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Ensemble projections for wine production in the Douro Valley of Portugal

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Abstract Wine production is largely governed by atmospheric conditions, such as air temperature and precipitation, together with soil management and viticultural/enological practices. Therefore, anthropogenic climate change is likely to have important impacts on the winemaking sector worldwide. An important winemaking region is the Portuguese Douro Valley, which is known by its world-famous Port Wine. The identification of robust relationships between atmospheric factors and wine parameters is of great relevance for the region. A multivariate linear regression analysis of a long wine production series (1932–2010) reveals that high rainfall and cool temperatures during budburst, shoot and inflorescence development (February-March) and warm temperatures during flowering and berry development (May) are generally favourable to high production. The probabilities of occurrence of three production categories (low, normal and high) are also modelled using multinomial logistic regression. Results show that both statistical models are valuable tools for predicting the production in a given year with a lead time of 3–4 months prior to harvest. These statistical models are applied to an ensemble of 16 regional climate model experiments following the SRES A1B scenario to estimate possible future changes. Wine production is projected to increase by about 10 % by the end of the 21st century, while the occurrence of high production years is expected to increase from 25 % to over 60 %. Nevertheless, further model development will be needed to include other aspects that may shape production in the future. In particular, the rising heat stress and/or changes in ripening conditions could limit the projected production increase in future decades.

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Abbreviations

DV	Douro Valley
IPCC	Intergovernmental panel on climate change
SRES	Synthesis report on emission scenarios
GCM	Global climate model
RCM	Regional climate model
DDR	Douro demarcated region
IVDP	Instituto dos Vinhos do Douro e Porto
VR	Vila Real
GHG	Greenhouse gas

1 Introduction

Air temperature and precipitation are the main forcing factors of crop production and quality. The different climates across the globe determine the geographical distribution of crops, whereas the temporal climatic variability explains changes in the crop productivity parameters, spanning from inter-annual to longer-term time scales (e.g., decades and centuries). Furthermore, weather conditions play a key role in triggering the different phenological stages of crops, and weather extremes are also known to have detrimental impacts on crop productivity and quality. For winegrapes (*Vitis vinifera* L.) in particular, atmospheric forcing on the crop system is prominent, as its yield and quality are largely dependent on weather conditions during the growing season (Jones and Davis 2000; van Leeuwen et al. 2004; Urhausen et al. 2011). Overall, the grapevine is a relatively demanding species in terms of radiation and temperature during its vegetative growth, development and berry maturation (Jones 2006). Further, it is adversely affected by late frost spells and by excessive rainfall in late spring/early summer and during ripening (Magalhães 2008).

Owing to these very selective climatic needs, some of the most important winemaking areas in Europe are located in Iberia, including the Portuguese Douro Valley (DV) region. The DV is largely known for its Port Wine, but also by the production of high-quality table wines. The DV is a very mountainous region located in the Portuguese Douro River Basin (northeastern Portugal; Fig. 1), where geology is mainly characterized by schist formations with sporadic outcrops of granite (Magalhães 2008). Its topographic configuration provides Mediterranean-like climatic conditions: growing season (April-September) precipitation of 100–250 mm (about 30 % of the annual total) and growing season mean temperatures of 18–21 °C (INMG 1991). These climatic characteristics lead to the occurrences of the main phenological stages of grapevine in the DV as follows: budburst in March, bloom in May, véraison (the onset of ripening) in July and ripening to full maturation in September (Malheiro 2005). These conditions permit the production of balanced composition wines that represent approximately 12 % of the total wine production in Portugal (IVV 2008). The grapevine varieties *Touriga Nacional*, *Touriga Franca* and *Tinta Roriz* (Tempranillo) are most widely grown in the DV, however numerous other regional and unique varieties are grown in the region (Magalhães 2008).

Due to the extremely high economic relevance of the winemaking sector in the DV (vineyards are grown as a monoculture system over large areas), the assessment of the relationships between atmospheric factors and wine production and quality parameters is of utmost relevance. For example, Santos et al. (2011) developed a statistical model to estimate grapevine yields in the DV from monthly temperature and precipitation data for the period 1986–2008. Their results showed that anomalously high (low) precipitation in March (May

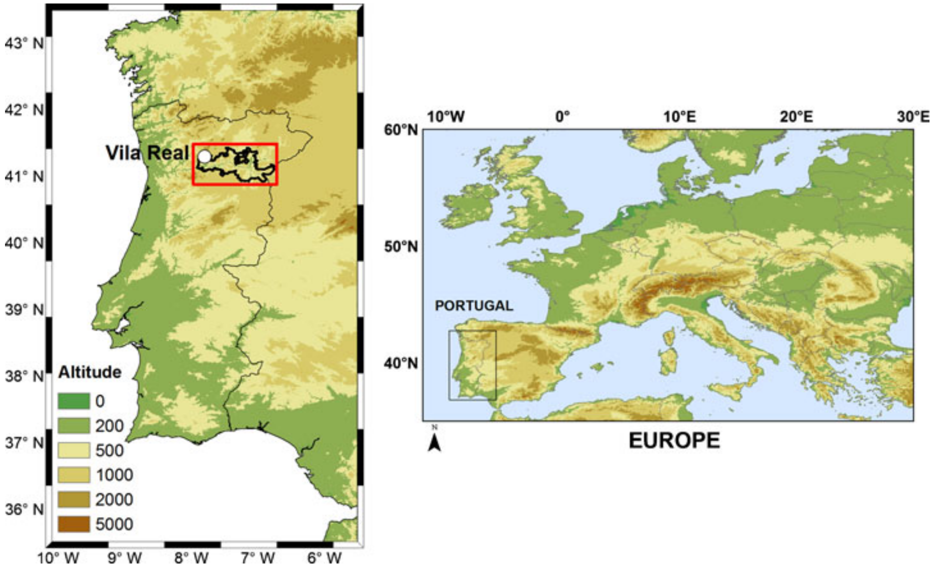


Fig. 1 Geographical location of the Portuguese Demarcated Douro Region (*bold line* on the left panel), the meteorological station of Vila Real and the Douro Sector used for the climate model domain (*red rectangle*)

and June) and anomalously high temperatures in May - June tend to be favourable to higher grapevine yields in the DV. Another recent study by Gouveia et al. (2011) also found that higher temperatures during late spring were beneficial to wine production in the DV. Furthermore, evidence has been given for the presence of cycles in the wine production time series in the DV that can be mostly attributed to springtime temperature variability (Cunha and Richter 2012).

