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ORIGINAL ARTICLE

Present and future climate conditions for winegrowing in Spain

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Abstract This study deals with the question of how winegrowing in Spain may be altered by anthropogenic climate change. The present state and expected future development of three bioclimatic indices relevant for winegrowing were assessed by observation, and four regional climate models from the EU-ENSEMBLES project were investigated. When comparing the 2061–2090 scenario period to the 1961–1990 reference period, the models unanimously indicate a significant increase in the mean of the two considered thermal indices over the entire study region. However, for the index based on temperature and precipitation, the models are heavily biased when verified against observations and generally disagree on the size of the projected future change. For this index, unanimous model agreement was only found for northwestern Spain where all models indicated a significant decrease in the mean. From these results, regional climate change is expected to negatively affect the quality of wine in the growing regions of central and southern Spain, and the Ebro valley, whereas positive effects should be expected in the northwest. No significant changes in the risk of mildew infestation are to be expected except for the northwest, where this risk is projected to decrease.

Keywords Viticulture · Spain · Regional climate models · Winkler index · Huglin index · Hydrothermic index of Branas · Bernon and Levadoux · Climate change

Introduction

The impact of climate on grapevine phenology, composition, production, and quality is commonly described in terms of air temperature and precipitation (Coombe 1987; Jones and Davis 2000; Webb et al. 2007; Camps and Ramos 2011; Santos et al. 2012). The mean temperature of the growing season ranges between 12 and 22 °C (Jones 2006), with an optimal vegetative response to daily average values of between 20 and 35 °C (Gouveia et al. 2011). When the 35 °C threshold is exceeded, vegetation activity is reduced and vineyards may suffer serious and permanent damage (Berry and Björkman 1980; Sepúlveda et al. 1986). Water resources and availability are key factors affecting vineyard productivity (Carbonneau et al. 1992; Deloire et al. 2004), and an excess of humidity favors pests and infestation with downy or powdery mildew (Winkler et al. 1974; Conradie et al. 2002; Centeno et al. 2010). For several European growing areas, Jones et al. (2005) observed an advance in the phenological stages, a shortening of the phenological intervals, and an increase in potential wine quality due to anthropogenic climate change. Furthermore, climate change may require a rearrangement of the growing areas, and wine production

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might become profitable in currently disadvantaged regions (Bock et al. 2011; Santos et al. 2012; Fraga et al. 2013). A comprehensive overview of how anthropogenic climate change may affect the European viticulture is available in Fraga et al. (2012).

In Spain—the region of interest in the present study—there are currently 89 wine production areas. Sixty-seven of them have "Denomination of Origin" status, two have "Denomination of Origin Qualified" status, six are quality wines with a geographical indication, and 14 have a "Wine Appellation", i.e., they strictly follow the EU directives for production, enological practices, and quality control. Due to favorable climate and soil characteristics, and a large variety in topographic aspects and planted grape cultivars, Spain is currently one of the most suitable regions for the production of high-quality wines (van Leeuwen et al. 2004), a status that might be altered by ongoing anthropogenic climate change (Déqué et al. 2012; Lorenzo et al. 2013). Despite this threat, a clear consensus on how climate change is likely to affect winegrowing in Spain is lacking at the stakeholder level and practical decisions are still taken on the basis of personal perception and experience rather than empirical data analysis.

The present study aims to fill this knowledge gap by, firstly, mapping the climatological mean value combination of three bioclimatic indices relevant for winegrowing (two indices are based purely on temperature, and one is based on temperature and precipitation), thereby obtaining a high spatial resolution of the current climate conditions relevant to winegrowing in the study region. The applied index values were derived from the observational dataset Spain02 (Herrera et al. 2012), which, in comparison with the Europe-wide dataset E-OBS (Haylock et al. 2008), was built on a much denser observational station network, making it the preferable dataset for this study.

Secondly, four regional climate models (RCMs) driven by global climate model (GCM) control runs (hereafter referred to as "control integrations") were assessed with respect to their capability to reproduce the observed climatology of the three bioclimatic indices (as represented by Spain02). This capability will hereafter be referred to as "model performance" (Giorgi and Francisco 2000).

Thirdly, the A1B emission scenarios (Nakicenovic and Swart 2000) of the RCMs mentioned above (hereafter: "scenario integrations") were used to generate climate change projections for the three viticultural indices until the end of the twenty-first century. There was an apparent relationship between the models' performance for present climate conditions and agreement on the magnitude of the potential climate change. The latter measure is commonly used to describe the uncertainty in climate change projections (Déqué et al. 2012).

Several previous studies have assessed the influence of climate variability on viticulture, and they developed climate projections tailored to winegrowing at different locations in the Iberian Peninsula (Gouveia et al. 2011; Lorenzo et al. 2013). The full spatial coverage provided by the datasets applied here allows us to obtain this information for all of Spain.

The study is outlined as follows: In "Description of the bioclimatic indices relevant to winegrowing" section, the applied bioclimatic indices are defined. In "Data" section, the datasets are introduced. The results are presented in "Results" section, and a discussion and some concluding remarks are given in "Discussion and conclusions" section.

