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Malbec viticultural zoning studies in Argentina based on the UCI bioclimatic index and bias-corrected CORDEX-CORE simulations

Cabré, M. F.[1 2]; Solman, S. A.[1 2 3]; Nuñez, M.[1 2 3]

[1]*Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) - Universidad de Buenos Aires, Centro de Investigaciones del Mar y la Atmósfera, Buenos Aires, Argentina*
[2]*Centro Nacional para la Investigación Científica de Francia (CNRS) - Instituto de Investigación para el Desarrollo (IRD) - Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET) - Universidad de Buenos Aires, Instituto Franco-Argentino de Estudios sobre el Clima y sus Impactos, Buenos Aires, Argentina*
[3]*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Buenos Aires, Argentina*

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Correspondence

María Fernanda Cabré
cabre@cima.fcen.uba.ar

Abstract

This study is the first to apply CORDEX-CORE simulations to analyze the climatic suitability for Malbec grape production (MGP) in Argentina, providing a foundation for future assessments under climate change scenarios. This zoning was evaluated through a Unique Combined Index (UCI) formed by four bioclimatic indices significantly related to MGP in Argentina[(20)]: three bioclimatic indices evaluated during the growing season, mean temperature (GST), accumulated precipitation (GSP), and mean thermal amplitude (GSTA), and one evaluated during the maturation month, March minimum temperature (CN). The models' performance was evaluated through the mean values spatial representation of UCI, GST, GSP, GSTA and CN. The modeled results were compared with the observed ones, the latter being considered the closest representation to reality. The indices were calculated with the maximum, minimum and average monthly temperature and monthly precipitation. Variables were corrected by a quantile mapping method, giving rise to a magnitude reduction of precipitation's overestimation and temperature's underestimation over northern Patagonia and mountainous regions as well as precipitation's underestimation and temperature's overestimation over the central-eastern area of Argentina. Finally, it was concluded that the bias-corrected CORDEX-CORE simulations satisfactorily reproduce the main characteristics of the observed MGP zoning. This motivates their use for future MGP zoning studies in Argentina, potentially useful information for climate change adaptation studies.

Keywords: Argentina, bioclimatic indices, Malbec, CORDEX-CORE simulations, viticultural zoning, climate suitability

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Estudios de zonificación vitivinícola Malbec en Argentina basados en el índice bioclimático UCI y en las simulaciones corregidas CORDEX-CORE

Resumen

Este estudio es el primero en aplicar simulaciones CORDEX-CORE para analizar la aptitud climática de la producción de uva Malbec (MGP) en Argentina, proporcionando una base para futuras evaluaciones de escenarios de cambio climático. Esta zonificación fue evaluada a través de un Índice Único Combinado (UCI) formado por cuatro índices bioclimáticos significativamente relacionados con la MGP en Argentina[20]: tres índices evaluados durante la estación de crecimiento, temperatura media (GST), precipitación acumulada (GSP) y amplitud térmica media (GSTA), y uno evaluado durante el mes de maduración, temperatura mínima de marzo (CN). El desempeño de los modelos fue evaluado a través de la representación espacial del valor medio de UCI, GST, GSP, GSTA y CN. Los resultados modelados fueron comparados con los observados, considerados estos últimos la representación más cercana a la realidad. Los índices fueron calculados con la temperatura máxima, mínima y media mensual y la precipitación mensual. Las variables fueron corregidas aplicando el método de quantile-mapping, dando origen a una reducción de la magnitud de la sobreestimación de la precipitación y de la subestimación de la temperatura sobre el norte de la Patagonia y las regiones montañosas, así como de la subestimación de la precipitación y de la sobreestimación de la temperatura sobre la zona centro-oriental de Argentina. Finalmente se concluye que las simulaciones corregidas CORDEX-CORE reproducen satisfactoriamente las principales características de la zonificación observada de MGP. Esto motiva su uso para estudios de zonificación futura de MGP en Argentina, información potencialmente útil para estudios de adaptación al cambio climático.