Climate change is expected to have important impacts on global temperature and precipitation patterns (Meehl et al. 2007), which may significantly reshape viticultural zoning in Europe (Bindi et al. 1996; Malheiro et al. 2010). In fact, climate change has the potential to strongly influence crop production and quality, particularly on a highly climate-sensitive product such as wine (Kenny and Harrison 1992; Jones et al. 2005). For the DV, existing studies considering a single climate model experiment for future climate conditions suggest an increase of both yield and production during the 21st century due to the combined effects of temperature and precipitation in late spring and early summer (Santos et al. 2011; Gouveia et al. 2011).

The present study uses a recently available longer time series for wine production in the DV (1932–2010, cf. Jones and Alves 2011) to examine temporal variability, relationships with climate, and to develop a more robust model for assessing future production characteristics in the region. The statistical modelling of the wine production is developed using both linear regression and logistic approaches (Wilks 2006). In addition, a multi-model GCM/RCM (Global Climate Model/Regional Climate Model) ensemble following the A1B scenario (with 16 simulations from transient model experiments) is used to estimate possible changes in the wine production in the DV for future decades. Further, model output statistics are used to fit the RCM data to observational data (model calibration). Hence, the present study is a novel approach using a recently available and long dataset of wine production, innovative statistical models and a large multi-model GCM/RCM ensemble with calibrated data.

2 Data and methods

A time series of the wine production (in 10^6 hl) from the Douro Demarcated Region (DDR) is used (Fig. 2a). This data is collected by the *Instituto dos Vinhos do Douro e Porto* (IVDP) and is currently available for the period 1932–2010 (79 years). This time series allows a quantification of the inter-annual variability in wine production, but is also dependent on the vineyard area, which has increased in the last decades. However, no reliable information is known about the changes in the vineyard area for the entire time period, which means that the upward long-term trend in the time series is mainly a reflection of the increasing production area (known factor). Moreover, earlier studies found no significant trend in the grapevine yield in 1986–2008 (Santos et al. 2011), which is independent of the vineyard area (units in $\mathrm{kg.ha}^{-1}$). Given that the linear correlation between both time series is $r=0.98$ within the common period of 1986–2008, the linear trend for the production time series was therefore removed prior to the application of any statistical method.

In order to establish statistical relationships between atmospheric factors and wine production, daily mean, minimum and maximum air temperatures, as well as daily precipitation totals are selected from the meteorological station of Vila Real (VR; Fig. 1). Data is available for the period of 1941–2010. Apart from 1947 and 1952 (which had missing data and are excluded from the analysis), the monthly mean time series are complete and homogeneous: no break points in trends (Mann-Kendall test; Sneyers 1975) and no statistically significant serial correlation (Wald-Wolfowitz test; Sneyers 1975). Although wine production data is available since 1932, only the common period between the wine production and the meteorological time series (1941–2010) is analyzed here.

Climate change projections for wine production in the DV are herein carried out using RCM data. For this purpose, datasets from 16 transient experiments for recent climate conditions (C20; 1961–2000) and the IPCC-SRES A1B emission scenario (2001–2099; Nakićenović et al. 2000) are considered, in a total of 15 different GCM/RCM model chains. For the ECHAM5/COSMO-CLM combination, two ensemble simulations are used. Information on the RCM designation, acronym, responsible institute, driving GCM, spatial (grid) resolution is included in Table 1, together with references featuring detailed descriptions of the datasets. Apart from the two ECHAM5/COSMO-CLM simulations (Lautenschlager et al. 2009a, b, c, d), all other datasets were provided by the ENSEMBLES project (http://ensembles-eu.metoffice.com/; van der Linden and Mitchell 2009).

The selected ensemble of model simulations (16 members) includes a wide range of different models, thus covering most of the uncertainties related to model design, parameterizations and initializations. In fact, the two additional COSMO-CLM simulations were used in order to enhance the spread of the results. This is indeed a very important aspect when evaluating the reliability of the climate change projections. Since the GCM outputs are defined over relatively coarse grids, they cannot be directly used for regional scale assessments that commonly need much finer resolutions, such as in the case of the wine production in the DV. Hence, only RCM outputs were used here, i.e., data obtained from dynamical downscaling (GCM-RCM chains). Although the RCM outputs can significantly depend on

Fig. 2 **a** Chronogram of the Douro wine production (in Mhl=10^6 hl) in 1932–2010 and corresponding least-squares linear trend. **b** Detrended anomalies of the observed production (*light solid line*) along with the corresponding modeled anomalies (*thick solid line*). Upper (*lower*) dotted line corresponds to the upper (*lower*) limit of the 95th confidence interval. **c** Chronogram of the three categories of wine production: High (3), Normal (2) and Low (1) production year, with the obsereved (modeled) categories represented by white squares (*black circles*). The bar chart below displays the modeled probabilities of occurrence of each category. Meteorological data gaps in 1947 and 1952 arise in panels **b** and **c** ▶

