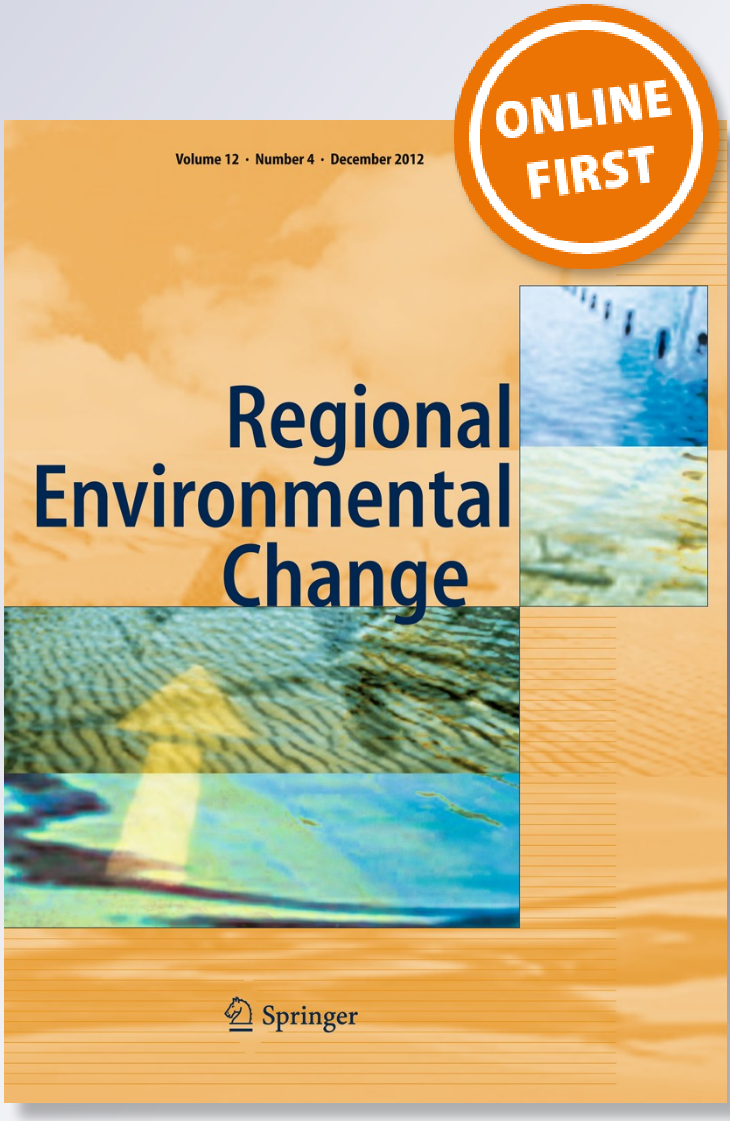
Influence of climate on grape production and wine quality in the Rías Baixas, north-western Spain

M. N. Lorenzo, J. J. Taboada, J. F. Lorenzo & A. M. Ramos

Regional Environmental Change

ISSN 1436-3798

Reg Environ Change
DOI 10.1007/s10113-012-0387-1



Reg Environ Change
DOI 10.1007/s10113-012-0387-1

ORIGINAL ARTICLE

Influence of climate on grape production and wine quality in the Rías Baixas, north-western Spain

M. N. Lorenzo · J. J. Taboada · J. F. Lorenzo · A. M. Ramos

Received: 18 June 2012 / Accepted: 1 December 2012

Abstract Climate exerts an important role on grape production and wine quality. For one of the main areas protected under the denomination of origin Rías Baixas, in Galicia, Spain, we explore the relationships among grape production, wine quality, rainfall and temperature for the period 1987–2005. The influence of climatic variability was analysed in terms of the relationship between the productivity of the grapevines and the main meteorological teleconnection patterns affecting the North Atlantic region. We also investigate the daily variation in atmospheric circulation through the study of the influence of weather types derived using an automated daily classification. We consider three bioclimatic indices for viticultural zoning, Winkler and Huglin, and the hydrothermic index of Branas, Bernon and Levadoux. While significant trends were identified in the Winkler and Huglin indices, there were no significant trends in the Branas, Bernon and Levadoux index, for the period 1958–2005. For the coming decades, using the scenario A1B evaluated by the regional climate models used in the ENSEMBLES project, the positive trends of Winkler and Huglin indices continue, while Branas, Bernon and Levadoux implies a negative trend. In all cases, these trends induce significant changes in the viticulture of the region.

Keywords Viticulture · Rías Baixas · Climate variability · Teleconnection patterns · Synoptic classification · Winkler index · Huglin index · Hydrothermic index of Branas · Bernon and Levadoux · Climate change

Introduction

The style of wine produced in a region is a result of the baseline climate, while the climatic variability determines differences in the quality of the vintage. The economics of a viticultural region are driven by the quality rating assigned to each year's vintage (de Blij 1983). As a result, the production and quality of wines is likely to be affected by changes in meteorological and climatic conditions. Wine grapes require a very specific set of climatic conditions; they need a mean temperature of between 12 and 22 °C during the growing season (Jones 2006). The local and regional atmospheric changes that result from global climate change could have a significant effect on grapevine phenology, grape production and wine quality.

During the past few decades, the impacts of meteorology and climate on wine quantity and quality have been the subject of extensive studies undertaken in many different parts of the world. The influence of climatic variability and of recent trends in the climate in different parts of Europe has been examined by Jones et al. (2005a) and Santos et al. (2012). Moreover, some studies centred on specific areas such as Alsace, the Northeast of Spain, Douro and Bordeaux have also been published in recent years (Duchêne and Schneider 2005; Ramos et al. 2008; Camps and Ramos

M. N. Lorenzo (✉) · J. F. Lorenzo · A. M. Ramos
EPhysLab, Facultade de Ciencias, Universidade de Vigo, Campus As Lagoas s/n, Ourense, Spain
e-mail: nlorenzo@uvigo.es
URL: http://ephyslab.uvigo.es

J. J. Taboada
MeteoGalicia, Xunta de Galicia, Santiago de Compostela, Spain

A. M. Ramos
Instituto Dom Luiz, Faculdade de Ciencias, Universidade de Lisboa, Lisbon, Portugal

Published online: 14 December 2012

2010, 2011; Santos et al. 2011; Gouveia et al. 2011). Climate change and its relationship with viticulture has also been a topic of interest (Jones et al. 2005b; Camps and Ramos 2010; Schultz and Jones 2010).

