3.3.3. *Climate change indices*

A group of six climate change indices from the group of indices developed by the Expert Team (ET) on Climate Change Detection and Indices (CCDI) [35] related with the incidence of cold waves, storms and heat waves, which could proof to be relevant for the grapevine, were calculated on a yearly basis. Namely, these indices were:

a. SU25, the number of summer days with T max >25 °C.
b. SU35, the number of very hot or stressful days with T max >35 °C.
c. CSDI, cool spell duration index or total number of days being part of cool spells longer than 6 consecutive days in duration.
d. WSDI, warm spell duration index or heatwave index, or the total number of days being part of warm spells longer than 6 consecutive days in duration.
e. R10, the number of days with heavy precipitation (daily precipitation >10 mm).
f. CWD, maximum number of consecutive wet days where daily precipitation >1 mm.

Table 1. Sources of yearly quality ratings for Port vintages.

Source	Acronym	Rating
(1) Berry Bros & Rudd	BBR	1–10
(2) Decanter	DC	1–5
(3) Instituto dos Vinhos do Douro e do Porto	IVDP	0–1
(4) Michael Broadbent	MB	0–5
(5) Sotheby's Wine Encyclopaedia Wine Encyclopaedia	SWE	0–100
(6) Vintages	VT	0–10
(7) Wine Advocate	WA	50–100
(8) Wine Enthusiast	WE	50–100
(9) Wine Spectator	WS	50–100

Table 2. Original vintage scores for 1986–2005 according to the vintage chart rating systems presented in Table 1 and a consensus ranking (CR).

Vintage	CR	1	2	3	4	5	6	7	8	9
86	18			0					84	
87	11		3	1	3		8		85	88
88	19			0					83	
89	10			1	3				86	
90	17			0	3				85	
91	5	7	4	1	4	95	9		92	93
92	6	8	4	1	4	85	9		93	94
93	20			0						
94	1	9	5	1	4	95	10		96	99
95	9		1	0	3	88	9		91	92
96	16		2	0	3				85	
97	4	8	4	1	4	90	10		93	96
98	13	6	3	0	3	80			87	
99	15			0	3	75			86	
00	2	9	5	1	5	95	10		90	97
01	12		4	0	3	86	8		84	
02	14		2	0	3	70			84	
03	3	8	4	1	5	94	10		96	98
04	8		4	0	4	88	9		90	
05	7		5	0	5	80	8		91	

A specific index for the grapevine, SU33, the number of very hot or stressful days for the grapevine (T max >33 °C) was added to the previous set. The final seven climate change indices were computed for each phenological stage as well (bud burst, flowering and *véraison*) yielding another 21 climate change indices computed on a yearly basis.

3.4. Porto vintage yield and quality data

The average yield (hl/ha) of all types of wines produced in the Douro valley region for the recent-past 1986-2005 period was considered. Data were available from [18] consisting on a compilation of data from the Portuguese Office for National Statistics (INE) taking into account the increase of planted areas since 1982.

Data on Port vintage quality were available from [18] and [10] consisting of ratings from six different sources, as illustrated in Table 1 where the highest values correspond to the best Port vintages.

The original vintage scores for the recent-past period (1986–2005) along with a derived consensus ranking (CR) can be found in Table 2 as compiled in [10].

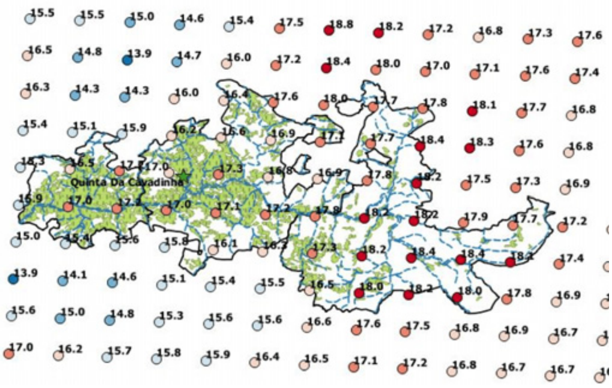

Figure 3. Growing Season Average Temperature (GST) as calculated by the 1986–2005 WRF-ERA simulation. The circles represent 9 × 9 km cell centres. Each WRF cell is associated with its GST value (°C). WRF cells with highest GST values are coloured with red tones whereas cooler areas are depicted with bluish tones. The DRR limits are represented with its main subdivisions (Baixo Corgo, Cima Corgo, and Douro Superior), main river courses and grapevine cultivated areas.