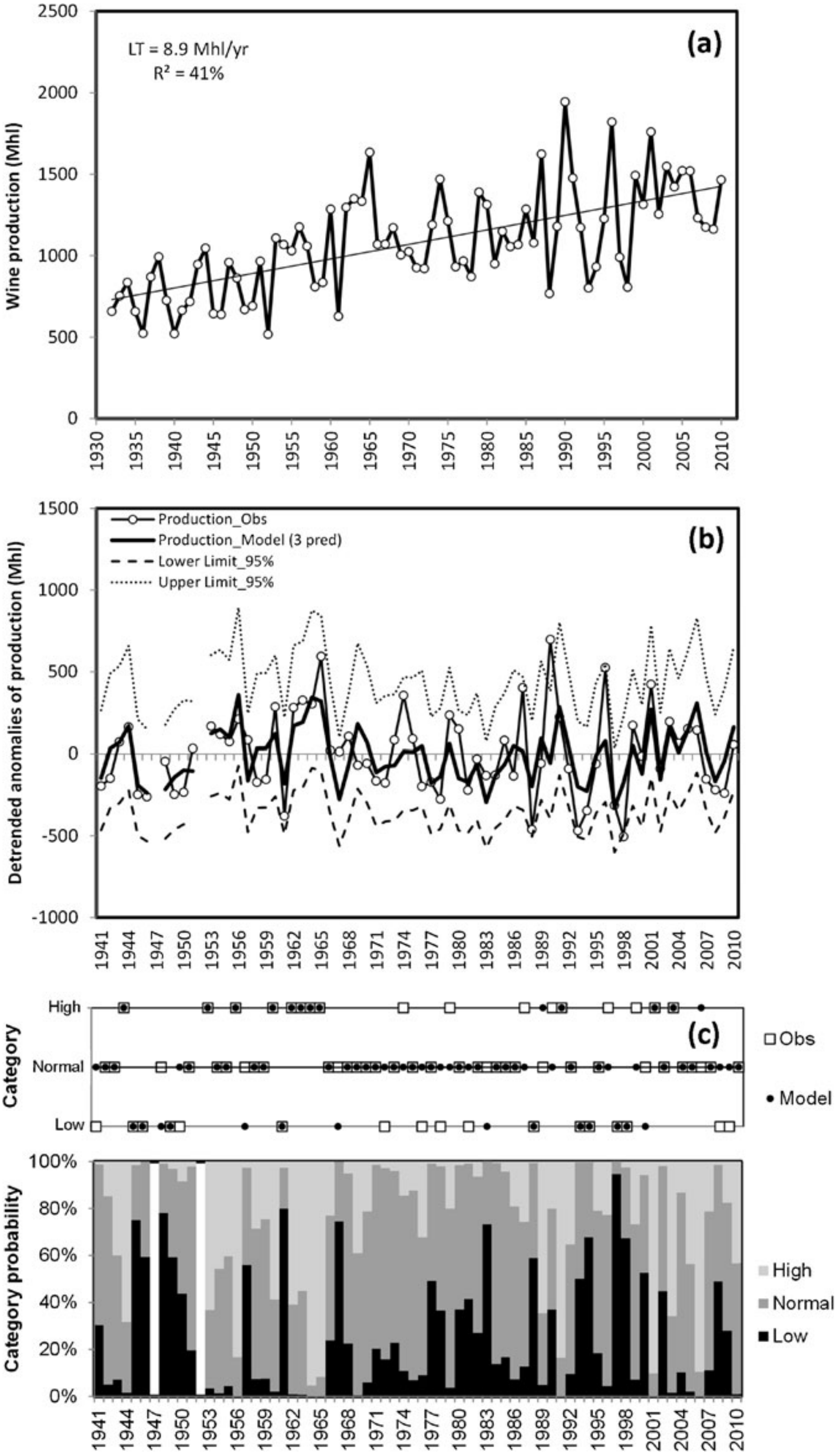

(a)
LT = 8.9 Mhl/yr
R² = 41%
Wine production (Mhl)
2500
2000
1500
1000
500
0
1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010
(b)
Production_Obs
Production_Model (3 pred)
Lower Limit_95%
Upper Limit_95%
Detrended anomalies of production (Mhl)
1500
1000
500
0
-500
-1000
1941 1944 1947 1950 1953 1956 1959 1962 1965 1968 1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004 2007 2010
(c)
Category
High
Normal
Low
□ Obs
• Model
Category probability
100%
80%
60%
40%
20%
0%
High
Normal
Low
1941 1944 1947 1950 1953 1956 1959 1962 1965 1968 1971 1974 1977 1980 1983 1986 1989 1992 1995 1998 2001 2004 2007 2010

Table 1 Summary table of all RCMs used in this study. The corresponding acronyms, responsible institutes, driving GCMs, grid resolutions and respective references are also listed. In all simulations the period 2001–2099 was used under the IPCC-SRES A1B scenario

RCM	Acronym	Institute	GCM	Grid	Reference
KNMI-RACMO2	EH5 RACMO(KNMI)	KNMI	ECHAM5-r3	25 km	Lenderink et al. (2003)
SMHI-RCA	EH5 RCA(SMHI)	SMHI	ECHAM5-r3	25 km	Kjellström et al. (2005) Samuelsson et al. (2011)
MPI-REMO	EH5 REMO(MPI)	MPI-M	ECHAM5-r3	25 km	Jacob and Podzun (1997) Jacob (2001)
DMI-HIRHAM	EH5 HIRHAM(DMI)	DMI	ECHAM5-r3	25 km	Christensen et al. (1996)
ICTP-RegCM3	EH5 RegCM(ICTP)	ICTP	ECHAM5-r3	25 km	Elguindi et al. (2007) Pal et al. (2007)
COSMO-CLM-1	EH5 COSMO-CLM1 (MPI)	MPI-M	ECHAM5-r1	18 km	Steppeler et al. (2003) Böhm et al. (2006)
COSMO-CLM-2	EH5 COSMO-CLM2 (MPI)	MPI-M	ECHAM5-r2	18 km	Steppeler et al. (2003) Böhm et al. (2006)
CNRM-Aladin	ARP Aladin(CNRM)	CNRM	ARPEGE-RM5.1	25 km	Gibelin and Déqué (2003)
DMI-HIRHAM	ARP HIRHAM(DMI)	DMI ARPEGE	ARPEGE	25 km	Christensen et al. (1996)
SMHI-RCA	BCM RCA(SMHI)	SMHI BCM	BCM	25 km	Steppeler et al. (2003) Gibelin and Déqué (2003)
SMHI-RCA	HC RCA(SMHI)	SMHI	HadCM3Q3 (low sens)	25 km	Kjellström et al. (2005) Samuelsson et al. (2011)
C4I-RCA3	HC RCA3(C4I)	C4I	HadCM3Q16 (high sens)	25 km	Kjellström et al. (2005) Samuelsson et al. (2011)
ETHZ-CLM	HC CLM(ETHZ)	ETHZ	HadRM3Q0 (normal sens)	25 km	Steppeler et al. (2003) Gibelin and Déqué (2003)
HC-HadRM3Q0	HC HadRM3Q0(HC)	Hadley Centre	HadRM3Q0 (normal sens)	25 km	Collins et al. (2011)
HC-HadRM3Q3	HC HadRM3Q3(HC)	Hadley Centre	HadRM3Q3 (low sens)	25 km	Collins et al. (2011)
HC-HadRM3Q16	HC HadRM3Q16(HC)	Hadley Centre	HadRM3Q16 (high sens)	25 km	Collins et al. (2011)