The northwest part of the Iberian Peninsula is a very productive winegrowing area, with some areas having denominations of origin (DO). The main aim of the present work is to investigate the influence of climate on viticulture in one of those areas, namely the Rías Baixas, which plays an important role in the economic production and culture of Galicia. Grapes and wine have been produced for a long time in this area, and the history of the DO Rías Baixas begins in 1980. It includes areas near the coast, at altitudes below 300 m, and generally in river valleys. The climate is characterised by mild temperatures; precipitation is common throughout the year, with a minimum in summer.

The interannual variability of rainfall and temperature at these latitudes can be characterised using different patterns of teleconnection that reflect climatic modes of oscillation. Several authors (Zorita et al. 1992, Rodó et al. 1997, Esteban-Parra et al. 1998) have investigated the relationship between rainfall and the most significant pattern of variability in the North Atlantic, known as the North Atlantic Oscillation (NAO; Wallace and Gutzler 1981). In addition, Rodríguez-Puebla et al. (1998) identified four regional regimes of precipitation over a monthly time scale in the Iberian Peninsula (IP), each associated with one of the following four large-scale atmospheric modes: North Atlantic Oscillation (NAO), East Atlantic (EA), Southern Oscillation Index (SOI) and Scandinavia (SCA). In our study area, different authors have previously shown the influence of more than one pattern of teleconnection on the variability of winter precipitation (Lorenzo and Taboada 2005; deCastro et al. 2006). In particular, NAO, EA, EA/WR (East Atlantic/Western Russia) and SCA are the main modes that may be used to explain this variability. Therefore, apart from the direct influence of temperature and rainfall on grape production and wine quality, the relationship between viticulture and the index that characterises each pattern of teleconnection can also be explored.

While the influence of climate on the different phenological stages of the grape is an important subject, it has also been established that the influence of daily variations in the weather can also have an influence on grape production and wine quality. In order to account for these day-to-day variations, it is possible to use an objective, automated classification of the daily patterns of circulation. The wide range of applicability of this classification in climatology, biometeorology, atmospheric physics and chemistry makes it a useful tool for investigating day-to-day meteorological variations (Jones et al. 1993; Trigo and DaCamara 2000; Goodess and Palutikof 1998). We herein use an automated classification of weather types recently published for the region of interest (Lorenzo et al. 2008).

Different bioclimatic indices calculated using variables such as temperature and rainfall, but also insolation or frost, are commonly taken into account in viticultural zoning. We use three different indices here, namely the Winkler index and the Huglin index, both of which take into account the heat accumulated during the growing season, and the hydrothermic index of Branas, Bernon and Levadoux, which combines the rate of precipitation and temperature, and is used to determine the possibility of attack by mildew.

The objective of this work was to study the influence of several climatic variables, on the different phenological stages of grape production and on wine quality in Rías Baixas. In a first step, the influence of rainfall, temperature, teleconnection pattern and frequency of weather types on grape production and wine quality is analysed. Furthermore, the evolution of different bioclimatic indices is evaluated for present and future climates.

Data and methods

The Denomination of Origin of Rías Baixas covers a number of areas located in south west Galicia, all of which share some common physical characteristics and produce wines of international renown among Spanish wines. The terrain of Galicia is varied and complex. Located in the northwestern corner of the IP (Fig. 1), Galicia lies in the North Atlantic-European (NAE) sector, which is characterised by the passage of cold fronts associated with lows that travel across the north Atlantic, mainly in autumn and winter, and tend to cause heavy rainfall. Spring is a season of transition, when the fronts associated with these lows tend to be displaced northwards, resulting in a lower rainfall than that seen in autumn and winter. Summer is characterised by areas of high pressure that frequently produce settled conditions over the north of the IP. The region of Rías Baixas generally lies at altitudes below 300 m, near the sea and the mouths of some rivers, which determines the climatic characteristics related to the oceanic influence. This area has an Atlantic climate with a mean annual temperature of about 15 °C and an annual rainfall of about 1,600 mm, well distributed along the year and with a decrease in summer months. However, the strong seasonal contrasts in climate imply that the daily changes in atmospheric conditions have an important role in determining the phenology of the plants that grow in this region (Jones and Davis 2000).

Data for grape yields in Rías Baixas, and the vintage ratings for 1987–2009, were retrieved from the website of the Denomination of Origin (http://doriasbaixas.com). Ratings are based on a single blind tasting of the individual varietals by a panel of experts. Categorisation is awarded on a scale of one to five (exceptional to bad).