Palabras clave: Argentina, índices bioclimáticos, Malbec, simulaciones CORDEX-CORE, zonificación vitivinícola, aptitud climática

Estudos de zoneamento vitivinícola de Malbec na Argentina com base no índice bioclimático da UCI e simulações CORDEX-CORE corrigidas de viés

Resumo

Este estudo é o primeiro a aplicar simulações CORDEX-CORE para analisar a adequação climática para a produção de uva Malbec (MGP) na Argentina, fornecendo uma base para futuras avaliações em cenários de mudanças climáticas. Este zoneamento foi avaliado por meio de um Índice Combinado Único (UCI) formado por quatro índices bioclimáticos significativamente relacionados à MGP na Argentina[20]. Três índices avaliados durante a estação de crescimento, temperatura média (GST), precipitação acumulada (GSP); amplitude térmica média (GSTA), e um avaliado durante o mês de maturação, temperatura mínima de março (CN). O desempenho dos modelos foi avaliado por meio da representação espacial dos valores médios de UCI, GST, GSP, GSTA e CN. Os resultados modelados foram comparados com os observados, sendo estes últimos considerados a representação mais próxima da realidade. Esses índices foram calculados com a temperatura máxima, mínima e média mensal e a precipitação mensal. Variáveis corrigidas por um método de mapeamento quantílico, dando origem a uma redução da magnitude da superestimação da precipitação e da subestimação da temperatura sobre o norte da Patagônia e regiões montanhosas, bem como da subestimação da precipitação e da superestimação da temperatura sobre a área centro-leste da Argentina. Por último, concluiu-se que as simulações CORDEX-CORE com correção de viés reproduzem satisfatoriamente as principais características do zoneamento observado no MGP. Isto motiva o seu uso em futuros estudos de zoneamento do MGP na Argentina, informações potencialmente úteis para estudos de adaptação às mudanças climáticas.

Palavras-chave: Argentina, índices bioclimáticos, Malbec, simulações CORDEX-CORE, zoneamento vitícola, adequação climática

1. Introduction

The effect of climate change on wine-growing regions can be investigated through climate zoning studies, which allow for, among other things, identifying the impact of climatic factors on the geographical delimitation and characterization of wine-growing suitability of production areas. Therefore, a climate zoning study consists on the calculation of bioclimatic indices based on the use of information provided by regional or global climate models. A detailed review on this regard was made by Droulia and Charalampopoulos[1]. Numerous works can be found worldwide based on the use of regional climate models (RCMs)[2][3][4][5][6][7]; particularly many based on the CORDEX simulations[8][9][10][11] and a few ones on the CORDEX simulations with the highest available spatial resolution. For example, Castillo and others[12] and Chauke and Pongrácz[13] in Mexico and South Africa, respectively. This highlights the lack of viticultural zoning studies over South America and mainly over Argentina based on them. Additionally, a few viticultural zoning studies focused on specific grapevine varieties were emerging recently in New Zealand and Europe[14][15][16][17]. However, in our country, even in the case of finding works based on any given grapevine variety, such as the Argentinean Malbec[18][19], these are not from a viticultural zoning perspective. To summarize, the above justifies the present work, the first to apply the CORDEX-CORE simulations with zoning purposes for representing the current climatic suitability for Malbec Grape Production (MGP) in Argentina.

In addition to being the first work to apply the CORDEX-CORE simulations for analyzing the climatic suitability for MGP in Argentina, this work is a continuation of Solman and others[20], which defined the current viticultural zoning of the Malbec Grape Production (MGP) in Argentina. This zoning was assessed in terms of a regional index, namely Unique Combined Index (UCI, for its acronym in English), based on the co-variability of a set of bioclimatic indices and actual Malbec grape productivity taking into account that interannual climate variability affects interannual grape production. As a consequence, this affects yield[21] and quality of grapes and typicity of wines[22]. For this reason, the UCI index contributes uniquely to understanding the climatic suitability of Malbec in Argentina. Therefore, the UCI index can be considered as a new regional index that (a) enables the definition of a proper zoning index for MGP in Argentina, (b) allows to differentiate not suitable Argentinean MGP areas from those that are suitable, and if so, it allows to measure its diverse degree of suitability, and (c) can be used to assess the potential impact of climate change on MGP in the country. The UCI index is formed by 4 bioclimatic indices significantly correlated to MGP in Argentina. These bioclimatic indices are: the growing season mean temperature (GST[23]), the mean thermal amplitude during the growing season (GSTA), the cool night index (CN[24]), defined as the monthly mean minimum temperature during the month before harvest, and the precipitation accumulated during the growing season (GSP[25]). The correlation between these bioclimatic indices and MGP in Mendoza resulted positive for GST and GSTA, suggesting that warmer than normal conditions during the growing season are more favourable for MGP. On the other hand, negative correlations were found for CN and GSP, suggesting that lower minimum temperatures during March and dryer conditions during the growing season are more favourable for MGP. Although these four bioclimatic indices are commonly applied in other parts of the world, they have not been calibrated or evaluated for Malbec in our region. This is precisely what differentiates the UCI index from existing indices applied in other parts of the world. According to the above described, the UCI index contributes uniquely to understanding the climatic suitability of Malbec in Argentina.