the choice of the driving GCM (e.g. Déqué et al. 2007; Räisänen 2007), carrying out a sensitivity analysis on the choice of the driving GCM is out of the scope of the present study and all ensemble members are herein considered as equally probable. Furthermore, the skills of the selected model chains and the differences that can be attributed to the driving GCM have already been discussed in previous studies (e.g. Kjellström et al. 2011).

Data from these simulations were extracted for the DV sector (41.0–41.5ºN; 6.75–8.0ºW), which optimally covers the DDR (red box in Fig. 1). This sector contains 3×4 grid points for datasets from the ENSEMBLES-project RCMs (25 km) and 4×7 grid points for datasets from COSMO-CLM (18 km). The atmospheric variables were then averaged over all grid cells within DV and are considered as representative of the regional temperature and precipitation characteristics.

As the statistical distributions of the simulated data commonly present biases with respect to observations, model output statistics were used to fit the raw model data to observations. Suitable transfer-functions were applied to obtain transformed (adjusted) data with the same statistical moments as the observational data recorded at VR. These transformations were undertaken for each variable and each RCM individually, for which linear, polynomial, exponential and logarithmic fits were tested. The best-fit function corresponds to the maximum determination coefficient (R-squared). The reference period used in the transfer-function estimation is 1961–2000 for both station and model data. This scaling procedure enables the correction (calibration) of some important biases in the model simulations, also enabling a comparison between the different RCMs.

The main aim of the present study is to develop a statistical tool for wine production modelling in the DV. With this aim, a multivariate linear regression analysis was performed (Wilks 2006). The wine production model was developed in the following steps:

1) The production time series shows a significant long-term trend ($+8.9\times10^6$ hl.year^{-1}; Fig. 2a), which can be largely attributed to the gradual increase in vineyard area in the DDR. This linear trend represents 41 % of the total variance in the time series, demonstrating its preponderance in the temporal variability. The least-squares linear trend for 1941–2010 was extracted, filtering out most of the red-noise (ultra-low frequencies) in the time series (Fig. 2b).
2) The production time series is not normally distributed. Therefore, a Box-Cox transformation with an optimal lambda coefficient of 0.4 (maximum of the Log-Likelihood Function; Wilks 2006) was then applied to the detrended time series.
3) The Box-Cox transformed detrended production was then modelled using a multivariate linear regression approach. Monthly mean temperatures and monthly precipitation totals for all calendar months, recorded at VR for 1941–2010, were considered as potential predictors, as well as all possible combinations amongst the months and variables. Other variables based on daily data, such as the number of days with temperatures/precipitations above a given threshold, were also tested, but no significant improvements were obtained in the model's skill. Quadratic terms were also tested in this model, but no significant improvements were found as well.
4) The most significant predictors were then selected by a stepwise approach and the modelled production was recalculated by inverting the Box-Cox transformation.

3 Results

3.1 Wine production modelling

Three robust predictors were selected by the stepwise multivariate regression approach for modelling the wine production (WP): the combination of February-March mean temperature

($T_{\text{Feb-Mar}}$), May mean temperature (T_{May}) and March precipitation (P_{Mar}), were retained according to the following regression equation:

$$WP^{0.4} = 15.730 - 0.428T_{\text{Feb-Mar}} + 0.498T_{\text{May}} + 0.005P_{\text{Mar}}$$

As such, anomalously low February-March mean temperature, anomalously high May mean temperature and anomalously high March precipitation tend to be favourable to wine production in the DDR. In other words, a wet and cool spring during budburst, shoot and inflorescence development (February-March) and warmer than normal conditions during flowering and berry development (May) tend to favour higher wine production in the DV. Thus, the leading role of springtime temperatures and precipitation in grapevine development and productivity is stressed by this model.

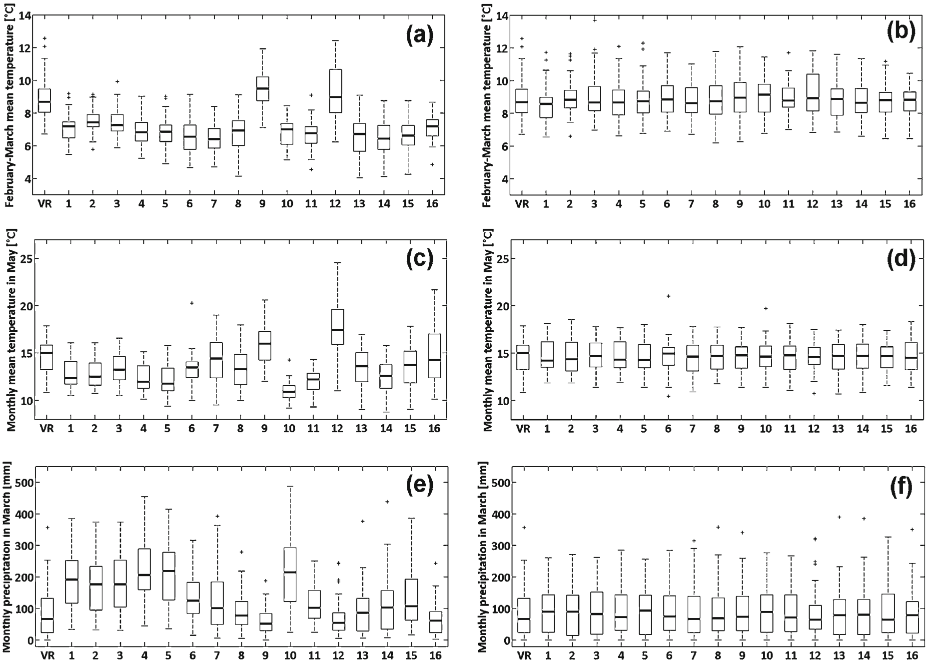
The model is statistically significant at a 0.01 % significance level and explains 43 % of the total variance in the time series after cross-validation. The residuals are independent according to the Durbin-Watson test (Wilks 2006) and their values do not show any preferential orientation when plotted against the modelled production (not shown). Taking into account the strong irregularity and inter-annual variability in the wine production time series, the model can be considered reasonably skilful in reproducing the observations; the observed and modelled production are in close agreement and the 95th confidence intervals comprise nearly all observations (Fig. 2b).