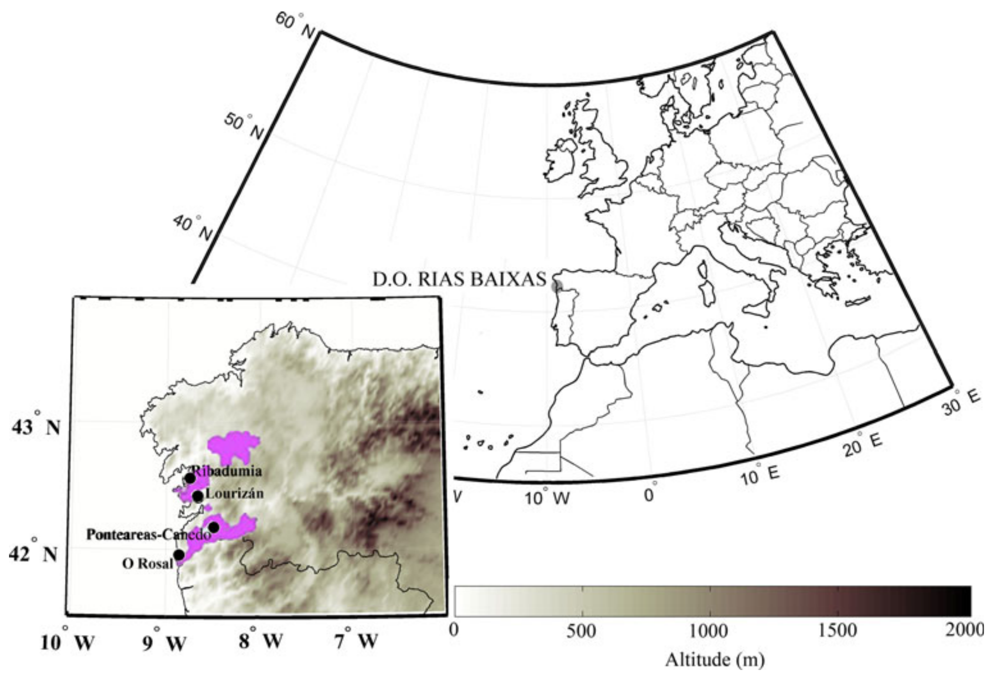


Fig. 1 Location of the study area and location of meteorological stations used in the analysis. The *shaded areas* correspond to the DO Rias Baixas

Data on the occurrence of the different phenological stages in Rías Baixas were obtained from Jones et al. (2005a). The phenological data contained therein for the region do not show any significant changes, and therefore, we assumed that their phenological records are appropriated for our study. The first stage is the inactive or dormant stage, which occurs during the winter between October and April. We did not consider this stage in our study due to the negligible influence of temperature at this time (known as latency, in which the static mass of the vine remains largely indifferent to changes in temperature), except for exceptional cases of intense frost. However, in this area, the winters are characterised by mild temperatures. The bud-break stage occurs usually between April and June and refers to the dates when sprouting begins. These are the first signs of growth. Then comes the bloom stage. This stage occurs between June and mid-August. Finally, the véraison stage occurs between mid-August and late September. During this period, fruits begin to enlarge, and they later change colour from green to yellowish in white grapes and to purple in black grapes.

For weather conditions, we used data from the Spanish Meteorological Agency (AEMET) together with data obtained from the stations of the regional government of Galicia under the control of MeteoGalicia. We chose three different stations located in the main subregions of wine production in the area of Rías Baixas (Ponteareas-Canedo, O Rosal and Ribadumia; see Fig. 1). Due to the short periods of the data available at these meteorological stations (18 or 19 years), data from the station at Lourizán were also considered, in order to provide a more robust indication of the trends in the climate. Lourizán is a meteorological station at which data are available for the period 1958–2005; these data represent the climatological characteristics of the region of Rías Baixas. The data from the first three stations correlate with those from the Lourizan station with values of around 0.97 at the 95 % level of significance.

According to Barnston and Livezey (1987), the most prominent modes of circulation in the NAE sector are the North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/Western Russia (EA/WR) and the Scandinavian (SCA). Over the last two decades, several authors have assessed the impact of these modes on the European climate (in particular on temperature and precipitation). The monthly values of the teleconnection indices NAO, SCA, EA, EA/WR were retrieved from the Climate Prediction Center (CPC) at the National Centre of Environmental Prediction (NCEP; http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml). We calculated an index for NAO, SCA, EA, EA/WR for each phenological stage and year following the periods obtained by Jones et al. (2005a). The index relating to the bud-break stage was obtained using an average of the indices for April and May, the index for the bloom stage was obtained using an average for June and July, and the index for the véraison stage was obtained using an average for August and September.

In order to account for day-to-day weather events, we used the manual Lamb circulation type methodology adapted to an objective automated classification by Jenkinson and Collison (1977) to calculate the daily patterns of circulation. This automated classification is based on the use of a set of indices associated with the direction and vorticity of geostrophic flow, and differentiates between meteorological conditions by describing them in terms of circulation parameters or local weather elements. Our data show that a consistent and distinct relationship exists between the circulation types and the temperature and rainfall. We considered ten weather types (NE, E, SE, S, SW, W, NW, N, Cyclone and Anticyclone; Lorenzo et al. 2008).

We also considered three indices commonly used in viticultural zoning. These were the Winkler index, the Huglin index and the hydrothermic index of Branas, Bernon and Levadoux. The first two are indices of heat accumulation or degree-days, and the third is related to the moisture (Blanco et al. 2007; Tonietto and Carbonneau 2004).

The Winkler index makes use of the sum of the daily average temperatures between April 1 and October 31. It provides information on the accumulation of heat during the growing season (Amerine and Winkler 1944).

$$\text{IndWinkler} = \sum_{1\,\text{April}}^{31\,\text{October}} ((T_{\max} + T_{\min})/2) - 10 \quad (1)$$

The Huglin index is calculated for the period April 1 to September 30 in the Northern hemisphere, with a coefficient of correction d that takes into account the average period of daylight for the latitude of interest (40°–50°) in our particular case $d = 1.03$ (Tonietto and Carbonneau 2004). This index enables the classification of different viticultural regions of the world in terms of the sum of the temperatures required for vine development and grape ripening (Huglin 1978).

$$\text{IndHuglin} = \sum_{1\,\text{April}}^{30\,\text{September}} (((T_{\text{mean}} - 10) + (T_{\max} - 10))/2) \times d \quad (2)$$

The hydrothermic index of Branas, Bernon and Levadoux (BBL) allows us to study the influence of temperature and precipitation on the grape yield and wine quality. This index is the sum of the monthly products of average temperature (in degrees Celsius) and rainfall (in mm), between April and August.

$$\text{IndBBL} = \sum_{1\,\text{April}}^{31\,\text{August}} T_{\text{mean\_monthly}} P_{\text{monthly}} \quad (3)$$

This index provides an upper limit above which the possibility of the vine being attacked by mildew is high. Mildew is one of the most common and most devastating diseases of vines. We calculated the value of this index at the different meteorological stations, and its relationship with grape production and wine quality in each case. We also analysed the trends in all indices for the period 1958–2005.