3.5. WRF cell selection and statistics

One 9 × 9 km cell representative for each of the three subdivisions (Baixo Corgo, Cima Corgo and Douro Superior) present in the DDR region was selected to compute the timing of different key phenological stages (bud burst, blooming, *véraison* and maturity) for each year belonging to the simulated 1986–2005 recent-past period. This was done by taking into account the GST values for each WRF-ERA cell within the DRR limits at the same time they were overlain on mapped vineyard areas as provided by the CORINE 2009 dataset [36] in a Geographic Information System (GIS) set-up as illustrated in Fig. 3 of the Results section.

Data on normalized vintage yield and quality scores, climate parameters, bioclimatic and climate change indices were submitted to a Pearson correlation test using the data visualization and statistical programming R software. Tests for the significance of differences in means and variances [37] of the statistical distributions of climate parameters and indices between the different 20-year periods (recent-past, mid-future, long-future) as modelled by WRF-MPI were also implemented in R.

4. Results

4.1. WRF-ERA data validation

The high-resolution WRF simulations forced by ERA-Interim reanalysis resulted in realistic patterns of surface atmospheric variables. Figure 3 shows the spatial pattern of the grapevine growing season average temperature (GST) over the Douro valley as modelled for the final nested highest resolution (9 × 9 km) domain. Within the DRR, the GST values portray an East-West trend resulting from the orientation of the main valley itself and the increasing distance from the sea.

Table 3. GST and *Véraison* statistics for the three DDR sub-regions.

1986–2005	**GST medians**		***Véraison*date**	
Region	Model	WorldClim	Model	Field
Baixo Corgo	17.1	17.5	234	175–229
Cima Corgo	17.0	17.5	234	
D. Superior	18.0	18.0	223	

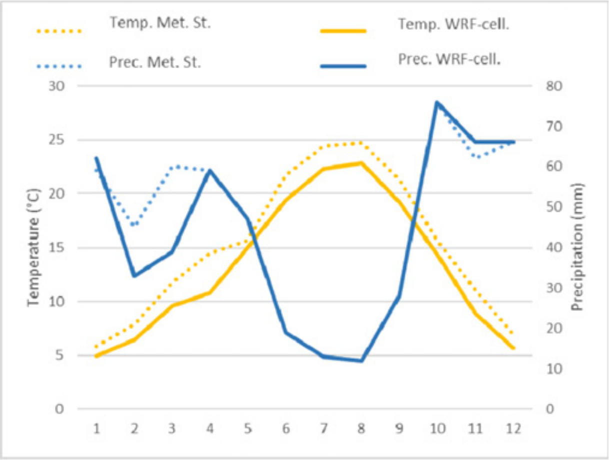

Figure 4. Ombrothermic chart comparing monthly average temperatures and total precipitations from the WRF-ERA cell selected within the Douro Superior region compared with literature sources [38]. Solid lines are for WRF-ERA cell data and dashed lines are for meteorological observations from the literature.

Table 3 portrays the resulting mean *véraison* dates along with the WRF-ERA GST median statistics obtained for each one of the DRR sub-regions. The GST median values are close to those reported for the area by [3] based on the WorldClim 1 km × 1 km 1950–2000 database [6]. Only the cell selected for Douro Superior sub-region presents an average *véraison* date within the 95% confidence limits of the timings reported for the area [32]. These rather delayed phenological figures could be attributed to an important difference between the average height of the selected WRF-ERA cells (434 m for the Baixo Corgo cell, 481 m for the Cima Corgo cell and 417 m for the Douro Superior cell) and that of the field plot where the phenological dates were observed (Quinta da Cavadinha, 205 m). In fact, the average height of the selected WRF-ERA cells corresponds more to transitional sub-plateau locations than to sheltered valley areas where the Mediterranean climate characteristics are stronger.