To estimate the probabilities of occurrence of three categories of wine production (low, normal and high production years) a logistic model is developed using the same predictors detailed for the linear model above. These categories correspond to production levels below the 25th percentile (low), within the 25th–75th percentile range (normal) and above the 75th percentile (high), for the period 1941–2010 (Fig. 2c). This type of information can be very useful for the viticultural sector in the DDR, by allowing timely implementation of strategies to manage the projected wine production level; this information can be provided in early June, right after having May mean temperature data, i.e. 3–4 months prior to harvest. The results show that the most-likely category predicted by the logistic model (lower part of Fig. 2c) effectively corresponds to the observed category (upper part of Fig. 2c) in 70 % of the years in the entire period of 1941–2010. This highlights the skilfulness and practical usefulness of this probabilistic model.

3.2 Wine production projections

The data for the three significant wine production predictors is extracted from the 16 transient simulations. The original simulated variables show clear differences towards the VR data (Fig. 3a, c, e). Nevertheless, after applying model output statistics (cf. section 2), the transformed variables depict similar medians and analogous ranges (Fig. 3b, d, f), highlighting the effectiveness of the applied scaling procedure (calibration).

Figure 4 shows the projections for each of the three transformed predictors over the period 1961–2099. The individual model projections are not detailed for the sake of succinctness, but their statistical spread is shown (ensemble means and 5th, 25th, 50th, 75th, 95th percentiles). Data are shown as 11-year running means to focus on decadal variability. For both the February-March and May mean temperatures clear upward (warming) trends are found with increasing greenhouse gas (GHG) forcing. The ensemble mean temperature increases for February-March from 9.0 °C in the year 2000 up to 12.0 °C by the end of the 21$^{\text{st}}$ century (+3 °C), whereas for May it



1- EH5 RACMO(KNMI)	5- EH5 RegCM(ICTP)	9- ARP HIRHAM(DMI)	13- HC CLM(ETHZ)
2- EH5 RCA(SMHI)	6- EH5 COSMO-CLM1(MPI)	10- BCM RCA(SMHI)	14- HC HadRM3Q0(HC)
3- EH5 REMO(MPI)	7- EH5 COSMO-CLM2(MPI)	11- HC RCA(SMHI)	15- HC HadRM3Q3(HC)
4- EH5 HIRHAM(DMI)	8- ARP Aladin(CNRM)	12- HC RCA3(C4I)	16- HC HadRM3Q16(HC)

Fig. 3 Box&whiskers diagrams of the raw (*left panel*) and transformed (*right panel*) distributions of the monthly mean air temperature in May for 1961–2000 and for the 16 RCM runs. Medians are indicated by the horizontal thick lines within the boxes. Lower (*upper*) box limits corresponds to the 25th (75th) percentile. Lower (*upper*) whisker limit corresponds to the non-outlier minimum and maximum. '+' indicate outliers

increases from 14.8 °C up to 18.8 °C (+4 °C). March precipitation is not expected to undergo any long-term change with increasing GHG forcing, remaining around 80 mm.

Based on the transformed data (right panel in Fig. 3), the resulting wine production projections are displayed in Fig. 5a. Despite the significant decadal variability, an upward long-term trend can be recognized for the ensemble mean, with a projected increase from about $1{,}165\times10^{6}$ hl in 2000 to $1{,}286\times10^{6}$ hl in 2095 (roughly +10 %). However, the uncertainty increases in time, as highlighted by the increasing spread between the 5th and 95th percentile during the 21st century. Such a net increase in production could be expected due to the warming in May, though partially offset by the warming in March.

The same transformed variables were used in the logistic model and the results show that while the probability of low production years remains nearly constant with increasing GHG forcing, the number of normal production years decreases and the number of high production years increases significantly (Fig. 5b). In fact, the probabilities of occurrence of high