In order to analyse the relationship between the different patterns and indices and the series of grape production and wine quality, we used the Pearson correlation coefficient and the Student's t test to identify the statistical significance of the correlations.

To avoid long-term trends, before calculating the correlations, we linearly detrended all the series. This process is especially important for those variables such as temperature or grape production, which have shown clear increasing trends in recent years due to global warming or improvements in viticulture (Gimeno et al. 2002). The significance of these trends was assessed using the non-parametric Mann–Kendall test (Mann 1945; Kendall 1975).

For the study of climate change, projections of temperature and precipitation fields were obtained from four models used in the ENSEMBLES project (http://www.ensembles-eu.org/) which provide future climate projections at a resolution of 25 km for the A1B scenario (Nakicenovic and Swart 2000). The models considered were the BCM-RCA, the ECHAM5-RCA, the ECHAM5-REMO and the HADCM3-RCA. Current conditions were analysed for the period 1961–1991 and future conditions for the period 2061–2091. With the data obtained from the four models, Winkler, Huglin and BBL indices and their trends for the period 1961–2091 were calculated.

Results

Influence of climate variability on grape production and wine quality

The relationship between the maximum, minimum, and mean temperature and precipitation and the grape yield and wine quality was analysed using the data from the Lourizán station. We considered the three main phenological periods of bud break, bloom and veraison. The results reveal generally positive correlations with temperature for almost all phenological states, for both grape yield and wine quality (Table 1). For precipitation, the correlation was negative for the bud-break and veraison stages for both yield and quality. However, the correlation shows a significantly positive value between grape production and precipitation for the bloom stage, which implies that rainfall is important during this period.

The variations in the spatial distribution, not only of temperature and precipitation, but also of other climate variables, are consequences of the variability of atmospheric circulation. With this in mind, we analysed the influence of these low-frequency modes (NAO, EA, EA/WR and SCA) in Rías Baixas, considering both the grape production and the wine quality in this DO (Table 2).

The results show that the bud-break stage has a negative correlation with SCA, considering its relationship with grape production. A positive phase for this pattern is represented by a north–south dipole, with settled low pressure over the Iberian Peninsula and high pressure to the north. This leads to wet weather during the bud-break stage, but more importantly, cold conditions with polar air masses reaching the Atlantic coast of Galicia, so the negative sign in the correlation shows that these conditions are detrimental to grape production in Galicia.

The index NAO during the bloom stage has a positive correlation on grape production in Rías Baixas. A positive NAO at this time of year implies a predominantly anticyclonic pattern of circulation, indicating generally high temperatures. Finally, the values of the teleconnection indices during the véraison stage showed no significant influence on grape production in Rías Baixas. In terms of quality, significant correlations were observed in the bloom and véraison stages. In the bloom stage, we found a positive correlation with NAO. As discussed previously, if the NAO is in a positive phase in this period, it is associated with warm temperatures (Ramos 2012).

In the véraison stage, there is a strongly negative correlation between the quality of the wine and EA/WR, possibly because previous studies showed a negative correlation of EA/WR with temperature in summer (Taboada et al. 2009), and when temperatures are low in August and September, the grape cannot attain its optimal level of maturation and the wine quality is poor.

In order to relate day-to-day weather events to grape production and wine quality, we compared the frequency of occurrence of each synoptic case with the production and classification of wines of DO Rías Baixas for the three main phenological stages (bud break, bloom and véraison;

Table 1 Correlation between the time series of temperature and precipitation with grape production and wine quality in the DO Rias Baixas for the different phenological stages of the grape: bud break, bloom and véraison for 1987–2005

	Tmax	Tmin	Tmean	Prec
Grape production				
Budbreak	0.4672**	−0.0046	0.3671*	−0.3538*
Bloom	0.16	0.4829**	0.3340*	0.3924**
Veraison	0.4924**	0.1746	0.4205**	−0.3195*
Wine quality				
Budbreak	0.3244*	0.3284*	0.3888**	−0.2884
Bloom	0.4848**	0.7041**	0.6339**	0.1481
Veraison	0.5724**	−0.0033	0.3957**	−0.6477**

** Correlations statistically significant at 95 % and * correlations statistically significant at 90 %

Table 2 Correlation between the time series of teleconnection patterns and grape production and wine quality in the area of DO Rías Baixas for the different phenological stages of the grape: bud break, floraison and véraison for 1987–2009

	NAO	EA	EA/WR	SCA
Grape production				
Bud break	0.002	0.02	−0.26	−0.36**
Bloom	0.55**	−0.16	−0.02	0.02
Véraison	−0.02	0.04	−0.23	0.11
Wine quality				
Bud break	−0.005	0.04	−0.24	−0.22
Bloom	0.29*	−0.23	−0.16	0.14
Véraison	0.19	−0.03	−0.50**	0.01

** Correlations statistically significant at 95 % and * correlations statistically significant at 90 %

Table 3). The results show that the preponderance of type A at the bud-break stage has a very positive influence on the grape production, while an excess of cyclones is detrimental to the production of grapes and wine quality. This finding is in agreement with the results shown in Table 1, where we see that higher temperatures and lower rainfall favour grape yield. The SE type probably favours wine quality; however, the low frequency of this type during the bud-break stage means that no significant correlation can be assumed. At the bloom stage, the frequency of type A is negatively correlated with grape production but the S and SW types are positively correlated, since these types are usually associated with rainfall days that will improve the grape production in our study region (Lorenzo et al. 2008). Similar results are found during this stage when analysing the wine quality; moreover, a negative correlation with the NW type is also observed. Finally, during the véraison stage, grape production is favoured by the A type, which supports the process of maturation of the grapes, and negatively influenced by the NW, N and S types, which are characterised by lower temperatures and sporadic rains (Ramos 2012). Wine quality is also favoured by the A type, but the rainy types C and SW and the colder types NW and N are detrimental to it (Lorenzo et al. 2008; Ramos 2012).