Description of the bioclimatic indices relevant to winegrowing

The three bioclimatic indices relevant to winegrowing applied here were (1) the Winkler index (WI, Winkler et al. 1974), (2) the Huglin index (HI, Huglin 1958), and (3) the hydrothermic index of Branas, Bernon, and Levadoux (BBLI, Branas et al. 1946). They have been frequently applied in previous studies (Jones et al. 2010; Santos et al. 2012).

The WI and HI indices are based on the concept of heat accumulation and pertain to the degree-day indices group. Both indices classify different viticultural regions in terms of temperature sums, i.e., they specify if a given region fulfills the thermal demands required for the growing and ripening of a specific variety. Furthermore, the HI can be used to estimate the potential grape sugar content, which is associated with the quality of the wine. Finally, the BBLI index measures moisture surpluses or deficits (Blanco-Ward et al. 2007).

The WI index is defined as the sum of the daily mean 2 m air temperatures (T_{mean}) during the April to October season, subtracting 10 °C on each day (Amerine and Winkler 1944). Daily mean temperatures can be derived from maximum and minimum temperatures ($T_{\max}$, $T_{\min}$):

$$\mathrm{WI} = \sum_{1\mathrm{April}}^{31\mathrm{October}} \frac{1}{2}\left(T_{\max} + T_{\min}\right) - 10 \tag{1}$$

Hence, WI measures the heat accumulation during the growing season.

The Huglin index (HI, Huglin 1958) is defined as the sum of the daily mean and maximum air temperatures during the April to September season, subtracting 10 °C on each day from both variables. The sum is then weighted by the average April to September daylight hours at the latitude of interest (d):

$$\mathrm{HI} = \sum_{1\mathrm{April}}^{30\mathrm{September}} \frac{1}{2}[(T_{\mathrm{mean}} - 10) + (T_{\mathrm{max}} - 10)] * d \quad (2)$$

Similar to WI, HI is a heat accumulation index that additionally takes into account the average daylight hours.

The hydrothermic index of Branas, Bernon, and Levadoux (BBLI) (Branas et al. 1946) takes into account the influence of both temperature and precipitation on grape yield and wine quality. This index is the sum of the products of monthly mean temperature (T_{mean}, in °C) and monthly accumulated precipitation amount (P_{amount}, in mm) during the April to August season.

$$\mathrm{BBLI} = \sum_{1\mathrm{April}}^{31\mathrm{August}} T_{\mathrm{mean}} P_{\mathrm{amount}} \quad (3)$$

Although the optimal climatic conditions for grapevine growth and wine quality differ from one variety to another, some general threshold values will be used here for the purpose of orientation. These values were partly derived for other regions (e.g., California) and are here assumed to be applicable to Spain as well. First, Jones (2006) found that the highest potential wine quality is typically obtained when the WI index values range between 1400 and 2000. Second, Malheiro et al. (2010) state that the risk of contamination with mildew, one of the most common and devastating vine diseases, is generally considered low for BBLI values below 2500 and elevated for values exceeding 5100.

Data

Daily temperature and precipitation data from the high-resolution dataset Spain02 (Herrera et al. 2012, publicly available from: http://www.meteo.unican.es/en/datasets/spain02, were used to calculate the observed climatologies of the three bioclimatic indices described above. The data were obtained for a regular 0.2° grid, and the climatologies were calculated for the period 1961–1991.

For comparison with the observed climatologies and for generating climate change projections, daily temperature and precipitation data from four control and A1B scenario integrations of the ENSEMBLES project (van der Linden and Mitchell 2009, publicly available from http://ensemblesrt3.dmi.dk) were used to calculate the three indices. These model data were obtained for a 25-km grid to which, for the sake of comparability, Spain02 was interpolated by using bilinear interpolation.

To assess the sensitivity of the results associated with the choice of the driving GCM, the Swedish Meteorological and Hydrological Institute's RCA model (Kjellström et al. 2005), driven by three distinct GCMs (BCM, ECHAM5, and HadCM3), was used. To assess the sensitivity associated with the choice of RCM, the Max Planck Institute for Meteorology's REMO model, driven by ECHAM5 (Jacob et al. 2001), was selected and the respective results were compared to the three RCA integrations. For ease of understanding, the four RCM-GCM combinations are hereafter referred to as BCM-RCA, ECHAM5-RCA, HadCM3-RCA, and ECHAM5-REMO, respectively. For more details on these climate models, the reader is referred to van der Linden and Mitchell (2009).