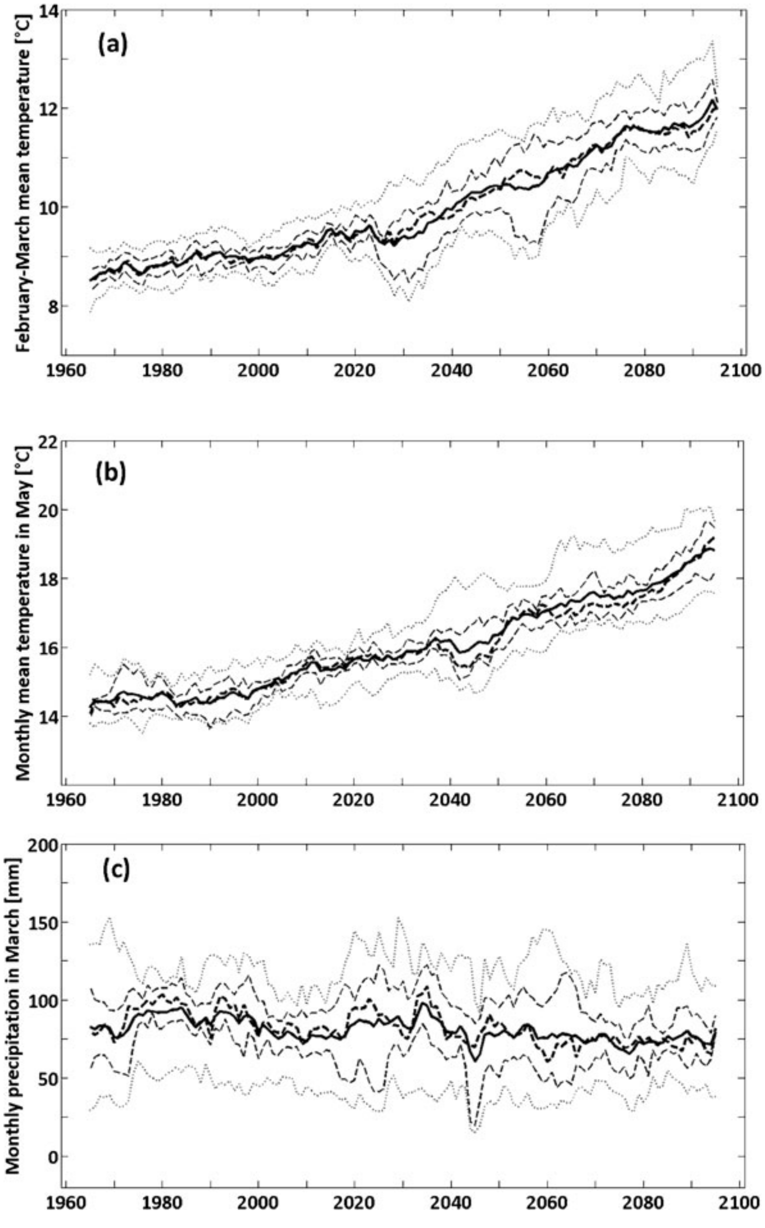


Fig. 4 16-member ensemble projections for the three transformed production predictors: **a** February-March mean temperature, **b** May mean temperature, and **c** March precipitation. The ensemble means (*thick solid lines*), medians (*thick dashed lines*), 5st (*lower dotted lines*), 25th (*lower light dashed lines*), 75th (*upper light dashed lines*) and 95th (*upper dotted lines*) percentiles of the 11-year running means of each variable are plotted. Here the shorter time period (1965–2095) is due to the moving averaging procedure

production years are projected to increase from 25 % (current values) to over 60 % by the end of the 21st century, becoming then the most frequent category. These outcomes are also in line with the projections for the production (Fig. 5a) and for the predictors (Fig. 4).

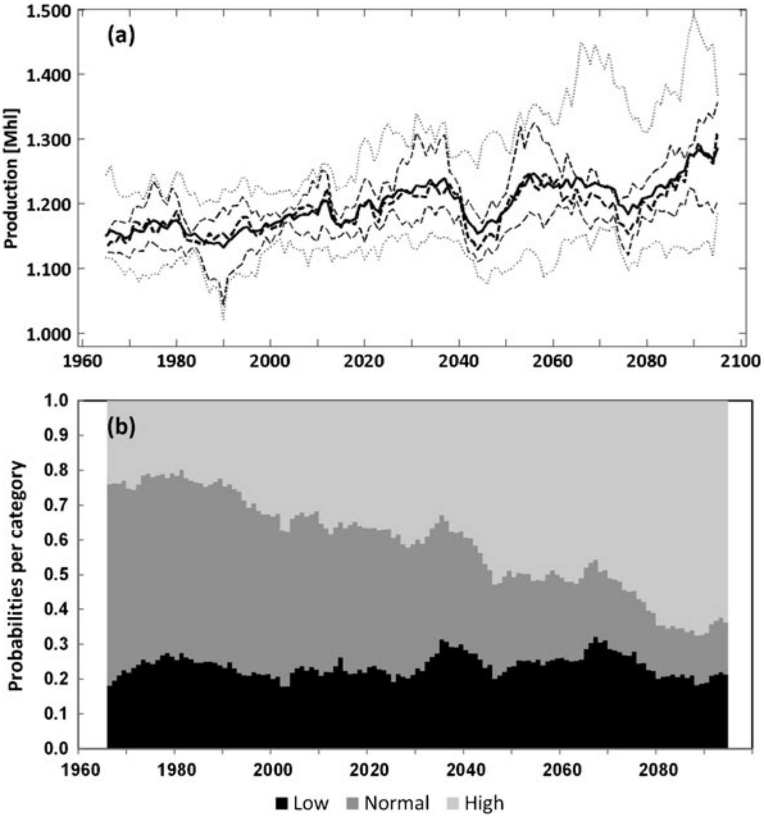


Fig. 5 As in Fig. 4, but now for the 16-member ensemble projections of the 11-year running mean of the (**a**) wine production and of the (**b**) probabilities of the three categories of wine production in C20 (1965–2000) and A1B (2001–2095). Here the shorter time period (1965–2095) is due to the moving averaging procedure

4 Discussion and conclusions

Winegrapes are a climatically sensitive crop whereby optimum conditions for production are limited geographically, often with significant climate risks that drive production variability, and may be further challenged by climate change in the future (Jones 2006). This research examines these issues in the DV of Portugal furthering our understanding of the relationships between historic and future climatic conditions and production in the region. The DV of Portugal is well known for its Port wine production, which is a strong contributor to the economy of the country. As such, understanding the relationships between the historic, current, and future climate and production is important for the region and the whole country.

Wine production in the DV of Portugal is shown to be strongly linked to spring and early summer conditions that largely determine the productivity of a given vintage. The results show that wet and cool springs during budburst, shoot and inflorescence development (February-March) and warmer than normal conditions during flowering and berry development (May) tend to favour higher wine production. These three climatic variables already explain almost half (43 %) of the inter-annual variability in the detrended wine production time series for the DV. Moreover, by adding the linear trend (largely related to the increase in the vineyard area) to our modelled time series the percentage of explained variance rises to 60 %. Most of the unexplained variance (40 %) can be attributed to other non-climatic factors, such as technological changes, agricultural and oenological practices, which are out of the scope of the present study. These results from the production model are in agreement with the results previously obtained using a yield model on a single GCM/RCM chain (Santos et al. 2011), but the robustness and confidence of the present study projections is substantially increased by the consideration of 16 transient experiments with different GCM/RCMs model chains and using a much longer production dataset for testing and calibrating the production model. Additionally, similar spring climate parameters driving phenology and fruit chemistry were also found in different winemaking regions, such as in the Bordeaux region, France (Jones and Davis 2000), or in the Moselle region, Germany (Urhausen et al. 2011).