The results obtained here may be compared with those made for other areas of wine production in Europe. Two recent studies (Gouveia et al. 2011; Santos et al. 2011) showed that for the Douro Region higher temperatures are beneficial to the bloom and véraison stages, in agreement with our results for Rías Baixas. They also showed the important role of precipitation at the end of spring, which is similar to our negative correlation with rainfall in the bud-break stage, but our results differ in the sense that in Rías Baixas, a wet June and July improve grape production. In addition, an analysis of different weather types in the Bordeaux region (Jones and Davis 2000) found that grape

Table 3 Correlation between the weather types and grape production and wine quality in the area of DO Rías Baixas for the different phenological stages of the grape: bud break, bloom and véraison for 1987–2009

	NE	E	SE	S	SW	W	NW	N	C	A
Grape production										
Bud break	−0.13	−0.17	−0.06	−0.02	0.14	0.03	−0.07	−0.12	−0.42**	0.44**
Bloom	−0.14	−0.08	−0.09	0.47**	0.38**	0.1	−0.07	0.02	0.14	−0.36**
Véraison	−0.1	0.01	−0.19	−0.37**	0.06	−0.27	−0.34*	−0.44**	−0.27	0.31*
Wine quality										
Bud break	−0.15	0.09	0.31*	0.04	−0.11	−0.16	−0.24	−0.06	−0.31*	0.21
Bloom	0.07	0.25	0.2	0.61**	0.19	−0.09	−0.34*	0.23	0.2	−0.51**
Véraison	0.11	0.02	−0.06	−0.16	−0.37**	−0.31*	−0.41**	−0.11	−0.36**	0.51**

** Correlations statistically significant at 95 % and * correlations statistically significant at 90 %

production and wine quality in general diminished with the increased incidence of cloudy or humid weather, while it improved with hot and dry conditions. Our analysis shows that the case of Rías Baixas is similar, apart from during the bloom stage, when humid conditions are beneficial and anticyclonic conditions are therefore not helpful. It is noteworthy that during this period, the average rainfall is higher in Bordeaux than in Rías Baixas, and for this reason, more humid conditions can benefit Rías Baixas.

Our results for NAO can be compared with those obtained for an area located on the west coast of Portugal (Esteves and Orgaz 2001), in which the authors showed a positive correlation with the wine quality for NAO in April. In our case, this positive correlation has been obtained for June and July. This difference may be explained in terms of the different correlations between the NAO and climate in this area and Galicia, which is a transitional region in this respect. The difference between the two areas can also clearly be seen in the calculations of the different indices for the whole of Europe (Santos et al. 2012).

Trends in temperature and rainfall for DO Rías Baixas during the twentieth century and twenty-first century

Trends with weather station data

In the light of climate change, it is interesting to analyse whether the changes observed to date in precipitation and temperature are having any effect on the characteristics of winegrowing areas. Previous studies on the Euro-region Galicia-North Portugal (Gomez-Gesteira et al. 2011) have shown positive trends in spring and summer temperatures and positive trends in spring rainfalls. This could be of benefit to the development of the vineyards during the bud-break and bloom stages. For the autumn, no significant trends in temperature are seen, but a slight positive trend in rainfall is observed. The effect of these trends on grape production and wine quality must be analysed by means of the indices used in viticultural zoning.

For this analysis, we considered three bioclimatic indices commonly used in previous works for viticultural zoning, namely the Winkler index, the Huglin index and the BBL index. These indices were calculated for three different meteorological stations representative of each of the sub-areas of production of DO Rías Baixas, namely Ribadumia, Rosal and Ponteareas-Canedo (the Ribadumia station represents Salnés, Rosal represents the sub-area of the same name, and Ponteareas-Canedo represents Condado, see Fig. 1). We also calculated the indices for Lourizán, which provided the longest time series for this area. The values obtained by the Winkler index place Rías Baixas in Region I, this being the coolest region (Amerine and Winkler 1944).

The correlation between this index and productivity and quality is significant, as shown in Table 4. Ribadumia station shows a positive correlation with production with a value of 0.55. This value rises to 0.62 if we take the quality of wine into account. If we look at the correlations with Rosal station, we can see that the values are almost the same as for the case of Ribadumia, with 0.50 for the correlation between Winkler index and production, and 0.55 for the correlation with quality. Finally, the station at Ponteareas-Canedo shows a somewhat lower correlation with productivity with a value of 0.43, although this is still significant at the 95 % level. This lower value may reflect the fact that this sub-area is not representative of the general climatic conditions, because the oceanic influence is not as strong in this region as it is elsewhere in the domain. However, the correlation is significant for the wine quality, with a value of 0.61, which is similar to that of the other sub-areas (Table 4). Similar results were found for the Lourizán station for the period 1987–2005.

The Huglin index provides similar results to the obtained with Winkler index, with positive correlations (significant at the 95 % level) both for production and quality. The values obtained for this index range between 1,600 and 2,200 which situates the DO Rías Baixas somewhere between cool and temperate climate.

The BBL index shows values greater than 2,000 for our stations, which implies that Rías Baixas DO could be at risk of exposure of its vines to diseases such a downy mildew. We calculated the correlations between the hydrothermic index BBL obtained for the four stations considered and grape production and wine quality. This index takes into account not only temperature but also precipitation patterns. In Table 4, it can be seen that the correlations between grape production and wine quality with the hydrothermic index of BBL are negative. This is because this index considers the amount of rainfall and reflects the detrimental role of the accumulated rainfall on the maturation of the grapes and the appearance of mildew. An increase in rainfall produces a greater value of the index, and this implies a greater likelihood that the vineyards will be affected by mildew. Mildew is one of the best known and most serious diseases of vines, because under certain environmental conditions, it can attack all the green organs in the vineyard, causing losses of up to 50 % or more of the crop. It is caused by the fungus Plasmopara viticola and appears in regions where the climate is hot and humid during the period of vegetative growth.