For each RCM-GCM combination, the twentieth-century control-run data over the period 1961–1991 and the A1B scenario-run data over the period 2061–2091 were considered. The control-run data (1961–1991) were used to evaluate whether the chosen RCMs were able to reproduce the observed climatological mean values of the three above-mentioned indices. Such an assessment of RCM "performance" (Giorgi and Francisco 2000) is relevant since model errors are indicative of model deficiencies in simulating relevant physical processes, which, in turn, may lead to unrealistic climate change projections (Räisänen 2007). The performance of a given RCM control integration is determined by (1) the RCM error itself, which is normally filtered out by driving it with reanalysis data assumed to provide "perfect" boundary conditions (Christensen et al. 2010; Kotlarski et al. 2014); (2) the driving GCM error (Rummukainen et al. 2001; Bedia et al. 2014); and (3) the error committed in the RCM-GCM coupling (Turco et al. 2013). The overall error resulting from these three sources was assessed in this study.

The A1B scenario-run data—covering the period 2061–2091—were used in conjunction with the control-run data mentioned above to obtain the climate change signal simulated by the RCMs by applying the commonly used "delta method": For each of the three considered bioclimatic indices, the mean value of the 1961–1991 control integration was subtracted from the mean value of the 2061–2091 scenario integration. These differences will hereafter be referred to as "delta-change estimates" or simply as "deltas." These deltas were added to the observed mean value obtained from Spain02 to obtain absolute index values for the 2061–2091 period. Here, it is assumed that the mean values simulated by the RCM control integrations are identical to the observed ones, which is a simple way to account for model bias (Lenderik et al. 2007).

Results

Bioclimatic indices in observations and regional climate models

Figure 1 shows the 31-year climatology for the three bioclimatic indices considered here (BBLI, WI, and HI from top to bottom). WI and HI will hereafter jointly be referred to as the "thermal" indices. The first column shows the observed values obtained from Spain02. The results for the respective RCM-GCM combination are shown in the remaining columns (2–5).

The observed climatology for BBLI reveals that the risk of infestation with mildew is generally low (BBLI < 2500) for almost the entire country except the north and the northwest. A sharp gradient is found between the interior of the country (Meseta) and the coastal regions in the north and northwest. The two regions are separated by mountain terrain, which is the key factor affecting the spatial distribution of precipitation in the study region. In some parts of the northern coastal regions, and particularly in the Basque country, BBLI values exceed the 5100 threshold, which indicates that the risk of mildew infestation is currently elevated (under present climate conditions). The similarity of the spatial patterns for BBLI and precipitation (see Figure S1 in the supplementary material) indicated that the BBLI was strongly related to precipitation.

The observed climatologies for WI and HI were similar to each other, and both were mainly determined by altitude/orography and latitude. These indices exhibited a north–south gradient as well as a clear separation between the northern and southern parts of the Meseta. With HI values ranging between 1400 and 2000, current thermal conditions were optimal in the Ebro valley and in the central and northern parts of the Meseta.

As can be seen from columns 2–5 in Fig. 1, the RCM control integrations (representative of the present-day climate simulated by the models) are able to roughly reproduce the observed spatial pattern of the thermal indices, but, with the exception of ECHAM5-REMO, suffer from a pronounced cold bias. For BBLI, i.e., the index based on both temperature and precipitation, the spatial patterns produced by the RCMs exhibit unrealistic wavelike structures which are caused by the model's failure to accurately simulate the climatological mean precipitation pattern. In fact, the unrealistic wavelike structures mentioned above are also visible in the simulated precipitation patterns (Figure S1 in the supplementary material). The generally poor BBLI model performance, particularly for precipitation, meant that the boundary conditions from ECHAM5 led to better results than the boundary conditions from HadCM3 and BCM.

To further assess the models' performance, a Taylor diagram (Taylor 2001) is provided in Fig. 2. This type of diagram provides a graphical summary on the similarity between the modeled and observed spatial patterns of a given variable (e.g., the 31-year mean WI index) in terms of (1) the Pearson correlation coefficient (r), (2) the centered root-mean-square difference (RMSD), where "centered" means that the difference is calculated for zero mean/anomaly fields, and (3) the ratio of standard deviations (*ratio*). Note that RMSD is additionally divided by the standard deviation of the reference Spain02 dataset to make the results of the three indices comparable. The Pearson correlation coefficient is a measure of the linear relationship between both patterns and is insensitive to the absolute difference between them, which is measured by RMSD, i.e., complementary information is provided by the two scores. Finally, *ratio* measures the similarity of the amplitudes for the spatial variations in the two fields. Values near to 1 indicate a close agreement, whereas values <1 (>1) indicate that the observed amplitude of spatial variations is increasingly underestimated (overestimated)