Accordingly, with the aim of studying the problem of representing the Malbec grapevine zoning in Argentina in a context of climate change, it is necessary firstly to assess how regional climate models (RCMs) represent the current zoning of MGP. The study is based on the CORDEX-CORE simulations for the historical period available for the South American CORDEX domain[26]. The study focuses on evaluating if the bias-corrected CORDEX-CORE RCMs for South America are reliable enough to represent the current observed wine zoning of Malbec grapes in Argentina. Thus, the general motivation of our research is which would be the future geography of MGP in Argentina represented by the CORDEX-CORE simulations. Answering this question involves

two stages: the representation of the current Malbec viticultural zoning (present work) and future Malbec viticultural zoning for later evaluating its projected changes (future work in progress). Concluding, it is expected that the outcomes of these two stages give very useful information for designing long-term planning and/or adaptation strategies for viticultural zoning at regional scale, information relevant at the decision making process for having a sustainable development of the activity in a climate change context.

2. Materials and Methods

2.1 Studied Area

The study area covers the Argentinean territory defined between 43° S to 21° S and 72° W to 56° W. **Figure 1** shows the map of Argentina, with a rectangle indicating the study area assessed in this work (panel a), and a zoomed-in view of the study area with the name of main viticultural Argentinean provinces (panel b). Inside the study area the traditional winegrowing region is located over the central-western area of Argentina extending to eastern Andes. This area is divided into 3 main regions: (a) the Northwest Region, between 22° and 29° S (Jujuy, Salta, Tucumán, Catamarca) with heights from 750-3330 m above sea level (a.s.l.) elevation; (b) the Cuyo Region, between 29° and 36° S (La Rioja, Mendoza and San Juan) with heights from 430-2000 m a.s.l. elevation; and (c) the Patagonia Region, between 36° and 43° S (La Pampa, Neuquén, Río Negro), 4 to 670 m a.s.l. A new winegrowing region, of similar elevation heights, named Atlantic Region and located over southwestern Buenos Aires, between 38° and 40° S, completes the Argentinean wine map.

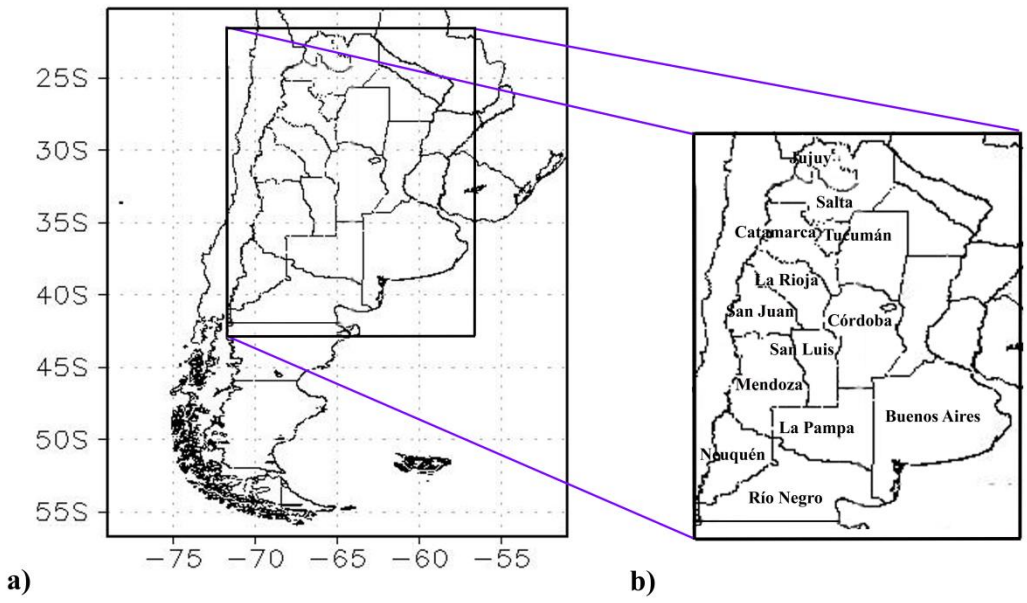

Figure 1. Map of Argentina, with a rectangle indicating the study area assessed in this work. (a) Map of the study region with the name of Argentinean provinces. (b) Only the provinces with viticultural relevance for this study were indicated in the map