A closer inspection of the ombrothermic chart (Fig. 4) for the Douro superior WRF-ERA cell against climatological observations reported by an equivalent sub-plateau location in that sub-region, reveals a quite close match for precipitation (except for February and March). However, temperatures are significantly lower for all months (−1.8 °C on average), which could be in part explained by the difficulty to reproduce the specific mesoclimates associated to the varied topography and shelter effects present in the area. WorldClim figures for annual precipitation in the Douro Superior sub-region are significantly higher (median 832 mm) than those reported by the literature for a sub-plateau location (in the order of 500 mm) [3,38].

Table 4. Correlation coefficients for the different vintage rating systems (* 95% significance level, ** 99% significance level).

	WE	**WS**	**SWE**	**MB**	**BBR**
WS	0.85**				
SWE	0.73**				
VT	0.76**	0.96**	0.79**		
MB	0.74**	0.78*			
DC				0.76**	0.94**

Table 5. Correlations among climate parameters and indices, grapevine yield and vintage quality (* 95% significance level, ** 99% significance level).

	Yield	**WE**	**MBR**	**DC**
GDDgs	0.56**			
HI	0.52*			
T max-b			0.51*	
T max-v	0.52*			
SU33-f		0.49*		
SU35-f		0.64**		
WSDI				–0.62*

4.2. Vintage yield and quality in relation to climate

Table 4 illustrates the significant correlations found among the normalized scores of the different vintage rating systems applied to vintage Port used in this study. All of these rating systems have high and significant Pearson's correlation coefficients with at least other two within the 1986–2005 period with the exception of BBR which presents only one significant correlation and WA with none (thus, not shown in the table). As the number of Port vintages specifically evaluated was higher in WE (19), MB (17) and DC (14) compared to the other rating systems, these were the final vintage chart systems selected to analyse the relationship between Port wine vintage quality and climate. It is worthwhile noticing that yield presented significant negative correlations with two of the rating systems used in this study (–0.74* WS, –0.72* VT). This suggests an inverse relationship between yield and quality.

The significant correlations found among the climate parameters and indices, as computed from the daily temperature and precipitation records from the Douro Superior sub-region WRF-ERA cell, and the corresponding vintage yield and quality records for the recent-past 1986–2005 time period were all of moderate type from a statistical point of view, as it can be observed in Table 5. However, it is worth noticing that, within a viticulture context, correlation values as low as 0.54 have been considered highly significant in an study relating water deficit with vintage quality [2]. These correlations are higher than those found in another study at a close latitude (Galicia, Northwest Spain) for the case of T max-b and T max-v [39] showing the benefit of using phenological timings based on accumulated heat for some of the climate indices and parameters (e.g. T max-b, T max-v, SU33-f, SU35-f) rather than using the conventional monthly schemes.

pcElevated heat sums (GDDgs, HI) along with elevated mean maximum temperatures from*véraison* to maturity time (T max-v) are related with high grapevine yields in the study area within the 1986–2005 time period, which is consistent with other studies performed in the area [10,12,40]. Port vintage quality ratings are positively related to the total incidence of days with T max >35°C from the flowering to the *véraison* stage (SU35-f), and to the mean maximum temperatures achieved from the bud burst to the flowering stage (T max-b), but they are inversely related to the occurrence of heat waves (WSDI). In one hand, these results could relate with the fact that the temperate range that favours vegetative development –and therefore yield- is slightly higher (23-25 °C) than the one which is considered best for fructification (22–22 °C) [41]. On the other hand, a moderate incidence of non-contiguous, stressful, scalding days between flowering and *véraison* (SU35-f) could result in a smaller number of grapes developed, which would result in a greater chance of a sufficient supply of photoassimilates to them [42]. At this point, it can be noted that another positive relation exists between vintage quality and the total incidence of days with T max > 33 °C from flowering to *véraison*, SU33-f, but the correlation coefficient was lower and less significant than that of SU35-f. Finally, prolonged periods of scalding days or heatwaves (WSDI) appear negatively related with vintage quality which might have to do with excessive plant damage or too unfavourable conditions for a balanced supply of metabolites (polyphenols, aromas) to the grape [4].