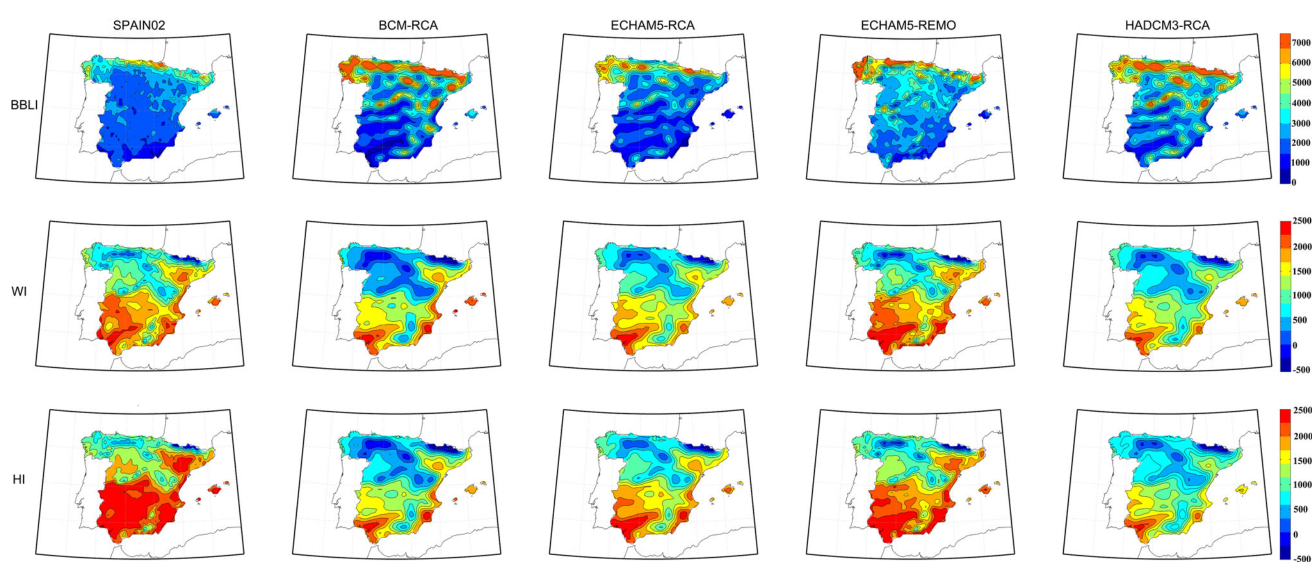


Fig. 1 Observed (*first column*) and simulated (*columns 2–5*) 31-year means of the BBLI, WI, and HI indices (1961–1991)

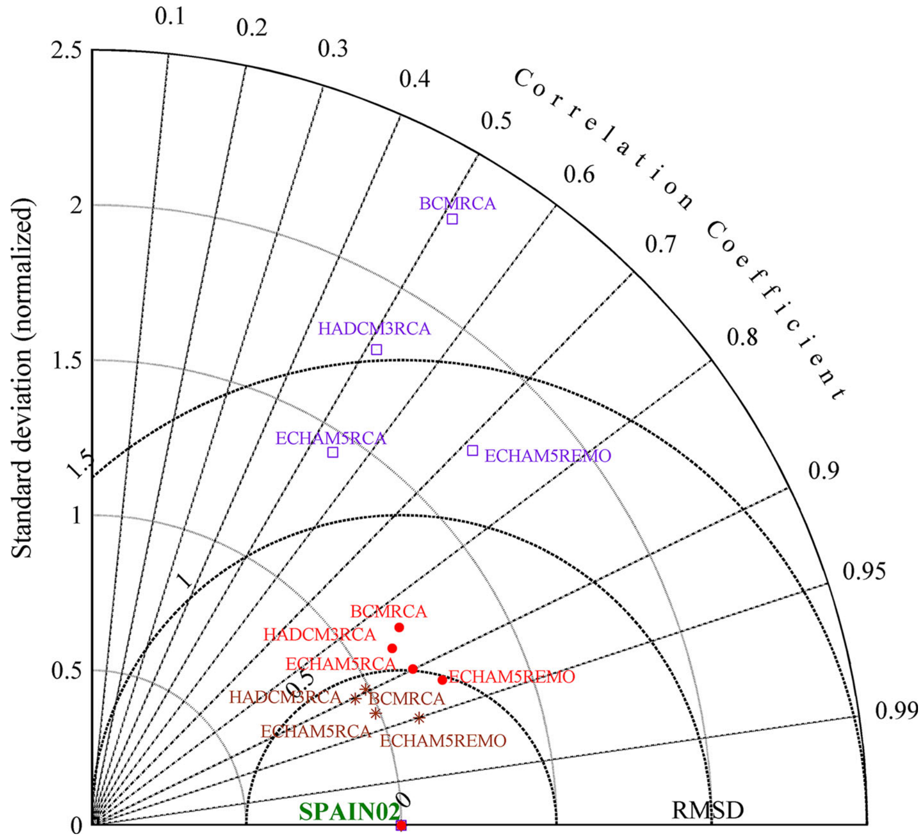


Fig. 2 Taylor diagram of model performance for the four applied RCMs versus Spain02 (1961–1991). The BBLI, WI, and HI indexes are displayed by *blue boxes*, *red points*, and *brown asterisks*, respectively (color figure online)

by the modeled value. In summary, a short distance to the reference point indicated by "Spain02" indicates high model performance and vice versa. The results for BBLI, WI, and HI are represented by blue boxes, red points, and brown asterisks, respectively. RMSD and *ratio* are indicated by dashed green circles and continuous gray circles, respectively, and r is represented by dashed blue lines.