We have also analysed the trend of these three indices for the period 1958–2005 (Fig. 2). These indices were calculated using only the values of temperature and rainfall of the Lourizán station. Data from this station are strongly correlated with those of the other stations considered (values of correlation >0.96; Lorenzo et al. 2008). The results obtained after applying the Mann–Kendall test to the series of the last 48 years show a significant positive trend at the 95 % level in the Winkler index and 99 %in the Huglin index, which suggests that the thermal conditions for the development and maturation of grapes are improving. These results are in agreement with previous findings for Europe (Santos et al. 2012).

Table 4 Correlation for the Winkler and Huglin indices, and for the BBL index calculated for the three stations representing the different sub-areas of DO Rías Baixas, with quality and production for 1987–2005

	Ribadumia	Rosal	Ponteareas-Canedo	Lourizán
Winkler index				
Grape production	0.55**	0.50**	0.43**	0.59**
Wine quality	0.62**	0.55**	0.61**	0.72**
Huglin index				
Grape production	0.58**	0.45**	0.40**	0.57**
Wine quality	0.60**	0.51**	0.52**	0.62**
BBL index				
Grape production	−0.36*	−0.60**	−0.38*	−0.41**
Wine quality	−0.31*	−0.55**	−0.38*	−0.39**

** Correlations statistically significant at 95 % and * correlations statistically significant at 90 %

Trends with regional climate model projections

The previous results obtained with weather station data lead us to think that one would expect changes in the categorisation of wine if the present rates of Winkler and Huglin indices continues into the twenty-first century. To study if these trends will continue in the coming decades, four models of the Ensembles project were considered to calculate the evolution of the three bioclimatic indices in the period 1961–2091 in Lourizán nearest grid point. This larger period was divided in two sub-periods: 1961–1991 and 2061–2091. The comparison between these two periods shows a significant increase in the indices related with the accumulation heat, namely, Winkler and Huglin (Table 5). This increase in temperature can lead to changes in regional categorisation, according to Winkler and Huglin index, leading to potential changes on the election of the grape varieties and wine styles. Meanwhile, there is also a decrease in the value of the BBL index, possibly associated with a decrease in rainfall. This change could diminish plant health spending in the future by reducing the possibility of attacks by pests such as the mildew.

The average trend and its standard deviation predicted by the 4 models for the period 1961–2091 can been seen in Fig. 3 where there is a higher uncertainty in the BBL index than in the other indices. This is because this index depends highly on rainfall that has large uncertainties in climate models. It should also be noted that the indices show values slightly smaller than those obtained with real data station (see Fig. 3). This may be because the models predict with reasonable accuracy the average values of temperature but it is more difficult to predict extreme values, and the Winkler and Huglin indices are calculated using 10 °C as base temperatures. In particular, most of the models of Ensemble project underestimate temperatures in particular the maximum temperatures (https://sites.google.com/site/rt3validation/). If we compare values of the Huglin index obtained with real data with the results of the model (Fig. 3), we can appreciate a significant bias that is maintained for the future projections. Besides the inner uncertainty of models, it must be noted that in this case, there are other uncertainties linked to bioclimatic indices. Those indices have been developed to take into account, in a synthetic way, the characteristics of a certain area to develop viticulture. They are used to made up zonification studies, but the application to a certain area, as the one studied in this paper may be taken with caution, because local details such as grape species or soil characteristics may also change in the future. Nevertheless, the main result is that the trends are confirmed which means that we might

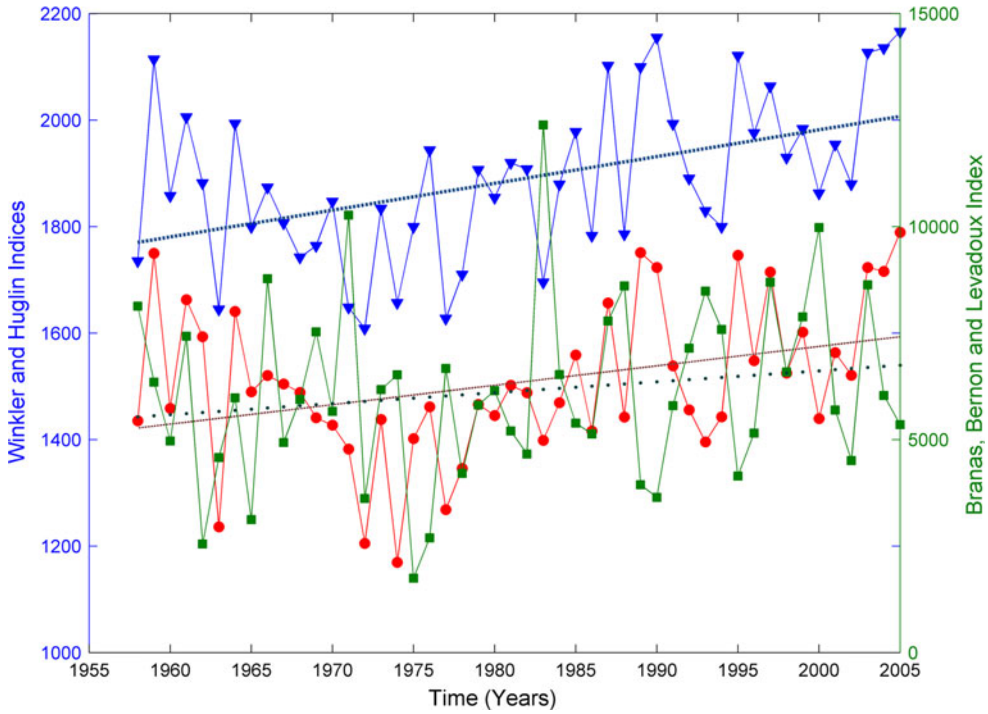


Fig. 2 Annual evolution and long-term trends of three bioclimatic indices for 1958–2005: The Winkler index shows a positive trend of 36 growing degree days per decade at the level of 95 % (*line with circles* and *thin slope with dashed line*), the Huglin index shows a positive trend of 50 units per decade at the level of 99 % (*line with triangles* and *wide slope with dashed line*), and the BBL index shows a non-significant trend (*line with squares* and *slope with dotted line*)