Table 6. Top quality and regular vintages from the climate perspective: positive factors are displayed in green cells whereas negative ones in orange.

Year	**CI**	**V**	**T max-v**	**SU35-f**	**WSDI**	**CWD-v**
Outstanding vintages						
95	9.9	229	23.3	4	0	3
00	12.7	228	23.3	3	0	3
03	12.8	217	29.3	7	14	3
97	15.2	217	28.0	5	6	2
91	14.4	225	29.0	6	0	3
Not outstanding vintages						
96	11.1	225	23.3	0	0	3
90	14.8	216	30.6	6	0	1
86	15.2	235	24.4	0	0	3
88	11.7	236	24.0	0	8	3
93	11.9	225	20.4	8	6	12
Avrg	12.7	223	26.4	4	7	

Table 6 portrays the five highest and the five lowest quality Port vintages for the 1986–2005 recent-past time period as scored according to a consensus ranking (CR in Table 2) taking into account all vintage rating systems.

When contrasted with the values of climate parameters and indices as computed from the Douro Superior sub-region WRF-ERA cell, it can be observed that, in one hand, all of the outstanding vintages had a moderate incidence of non-contiguous, isolated, 'extremely hot' or 'scalding' days from flowering to *véraison* (SU35-f). Despite this fact, the two top quality vintages present below-average *véraison* to maturity mean maximum temperatures (T max-v) and cool to very cool September mean minimum temperatures (CI), which are conditions of slow maturation and high qualitative potential for the grape. On the other hand, three of the worse classified vintages (96, 86 and 88) totally lack any incidence of 'scalding days' from flowering to *véraison* time (SU35-f) with two of them portraying a considerable delay on the onset of *véraison.* Vintage 90 displays incidence of a suitable number of SU35-f days but the average maximum temperature from *véraison* to maturity (T max-v) was considerable higher

Table 7. Future scenarios for some key grape growing parameters (* 95% significance level, ** 99% significance level).

		MPIr	MPIm	MPIl
GST (°C)	μ	15.6**	18.0**	20.1**
	σ^2	0.8	0.9	0.8
Véraison **onset**	μ	236**	213**	198**
	σ^2	159	84	57
SU35 (°C)	μ	2**	15**	42**
	σ^2	12**	71*	176*

(30.6 °C). GGDs for that vintage were also quite elevated (1664 GGDs against an average of 1525 GDDs) being the vintage of highest yield of the 1986–2005 recent-past period. Finally, vintage 93 clearly shows too low mean maximum temperatures from *véraison* to maturity (T max-v=20.4 °C) accompanied with a too prolonged contiguous rain period from *véraison* to maturity time (CWD-v =12) which caused quite unfavourable conditions both for vintage yield (19th ranking position regarding yield) and quality (last position not being scored for any of the vintage charting systems).

4.3. Future scenarios

The GST, the *véraison* timing and the SUF35 ETCCDI index were calculated for the previously selected Douro superior 9 × 9 km cell according to the daily temperature records provided by the WRF-MPI 1986–2005 recent-past (MPIr), 2046–2065 mid-future (MPIm) and 2081–2100 long-term (MPIl) RCP8.5 modelling scenarios. Tests for stability of means (t-test) and variances (F-test) (Table 7) illustrate a significant increase of GST means (2.4 °C for the mid-future, and 2.1 °C more for the long-term future) not accompanied by significant differences in GST variance. Regarding timing of *véraison*, there is a significant advancement in the means (22 days for the mid-future and other 15 more days in advance for the long-future compared with the recent-past period) without significant differences in the variances. Finally, the mean number of 'scalding days' or too hot days, SU35, increases very significantly (from 2 days to 15 days in the mid-future and 27 days more in the long-term future) with a significant increase in their variances too.