For BBLI (blue boxes in Fig. 2), the unrealistic wave-like patterns shown in Fig. 1 translate into a systematic (i.e., valid for any of the four RCM-GCM combinations) overestimation of the amplitude of the spatial variations ($ratio > 1.4$), comparatively low Pearson correlation coefficients ($r \leq 0.7$), and large centered root-mean-square differences (RMSD $\geq$ 1.25). As pointed out above, the two RCMs driven by ECHAM5 perform better than those driven by HadCM3 or BCM. As shown in Fig. 3, the error locations for precipitation (within the Taylor diagram) are in close agreement with those obtained for BBLI, showing again that the errors for the latter index are mainly determined by the poor performance for precipitation.

In agreement with Fig. 1, the models perform systematically better for the two thermal indices than for BBLI (see Fig. 2). With $r \geq 0.95$, RMSD $\leq$ 0.5, and $ratio \sim 1$, the HI model performance is slightly better than the WI performance. Inter-model performance differences are clearly smaller for HI and WI than for BBLI. The RCMs driven by ECHAM5 perform better than those driven by HadCM3 or BCM, and BCM-RCA is the worst performing combination.

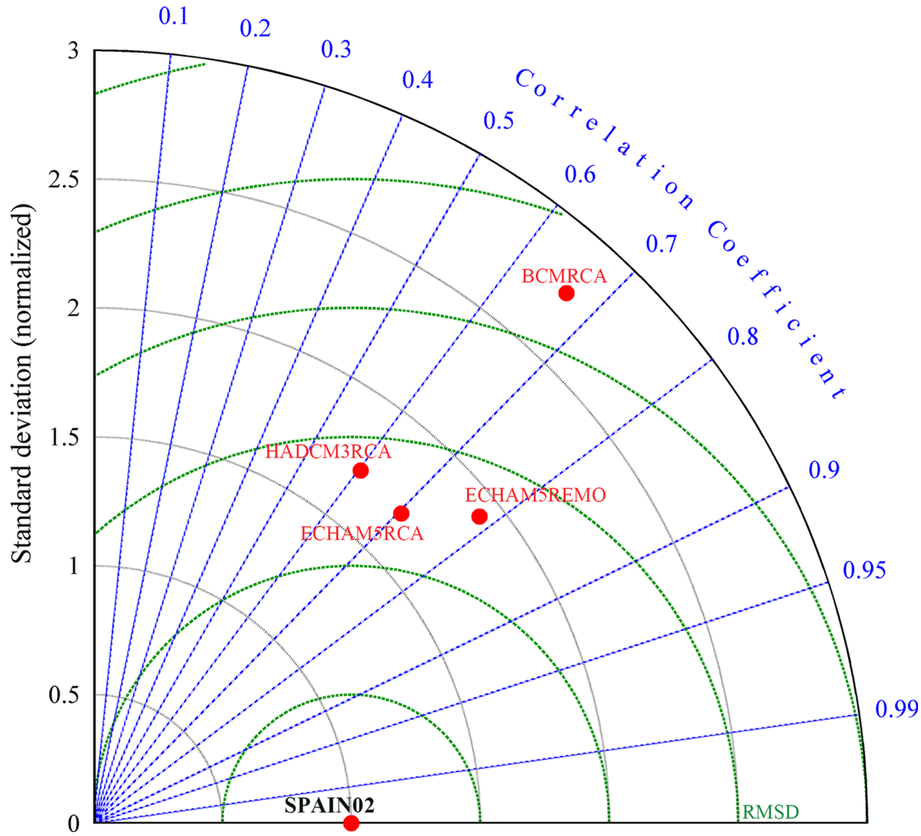
Bioclimatic indices under the A1B emission scenario

Figure 4 provides the maps for the delta-change estimate, defined as the 2061–2091 scenario integration mean minus the 1961–1991 control integration mean, i.e., they display the climate change projections in relative terms. Only the significant delta-change estimates (alpha = 0.05), obtained from a two-sided Wilcoxon rank-sum test, are shown. In contrast to the *relative* values shown in Fig. 4, Fig. 5 shows the corresponding results for the absolute index values between 2061 and 2091, obtained by adding the delta-change estimates to the observational mean values. The spatial averages of the observed and projected absolute index values, as well as the percentage deviations from the observed value (P), are provided in Table 1,

$$P = \frac{I_{\mathrm{A1B}} - I_{\mathrm{obs}}}{I_{\mathrm{obs}}} \times 100 \qquad (4)$$

where, for a given bioclimatic index I, I_{A1B} is the delta-change estimate added to I_{obs}, and I_{obs} is the observed climatological mean obtained from Spain02.