Table 5 Differences averages of the four models and the ensemble of them between 2061 and 2091 period minus and 1961–1991 period for the three agroclimatic indices calculated at the point nearest to Lourizán station

Models	Winkler index	Huglin index	BBL index
BCM-RCA	384**	368**	−1,163**
ECHAM5-RCA	579**	556**	−2,234**
ECHAM5-REMO	526**	485**	−8,560**
HADCM3-RCA	662**	642**	−576*
Ensemble mean	538**	512**	−3,134**

** Significant differences at level 95 %,* significant differences at level 99 % using a Wilcoxon rank sum test

expect in the coming years higher indices of Winkler and Huglin and lower BBL index in the region of Rias Baixas. With these trends, the DO Rías Baixas could in future belong to the Warm Temperate region as defined by the Huglin index, and this would allow the introduction of new varieties of grape in this region.

Conclusions

Agriculture in general and viticulture in particular are strongly influenced by climate. In the present paper, we have investigated the relationships between climatic variability and grape production and wine quality in the DO Rías Baixas. Our main conclusions are as follows:

- There are significant positive correlations between temperature and grape production and wine quality in the area. Rainfall has a negative correlation apart from during the bloom period when rainfall is beneficial.
- The NAO and EA/WR teleconnection patterns have a positive correlation with grape production in the bud-break phenological stage. Considering the quality of the wine, we have seen a positive correlation between the NAO index and grape production, but only during the bloom stage. During the véraison stage, we found a negative correlation between grape production and EA/WR.
- Day-to-day variations in weather also influence both grape production and wine quality. Thus, S and SW circulation types are beneficial when they appear during the bloom stage, but S types cause damage during

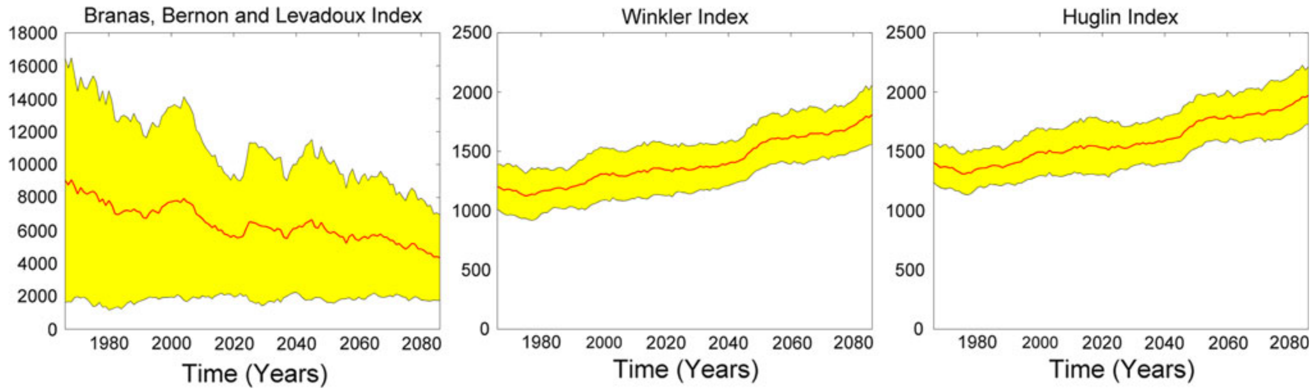


Fig. 3 Values for the period 1961–2091 of the three agroclimatic indices. The *wide solid line* represents the average of the 4 models, and the *shaded region* represents the dispersion. The trends of the average of the 4 models are positive in the case of Winkler and Huglin index (53 and 51 units per decade, respectively) and negative in the case of BBL index (−300 units per decade), in all cases are significant at level 95 % using a Mann–Kendall test

véraison. NW and N types are also harmful in this final phenological stage. C types are detrimental in bud-break stage, and A types are positively correlated with grape production during bud break and véraison, but the correlation is negative during the bloom stage. Wine quality correlations are similar, considering again the harmful role of A types during the bloom stage that then become favourable during véraison. In this last stage, C, NW and SW types are negatively correlated with quality due to the rainfall and low temperatures associated with them at this time.

- In the analysis of weather station data, the Winkler index shows that the DO Rías Baixas is located in Region I, while the Huglin index shows that the region is classified between Cool and Temperate. The hydrothermic BBL index shows values in excess of 2000. As expected, a significantly negative correlation was found between it and grape production and wine quality. At the same time, there is a strongly positive correlation for the Winkler index, which reflects the heat accumulated between April and October. Moreover, the trends in temperature in recent decades have caused a positive significant trend in the Winkler and Huglin indices, while the BBL index shows no significant trend because there has not been a clear trend in precipitation in the region. If maintained, those trends imply that Rías Baixas will be a warm temperate area in future decades.
- In the analysis of climate models, a significant increase in the values of the Winkler and Huglin indices at the end of twenty-first century and a decrease in the BBL index is observed for the scenario A1B. Although more analysis must be done with more models and scenarios, the results confirm a warming of the area with less precipitations. This means a change in the categorisation of the DO Rias Baixas and it could allow the introduction of new varieties of grapes in the next decades. On the other hand, these changes could incorporate possible mitigation strategies through cultivation methods. The main result of this study would be that the varietal spectrum of the DO Rías Baixas could change substantially since the suitability for the cultivation of a given cultivar is largely temperature driven.

Our findings have allowed the characterisation of the relationship between different climatic factors and grape production and wine quality in DO Rías Baixas and to infer trends associated with climate change that suggest better conditions in future for the development and maturation of crops.

Acknowledgments This work was supported by the Xunta de Galicia under Research Grant No. 10PXIB383169PR and cofinancing by European Regional Development Fund (FEDER). J. J. Taboada acknowledges the financial support from the Department of Environment of the Galician Government (Xunta de Galicia).