The assessment of future climate conditions in the region show ensemble mean temperature increases for February - March of 3 °C (warming from 9.0 °C to 12.0 °C during 2000–2099). Given that mean temperatures above 10 °C are known to initiate grapevine growth in the spring (Winkler et al. 1974), the springtime warming projected from the ensemble would indicate the potential for earlier budburst in the region. These conditions would drive earlier phenology over the growth cycle of the vine, likely resulting in earlier harvests that would occur in a warmer part of the year. While the model results indicate that the conditions might be favourable for higher production, other research has shown that ripening during a warmer part of year would be detrimental to quality (Webb et al. 2008).

Although the ensemble model projections for the region show a trend toward increased production, the results also indicate potential increases in vintage to vintage and decadal variability in production. Furthermore, while the results of this study are based on a historical record of production in the DV of Portugal, the historic conditions may not be completely indicative of future conditions and model development will need to evolve to include other aspects that shape production in the future. For example, changes in plant material, slope management, water for irrigation, trellis systems, etc. will likely occur over time in parallel with changes in climate and will require further model development to account for their influences. In addition, while the results here indicate the importance of spring and early summer conditions on productivity, the rising heat stress and/or changes in ripening conditions could limit the projected production increase in future decades. Furthermore, although the enhanced concentrations of carbon dioxide in the future might have beneficial impacts on the grapevine vegetative development (Moutinho-Pereira et al. 2009), this forcing is disregarded in the present study. Although results using other emission scenarios (Nakićenović et al. 2000) are under development and will be discussed in forthcoming studies, it can be stated that their corresponding climate change projections are analogous to the A1B scenario, with only slight variations in the amplitude of the projections, particularly until 2070 (not shown). Furthermore, under anthropogenic forcing, changes in both the frequency and strength of temperature and precipitation extremes in Portugal, and in the DV in particular, are expected to occur in the next few decades (e.g. Costa et al. 2012). The role played by these extreme events on the DV wine production is also an important issue for future research.

Another issue might include the evolving relationship between wine quality and production with growers reducing crop yield late in the year (i.e., dropping clusters) to maintain producer quality standards. Finally it is important to note that production limits in the region are currently set by the *Instituto do Vinho do Porto* in order to maintain economic sustainability in response to the supply and demand of an international market. These limits may be more or less influential in controlling production trends in the future.

This research has examined a long time series of wine production in the DV of Portugal, developing a model that details the relationship between climate and productivity in the region. The results show that early to late spring temperature and precipitation are important for overall productivity. Given that the best climatic predictors of productivity occur early in the growth cycle of the vine, the results provide producers in the region a measure of the ensuing harvest volume such that appropriate strategies can be planned and implemented. These include the management of the fruit load that a given vineyard will be able to ripen and planning for the amount of labour and supplies needed for the harvest and winery processing.

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References

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modeling the impact of future climate scenarios on yield and variability of grapevine. Clim Res 7:213–224. doi:10.3354/cr007213

Böhm U, Kücken M, Ahrens W, Block A, Hauffe D, Keuler K, Rockel B, Will A (2006) CLM- the climate version of LM: brief description and long- term applications. COSMO Newsletter 6:225–235

Christensen JH, Christensen OB, Lopez P, van Meijgaard E, Botzet M (1996) The HIRHAM4 Regional Atmospheric Climate Model. DMI Scientific Report 96–4

Collins M, Booth BBB, Bhaskaran B, Harris GR, Murphy JM, Sexton DMH, Webb MJ (2011) Climate model errors, feedbacks and forcings: a comparison of perturbed physics and multi-model ensembles. Clim Dynam 36:1737–1766. doi:10.1007/s00382-010-0808-0

Costa AC, Santos JA, Pinto JG (2012) Climate change scenarios for precipitation extremes in Portugal. Theo Appl Climatol 108:217–234. doi:10.1007/s00704-011-0528-3

Cunha M, Richter C (2012) Measuring the impact of temperature changes on the wine production in the Douro region using the short time Fourier transform. Int J Biometeorol 57:357–370. doi:10.1007/s00484-011-0439-0

Déqué M, Rowell D, Lüthi D, Giorgi F, Christensen J et al (2007) An inter-comparison of regional climate models for Europe: model performance in present-day climate. Clim Change 81:53–70. doi:10.1007/s10584-006-9228-x

Elguindi N, Bi X, Giorgi F, Nagarajan B, Pal J, Solmon F, Rauscher S, Zakey A (2007) RegCM version 3.1 user's guide. PWCG Abdus Salam ICTP

Gibelin AL, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim Dynam 20:327–339. doi:10.1007/s00382-002-0277-1

Gouveia C, Liberato ML, DaCamara CC, Trigo RM, Ramos AM (2011) Modelling past and future wine production in the Portuguese Douro Valley. Clim Res 48:349–362. doi:10.3354/cr01006

INMG (1991) O clima de Portugal: normais climatológicas da região de "Trás-os-Montes e Alto Douro e Beira Interior" correspondentes a 1951–1980. Instituto Nacional de Meteorologia e Geofísica, Lisboa

IVV (2008) Vinhos e Aguardentes de Portugal, Anuário'08. Ministério da Agricultura, do Desenvolvimento Rural e das Pescas: Instituto da Vinha e do Vinho, Lisboa

Jacob D (2001) A note to the simulation of the annual and inter-annual variability of the water budget over the Baltic Sea drainage basin. Meteorol Atmos Phys 77:61–73. doi:10.1007/s007030170017

Jacob D, Podzun R (1997) Sensitivity studies with the regional climate model REMO. Meteorol Atmos Phys 63:119–129. doi:10.1007/BF01025368