Fig. 3 As Fig. 2, but for precipitation



The four RCMs agree on the sign of the change for the spatial average values of the thermal indices, which is positive in each case (see Table 1). They also roughly agree on the magnitude of the change, with the projections differing by only 20 % at most (Table 1). The corresponding maps (Fig. 4) reveal that this increase is significant and widespread in all four RCMs. With absolute WI values in excess of 2000 index points (Fig. 5), the four RCMs indicate that the thermal conditions in central to southern Spain, as well as in the Ebro valley, would no longer be optimal for the production of quality wine, which is in contrast to the north and northwest, where thermal conditions would become more favorable. In particular, the "Rias Baixas" region in northwestern Spain is projected to pass the WI threshold of 1400, i.e., thermal conditions optimal for quality wine production would be reached.

The four RCMs agree that there will be a decrease in the spatial average of the projections for BBLI (Table 1). However, the projections differ by up to 37 %, which indicates that the agreement on the magnitude of change is much weaker than for the two thermal indices. The largest (smallest) decrease is projected by ECHAM5-REMO (BCM-RCA). The four RCMs agree on a large and significant decrease in spatial pattern of change for northwestern Spain (alpha = 0.05) (Fig. 4). In particular, values above 5100 disappear in the absolute projections (Fig. 5), which indicate that the risk of infestation with mildew would shift from "elevated" to "normal" in this region. For the remaining study area, three of the four RCMs agree on a spurious decrease in BBLI. Note that the unrealistic wavelike patterns found in the control integrations were also found in the delta-change estimates (Fig. 1 compared to Fig. 4). By adding the deltas to the observed values obtained from Spain02 (i.e., to the correct spatial pattern), the wavelike structures are partly corrected (Fig. 4 compared to Fig. 5).

These results are in agreement with the linear decadal trend of the modeled indices' annual mean values over the period 2010–2091 (Figures S2, S3, and S4 in the supplementary material). For BBLI, three of the four models agreed on a significantly negative trend in northwestern Spain where significance was tested with a two-sided Mann–Kendall test (Mann 1945). For WI and HI, the trends are significantly positive over all of Spain in the four models.

Discussion and conclusions

In this study, present-day climatologies for three bioclimatic indices relevant for winegrowing (Winkler, Huglin and Branas, and Bernon and Levadoux) were developed for