References

Amerine MA, Winkler AJ (1944) Composition and quality of musts and wines of California grapes. Hilgard 15:493–673

Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low frequency atmospheric circulation patterns. Mon Weather Rev 115:1083–1126

Blanco D, Queijeiro JM, Jones GV (2007) Spatial climate variability and viticulture in the Miño River Valley of Spain. Vitis 46:63–70

Camps JO, Ramos MC (2010) Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-east Spain with a Mediterranean climate. Int J Biometeorol. doi:10.1007/s00484-011-0489-3

Camps JO, Ramos MC (2011) Grape harvest and yield responses to inter-annual changes in temperature and precipitation in an area of north-east Spain with a Mediterranean climate. Int J Biometeorol. doi:10.1007/s00484-011-0489-3 de Blij HJ (1983) Geography of viticulture: rationale and resource. J Geogr 82:112–121

deCastro M, Lorenzo MN, Taboada JJ, Sarmiento M, Álvarez I, Gomez-Gesteira M (2006) Teleconnection patterns influence on precipitation variability and on river flow regimes in the Miño River basin (NW Iberian Peninsula). Clim Res 32:63–73

Duchêne E, Schneider C (2005) Grapevine and climatic changes: a glance at the situation in Alsace. Agron. Sustain. Dev. 25:93–99. doi:10.1051/agro:2004057

Esteban-Parra MJ, Rodrigo FS, Castro-Diez Y (1998) Spatial and temporal patterns of precipitation in Spain for the period 1880–1992. Int J Climatol 18:1557–1574

Esteves MA, Orgaz MDM (2001) The influence of climatic variability on the quality of wine. Int J Biometeorol 45:13–21

Gimeno L, Ribera P, Iglesias R, de la Torre L, García R, Hernández E (2002) Identification of empirical relationships between indices of ENSO and NAO and agricultural yields in Spain. Clim Res 21:165–172

Gomez-Gesteira M, Gimeno L, deCastro M, Lorenzo MN, Alvarez I, Nieto R, Taboada JJ, Crespo AJC, Ramos AM, Iglesias I, Gómez-Gesteira JL, Santo FE, Barriopedro D, Trigo IF (2011) The state of climate in North-West Iberia. Clim Res. 48:109–144. doi:10.3354/cr00967

Goodess CM, Palutikof JP (1998) Development of daily rainfall scenarios for southeast Spain using a circulation-type approach to downscaling. Int J Climatol 18:1051–1083

Gouveia C, Liberato MLR, 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

Huglin P (1978) Nouveau mode d'évaluation des possibilities héliothermiques d'un milieu viticole. CR Acad Agric Fr 64:1117–1126

Jenkinson AF, Collison FP (1977) An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memorandum No. 62, Meteorological Office, Bracknell

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. Geosci Can Repr Ser 9. Geological Association of Canada, St. John's

Jones GV, Davis RE (2000) Using a synoptic climatological approach to understand climate—viticulture relationships. Int J Climatol 20:813–837

Jones PD, Hulme M, Briffa KR (1993) A comparison of Lamb circulation types with an objective classification scheme. Int J Climatol 13:655–663

Jones GV, Duchêne E, Tomasi D, Yuste J et al (2005a) Changes in European winegrape phenology and relationships with climate. In: Proceedings of the Groupe d'Etude des Systèmes de Conduite de la vigne (GESCO 2005), Geisenheim

Jones GV, White MA, Cooper OR, Storchmann K (2005b) Climate change and global wine quality. Clim Change 73:319–343

Kendall MG (1975) Rank correlation methods. Griffin, London

Lorenzo MN, Taboada JJ (2005) Influences of atmospheric variability on freshwater input in Galician Rías in winter. J Atmos Ocean Sci 10:377–387

Lorenzo MN, Taboada JJ, Gimeno L (2008) Links between circulation weather types and teleconnection patterns and their influence on precipitation patterns in Galicia (NW Spain). Int J Climatol 28:1493–1505

Mann HB (1945) Nonparametric tests against trend. Econometrica 13:245–259

Nakićenović N, Swart R (2000) Special report on emissions scenarios: a special report of Working Group III of the intergovernmental panel on climate change, Cambridge University Press, ISBN 0-521-80081-1, 978-052180081-5 (pb: 0-521-80493-0, 978-052180493-6)

Ramos AM (2012) Improving circulation weather type classifications using a 3D framework: relationship with climate variability and projections for future climates. Dissertation, University of Vigo

Ramos MC, Jones GV, Martínez-Casasnovas JA (2008) Structure and trends in climate parameters affecting winegrape production in northeast Spain. Clim Res 38:1–15

Rodó X, Baert E, Comín FA (1997) Variations in seasonal rainfall in Southern Europe during the present century: relationships with the North Atlantic Oscillation and the El Niño-Southern Oscillation. Clim Dyn 13:275–284

Rodríguez-Puebla C, Encinas AH, Nieto S, Garmendia J (1998) Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. Int J Climatol 18:299–316

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

Santos JA, Malheiro AC, Pinto JG, Jones GV (2012) Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Clim Res 51:89–103

Schultz HR, Jones GV (2010) Climate induced historic and future changes in viticulture. Journal of Wine Research 21:137–145

Taboada JJ, Lorenzo MN, Gimeno L (2009) Variabilidade e tendencias na escala sinóptica. Evidencias e Impactos do Cambio Climático en Galicia. Xunta de Galicia

Tonietto J, Carbonneau A (2004) A multicriteria climatic classification system for grape-growing regions worldwide. Agric Meteorol 124:81–97

Trigo RM, DaCamara CC (2000) Circulation weather types and their influence on the precipitation regime in Portugal. Int J Climatol 20:1559–1581

Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the Northern Hemisphere Winter. Mon Wea Rev 109:784–812

Zorita E, Kharin V, von Storch H (1992) The atmospheric circulation and sea surface temperature in the North Atlantic area in winter: their interaction and relevance for Iberian precipitation. J Clim 5:1097–1108