2.2 Observed and Modeled Gridded Database and Climatic Variables

The database utilized was: (a) time-series of monthly data from the observational Climate Research Unit (CRU), time-series (TS), Version 3.21 (CRU TS3.21), period: 1901-2012, horizontal resolution of 0.5º × 0.5º; coverage: all land areas excluding Antarctica[27]; (b) time-series of monthly data from the CORDEX-CORE simulations[26], period: 1951-2005, horizontal resolution of 0.22º × 0.22º, coverage: South America. A horizontal resolution of 0.22° × 0.22° may be considered not enough for the needed spatial detail in vineyard scale

studies since the spatial resolution limits capturing microclimate features forced by topography or soil characteristics (texture, depth). Undoubtedly, higher resolution is desirable, but CORDEX-CORE is the only climatic information available, even if not able to capture microclimatic variability within wine-growing areas. The CORDEX-CORE simulations belong to the regional initiative within the Coordinated Regional Climate Downscaling Experiment, the CORDEX Project, for the South America domain. They are a set of regional climate models (RCMs) from the CORDEX Project designed to provide an equal number of simulations for all domains for the 6th Intergovernmental Panel on Climate Change Report[28]. The RCMs are nested in global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and consist on a set of 6 combinations RCM/GCM: composed by 2 RCMs (REMO2015 and RegCM4.7) nested in 3 GCMs (MPI, HadGEM2 and NorESM1). The acronyms of RCMs REMO2015 and RegCM4.7 will be referred to as REMO and RegCM, respectively, from now on. Detailed information about the CORDEX-CORE initiative can be found at Giorgi and others[29]. Reference bibliography about the CORDEX-CORE simulations assessment can be found at Teichmann and others[30] for their multiple domains and at Blázquez and Solman[31] for South America. Monthly mean, minimum and maximum temperature, and monthly accumulated precipitation were the climatic variables used for calculating the UCI index.

2.3 The UCI Index

The UCI index is a multi-criteria index accounting for thermal and humidity conditions that identifies the key bioclimatic indices and their optimum intervals for MGP in Argentina. From now on, the key bioclimatic indices will be referred to as the UCI's components. Three of them (GSTA, GSP and GSTA) are calculated during the growing season and one of them (CN) during the month before harvest, defined in the southern hemisphere as the 7 month-period (October-April) and March, respectively. The methodology for obtaining the UCI index, its components and equations was thoroughly explained in Solman and others[20]. The UCI index is defined as follows:

$UCI(k) = I_{GST}(k) + I_{GSTA}(k) + I_{CN}(k) + I_{GSP}(k)$ if every individual index ≠ 0
$UCI(k) = 0$ if any of the individual indices = 0

k indicates year

The values of UCI index range from 4 to 12 as minimum and maximum values, respectively. Value of UCI = 4 indicates that each component belongs to a limiting adverse climatic condition; while value of UCI = 12 indicates that each component belongs to optimum climatic conditions. Values of UCI ≤ 3 indicate that at least one of the UCI's components belongs to non suitable climatic conditions for MGP. The UCI index should be interpreted in terms of its absolute value: the larger (smaller) the value of UCI the better (worse) the climatic conditions for MGP, which in turn translate into greater (lower) viticultural aptitude or suitability. Accordingly, this index provides information about the degree of suitability, indicating where the climatic conditions are suitable for MGP and, furthermore, where this suitability is higher or lower.

2.4 Methodology

Since the Argentinean grapevine growing region is located close to a complex topography area, an elevation correction of monthly mean temperatures was first applied, considering the elevation of each grid point of the two RCMs. Even though RCMs simulations are considered the most reliable tool to represent the characteristics of the regional climate, the information coming from them is affected by systematic errors (biases). For this reason climate model data must be corrected for being reliable enough to be used in impact studies. Bias correction is a statistical technique to adjust the model output to better match the observed data. This technique is widely applied in impact studies (e.g. hydrology, agriculture), and viticultural ones are not exception[32][33][34][35]. A schematic explanation of the bias correction methodology can be found in Kim and others[36] (their **Figure**

2). Numerous methods have been developed from the simplest calibrating the mean to the more sophisticated ones adjusting all quantiles, either parametric or empirical, trend-preserving or not[37][38][39][40], being the quantile mapping one of the best available methodologies[41][42].