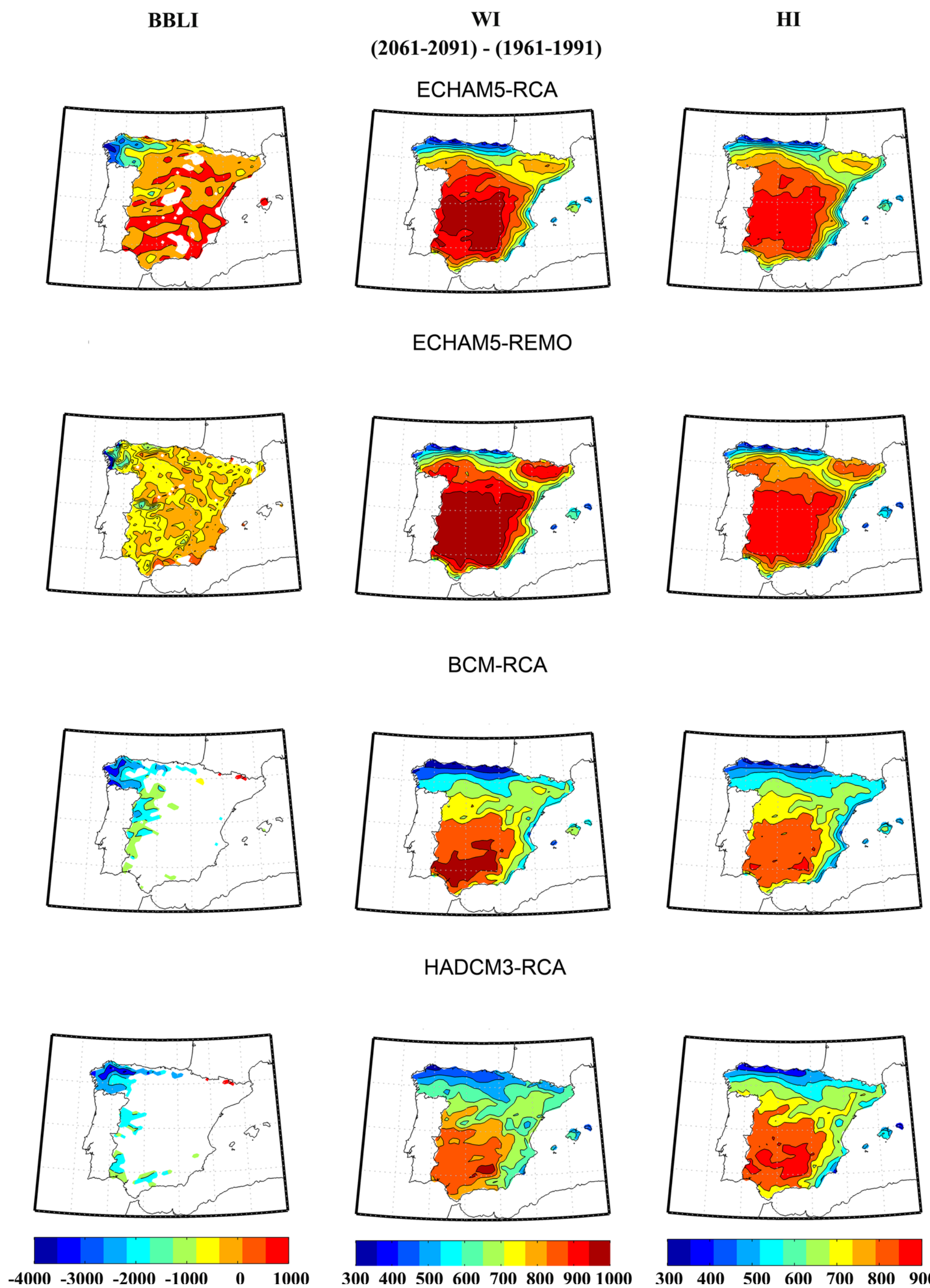


Fig. 4 Delta-change estimates obtained by subtracting the mean value of the RCM control integration (1961–1991) from the mean value of the A1B scenario integration (2061–2091). Only significant values (alpha = 0.05) are displayed

Spain, using the observational Spain02 dataset. Then, four regional climate models from the ENSEMBLES project were evaluated to assess how well they reproduced the observed climatologies. Finally, climate change projections for the twenty-first century were generated using the A1B emission scenario.

With respect to their ability to reproduce the observed present climate conditions, the RCM control integrations were found to perform systematically poorer for the index based on *both* temperature and precipitation (BBLI) than for the indices based on temperature *only* (WI and HI). The poor BBLI model performance was found to be associated with the poor performance for precipitation. The spatial patterns of both variables are characterized by unrealistic "wavelike" structures, which apparently are unique characteristics of the RCM control integrations (i.e., have not been documented for the RCMs driven by reanalysis data) and might be related to GCM errors (Brands et al. 2011) and/or errors in the coupling procedure (Turco et al. 2013). Since the erroneous wavelike patterns were also found in