Jones GV (2006) Climate and terroir: impacts of climate variability and change on wine. In: Macqueen RW, Meinert LD (eds) Fine wine and terroir - the geoscience perspective, vol 9. Geological Association of Canada, St. John's, Canada, Geoscience Canada Reprint

Jones GV, Alves F (2011) Impacts of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal. Proceedings of the Global Conference on Global Warming 2011, 11–14 July 2011, Lisbon, Portugal

Jones GV, Davis RE (2000) Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am J Enol Viticult 51:249–261

Jones GV, White MA, Cooper OR, Storchmann K (2005) Climate change and global wine quality. Clim Change 73:319–343. doi:10.1007/s10584-005-4704-2

Kenny GJ, Harrison PA (1992) The effects of climate variability and change on grape suitability in Europe. J Wine Res 3:163–183

Kjellström E, Bärring L, Gollvik S, Hansson U, Jones C, Samuelsson P, Rummukainen M, Ullerstig A, WillØn U, Wyser K (2005) A 140-year simulation of European climate with the new version of the Rossby Centre regional atmospheric climate model (RCA3). Reports Meteorology and Climatology, 108, SMHI, SE-60176 Norrköping, Sweden

Kjellström E, Nikulin G, Hansson U, Strandberg G, Ullerstig A (2011) 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Tellus 63A:24–40. doi:10.1111/j.1600-0870.2010.00475.x

Lautenschlager M, Keuler K, Wunram C, Keup-Thiel E et al (2009a) Climate simulation with CLM, Climate of the 20th Century run no.1, Data Stream 3: European region MPI-M/MaD. World Data Center for Climate. doi: 10.1594/WDCC/CLM_C20_1_D3

Lautenschlager M, Keuler K, Wunram C, Keup-Thiel E et al (2009b) Climate simulation with CLM, Climate of the 20th Century run no.2, Data Stream 3: European region MPI-M/MaD. World Data Center for Climate. doi: 10.1594/WDCC/CLM_C20_2_D3

Lautenschlager M, Keuler K, Wunram C, Keup-Thiel E et al (2009c) Climate simulation with CLM, Scenario A1B run no.1, Data Stream 3: European region MPI-M/MaD. World Data Center for Climate. doi: 10.1594/WDCC/CLM_A1B_1_D3

Lautenschlager M, Keuler K, Wunram C, Keup-Thiel E et al (2009d) Climate simulation with CLM, Scenario A1B run no.2, Data Stream 3: European region MPI-M/MaD. World Data Center for Climate. doi: 10.1594/WDCC/CLM_A1B_2_D3

Lenderink G, van den Hurk B, van Meijgaard E, van Ulden A, Cuijpers H (2003) Simulation of present-day climate in RACMO2: first results and model developments. Ministerie van Verkeer en Waterstaat, Koninklijk Nederlands Meteorologisch Instituut, Netherlands

Magalhães NP (2008) Tratado de Viticultura - A videira, a vinha e o “terroir”. Chaves-Ferreira Publicações, Portugal

Malheiro ANC (2005) Microclimate, yield and water-use of vineyards in the Douro Region, Portugal. Dissertation, Cranfield University, UK

Malheiro AC, Santos JA, Fraga H, Pinto JG (2010) Climate change scenarios for viticultural zoning in Europe. Clim Res 43:163–177. doi:10.3354/cr00918

Meehl GA et al. (2007) Global Climate Projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Moutinho-Pereira J, Gonçalves B, Bacelar E, Cunha JB, Coutinho J, Correia CM (2009) Effects of elevated CO2 on grapevine (*Vitis vinifera* L.): physiological and yield attributes. Vitis 48:159–165

Nakićenović N et al (2000) IPCC special report on emissions scenarios. Cambridge University Press, New York

Pal JS, Giorgi F, Bi X, Elguindi N, Solmon F, Gao X, Ashfaq M, Francisco R, Bell J, Diffenbaugh N et al (2007) The ICTP RegCM3 and RegCNET: regional climate modeling for the developing world. Bull Am Meteorol Soc 88:1395–1409. doi:10.1175/BAMS-88-9-1395

Räisänen J (2007) How reliable are climate models? Tellus 59:2–29. doi:10.1111/j.1600-0870.2006.00211.x

Samuelsson P, Jones CG, WillØn U, Ullerstig A, Gollvik S, Hansson U, Jansson C, Kjellström E, Nikulin G, Wyser K (2011) The Rossby centre regional climate model RCA3: model description and performance. Tellus A 63:4–23. doi:10.1111/j.1600-0870.2010.00478.x

Santos JA, Malheiro AC, Karremann MK, Pinto JG (2011) Statistical modelling of grapevine yield in the Port Wine region under present and future climate conditions. Int J Biometeorol 55:119–131. doi:10.1007/s00484-010-0318-0

Sneyers R (1975) Sur L’analyse statistique des séries d’observation. World Meteorological Organization, Technical note 143. Geneva, Switzerland

Steppeler J, Doms G, Schättler U, Bitzer HW, Gassmann A, Damrath U, Gregoric G (2003) Meso-gamma scale forecasts using the nonhydrostatic model LM. Meteorol Atmos Phys 82:75–96. doi:10.1007/s00703-001-0592-9

Urhausen S, Brienen S, Kapala A, Simmer C (2011) Climatic conditions and their impact on viticulture in the Upper Moselle region. Clim Change 109:349–373. doi:10.1007/s10584-011-0059-z

van der Linden P, Mitchell JFB (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3 PB, UK

van Leeuwen C, Friant P, Choné X, Tregoat O, Koundouras S, Dubourdieu D (2004) Influence of climate, soil, and cultivar on terroir. Am J Enol Vitic 55:207–217

Webb L, Whetton P, Barlow EWR (2008) Climate change and wine grape quality in Australia. Clim Res 36:99–111. doi:10.3354/cr00740

Wilks DS (2006) Statistical methods in the atmospheric sciences. Elsevier Academic Press, UK

Winkler AJ, Cook JA, Kliwer WM, Lider LA (1974) General viticulture. University of California Press, USA