Although the change of GST provided by these modelling scenarios remains within the general 13–21 °C interval considered as suitable to grape growing, it can be clearly observed that an ETCCDI index such as SU35 will pass from tolerable levels (a mean value of 2 incidences per year according to WRF-MPIr and of 7 according to WRF-ERA) to much higher frequencies covering, on average, half a month for the mid-tem future scenario, and almost a month and a half for the long-term future scenario. These results suggest a strong likelihood of present-baseline heatwaves and water deficits.

5. Conclusions

Several conclusions can be drawn from this study at the research level:

a. Climate parameters and indices calculated from daily climate variables from the WRF-ERA climate simulation for the recent-past time period (1985–2005) can be successfully related with vintage yield and quality scores records.
b. Results confirm previous studies on the positive current relation between higher growing season heat accumulations and greater vintage yields.
c. A moderate incidence of 'scalding' days from the flowering to the *véraison* stage has been found positively related with vintage quality.
d. The negative relation between vintage quality and the incidence of heat waves also confirms previous studies and much background work regarding berry ripening.
1. Correlations found by using a phenological set-up are usually higher than those found using a regular monthly set-up.
e. The changes in climate estimated under the RCP8.5 scenario are triggering advancement on phenology in a very significant way with the consequent risk of overexposing the grapes to too warm conditions for balanced ripening.
f. Although GST remains within range for quality wine production, a very significant increase of 'scalding' days is forecasted for both mid and long-term future scenarios, which also increases the likelihood of incidence of present-baseline heatwaves. These conditions can impair the ripening of the berries with regards the high quality standards and the wine typicity of the region.

As the future modelled WRF-MPI climate scenarios illustrate and advancement on vine phenology and changes in temperature conditions in the DRR, where grape ripening can be significantly affected with regards to the balance of sugars, acidity, secondary metabolites and aromas, several actions can be proposed to preserve as much as possible DRR wine typicity taking current state-of-the-art knowledge [2] and previous work done in the study area [3]:

a. Too early ripeness can be delayed in the order of seven to ten days by means of clonal selection and use of suitable rootstocks. Longer delays can be achieved by using late-ripening varieties or carefully selected non-local varieties.
b. Training systems and late pruning can also be useful to delay phenology. Training systems can also have an impact on water deficit. Care should be taken to maintain an appropriate leaf area/fruit weight ratio.
c. Increase the water-holding capacity (SWHC) of soils or look for soils with greater SWHC and select rootstocks resistant to water deficits.
d. Irrigation of a drought-resistant plant such as the vine should be considered a last option as it has an economic, environmental and social cost.
e. Move the vineyards to higher altitudes.

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List of abbreviations

1. **DDR:** Douro Demarcated Region.
2. **MCC:** Multicriteria Climatic Classification.
3. **ERA-Interim:** European Reanalysis-Interim forcing.
4. **MPI-EMS-LR:** Max Plank Institute Earth System low resolution model forcing.
5. **WRF:** Weather and Research Forecasting model.
6. **T max:** daily maximum temperature.
7. **T min:** daily minimum temperature.
8. **T avg:** daily mean temperature as (T max + Tmin)/2
9. **P:** daily total precipitation.
10. **b:** bud burst to flowering phenological stage.
11. **f:** flowering to *véraison* phenological stage
12. **v:** *véraison* to maturity phenological stage.
13. **T max Apr-May:** mean of daily maximum temperatures from April to May.
14. **T max-f:** mean of daily maximum temperatures from the flowering to the *véraison* phenological stage.
15. **GDD:** growing degree days.
16. **gs:** growing season.
17. **GST:** growing season mean temperature.
18. **GSP:** growing season total precipitation.
19. **WI:** Winkler index.
20. **HI:** Huglin index.
21. **CI:** cool night index.
22. **DI:** dryness index.
23. **SU25:** number of summer days per year.
24. **SU33:** number of ‘scalding’ days for the vine per year.
25. **SU35:** number of very hot days per year.
26. **CSDI:** cool spell duration index.
27. **WSDI:** warm or heatwave duration index.
28. **R10:** number of days with heavy precipitation per year.
29. **CWD:** maximum number of wet days per year.
30. **SU33-f:** yearly SU33 from flowering to *véraison*.
31. **SU35-f:** yearly SU35 from flowering to *véraison*.

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