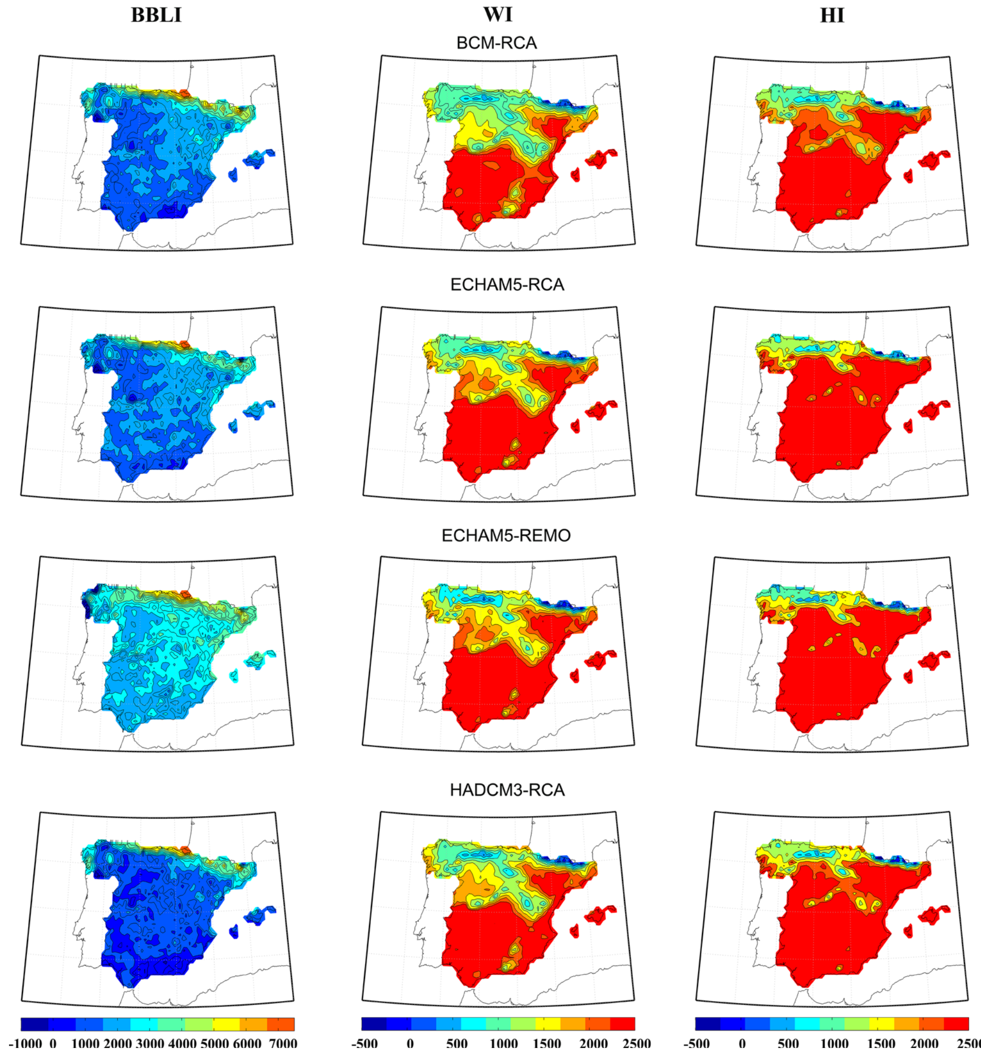


Fig. 5 Regional climate change projections for 2061–2091 (A1B) in absolute terms. Displayed are the delta-change estimates simulated by adding the RCMs to the 1961–1991 observational mean obtained from Spain02. The delta-change estimates are obtained by subtracting the mean value of the RCM control integration (1961–1991) from the mean value of the A1B scenario integration (2061–2091)

the delta-change estimates, it is the performance of the RCM control integration (and not of the RCM driven by reanalysis data), which should be used to judge the "credibility" of the respective climate change projections.

One might argue that RCM errors can be corrected ad hoc by using bias correction methods (e.g., Wilcke et al. 2013), as was done here. However, bias correction only offers a partial solution for this problem because RCM errors are probably caused by problems with the model physics and might not be constant in time.

For WI and HI, the four RCMs agree on a significantly positive delta-change estimate (i.e., an increase in the mean) as well as on a significantly positive long-term tendency affecting the entire study region. For BBLI, the models' agreement on the magnitude of climate change is much weaker than for the two thermal indices. An exception is the northwestern Iberian Peninsula where the four RCMs agree on a statistically significant decrease in the mean and three out of four RCMs agree on a significantly negative long-term trend. Hence, some confidence is provided for a decrease in the risk of mildew infestation in this region (Branas et al. 1946).

All RCMs agree on an intense increase in accumulated heat in central and southern Spain, which would negatively impact wine quality in these regions. Particularly in southern Spain, the excessive warming projected for the end of the twenty-first century would impede the production of high-quality wine and would hinder grapevine growth (Schultz 2000; Kenny and Harrison 1992; Jones et al. 2005). In previous studies, this excessive warming has been partly attributed to model deficiencies and the results presented here are probably affected by this type of error. However, the fraction of heating due to this error is relatively small when compared to the overall delta-change estimate (Boberg and Christensen 2012).

Regarding northwestern Spain, our results agree with those obtained from the region-specific analyses conducted in Lorenzo et al. (2013). They are also in agreement with

Table 1 Spatial averages of the three bioclimatic indices for (1) the observations taken from Spain02 (1961–1991 mean) and (2) the climate change projections obtained from adding the delta change (A1B 2061–2091 mean minus the control 1961–1991 mean) to the observed values from Spain02

HI				WI				BBLI			
Spain02 1961–1991	GCM-RCM	Spain02 1961–1991 +delta	Deviation	Spain02 1961–1991	GCM-RCM	Spain02 1961–1991 +delta	Deviation	Spain02 1961–1991	GCM-RCM	Spain02 1961–1991 +delta	Deviation
2054	ECHAM5-RCA	2806	**+37**	1592	ECHAM5-RCA	2342	**+47**	2796	ECHAM5-RCA	1958	**−30**
	ECHAM5-REMO	2838	**+38**		ECHAM5-REMO	2402	**+51**		ECHAM5-REMO	1457	**−48**
	BCM-RCA	2548	**+24**		BCM-RCA	2087	**+31**		BCM-RCA	2502	−11
	HADCM3-RCA	2749	**+34**		HADCM3-RCA	2293	**+44**		HADCM3-RCA	2390	−15

Also shown is the percentage deviation from the observed value (see Eq. (4) in the text). Significant differences (alpha = 0.05) are in bold

the results found in Fraga et al. (2013) who found a decreasing risk of infestation with mildew due to climate change in southern Europe (including Spain) and further discussed the impacts of a drying and warming climate on winemaking in this region.

Focussing on Spain, our results indicate that climate change adaptation measures are particularly needed in the southern part of the country. This may include changing the grape varieties, applying irrigation, or displacing the growing areas to higher elevations, characterized by colder climate conditions. An overview of the adaptation strategies currently applied at the national and transnational level is given by the European Climate Adaptation Platform (Climate-ADAPT, available at http://climate-adapt.eea.europa.eu/).

Northwestern Spain might benefit from the projected warming, which, in this region, would lead to an increase in potential wine quality. However, it is important to note that this benefit might vanish over longer timescales not assessed here (i.e., beyond 2100). On these timescales, the mean climate conditions in northwestern Spain might gradually become unfavorable for winegrowing. Similarly, and already on the timescales assessed here, a shift in the mean climate conditions may be accompanied by an increase in inter-annual variability (Schär et al. 2004; Rodríguez-Puebla et al. 2010; Fraga et al. 2013), which would negatively affect winegrowing in years experiencing large climate anomalies.

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