Since the evaluated RCMs present a systematic bias in both the mean temperature and precipitation[31], after applying the elevation correction, a bias correction method was implemented using CRU as the observational reference. The methodology used is known as quantile-based mapping[43], consisting of fitting the modelled empirical frequency distribution to the observed empirical frequency distribution for each variable at each grid point. Correction factors are calculated for each percentile, for temperature as the difference between the corresponding monthly value from the model and the observations, and for precipitation as the quotient between the corresponding monthly value of the model and the observations. The correction factors are then added to the modelled temperature for each percentile and multiplied by the modelled precipitation for each percentile. This bias-correction method was selected because, even though not being a multivariable one (that considers the inter-relation between variables), it is adequate for the monthly temporal scale used here. The methodology for calibration is simple, and it has been widely used elsewhere. In addition, this method is considered adequate for this study region. This is supported by the systematic error assessment (evaluation of model accuracy) of the climate variables needed for calculating the UCI's components (not shown) (an evaluation performed in terms of spatial pattern, magnitude and sign). But also, the evaluation of model accuracy was carried out for the UCI's components (shown here), which is in agreement with the previous one. In conclusion, all mentioned aspects support its application for this region. When referring to systematic error assessment it must be understood as a synonym of evaluation of model accuracy.

For applying the quantile-based mapping, two sets of data are required: (a) observation data considered unbiased; (b) climate model data to be corrected considered biased. The two data sets cover a common historical reference period that is the calibration period. Accordingly, monthly time series of climatic variables were prepared for the CORDEX-CORE simulations and the gridded CRU observations for the recent-past period (1975-2005), after bilinear interpolation of the RCMs data into the CRU grid. A calibration period of 21 years (1975-1995) was considered to calculate the correction factors and a period of 10 years (1996-2005) was considered for validating the bias correction methodology. Regarding the 21 years of calibration period, the justification of its selection is explained hereafter. It should be recalled that for applying a bias correction it is necessary to consider a sufficiently long time-period for calculating the correction factors for the climate variables for calibrating the bias correction methodology. A calibration period of 21 years (1975-1995) considers 20 growing seasons to calibrate the UCI's components. A 10 year-period (1996-2005) is then used for validating the bias correction methodology. The bias correction method was applied to the four climatic variables for each of the 6 RCM/GCM combinations and then the UCI's components were computed. In order to assess the impact of the systematic errors, the UCI's components were also computed from the raw model outputs. A comparison of individual RCM/GCM combination (raw and corrected) was performed for the UCI's components. Finally, the performance of the bias-corrected CORDEX-CORE simulations was assessed in terms of the spatial distribution of mean value of the UCI's components (GST, GSP, CN, GSTA) and the UCI index over the study region. The softwares, programming languages and tools used here were MATLAB, Fortran, Climate Data Operators (CDO) (https://code.mpimet.mpg.de/projects/cdo) for data processing and GrADS scripting language (http://cola.gmu.edu/grads/) for visualization.

3. Results

3.1 Figures and Tables

Figure 2 shows the spatial distribution of systematic errors of each UCI's component that were examined by comparing the raw and bias-corrected model outputs. It is observed that regardless of the UCI's components, systematic errors are quite large and the bias correction method effectively reduces the biases.

In general, a greater predominance of positive (warm) bias of GST and negative (dry) bias of GSP is observed over centre-eastern Argentina, and a greater predominance of negative (cold) bias of GST and positive (wet) bias of GSP is observed over northern Patagonia and areas of complex topography. Regardless of the two evaluated indices, the RegCM model has larger biases compared with the REMO model. However, even though the overestimations and underestimations do still persist after the correction's application, they are of smaller magnitude. Accordingly, a significant reduction of the warm and dry bias located over centre-eastern Argentina and the cold and wet bias located over the northern Patagonia and areas of complex topography was reached after the application of bias correction (**Figure 2** a, b). Summarizing, the bias correction's application reduces the range of the systematic error of GST and GSP, finding: |bias GST corr| ≤ 1 °C, |bias GSP corr| ≤ 40% for the REMO model and |bias GST corr| ≤ 2 °C, |bias GSP corr| ≤ 40% for the RegCM model.

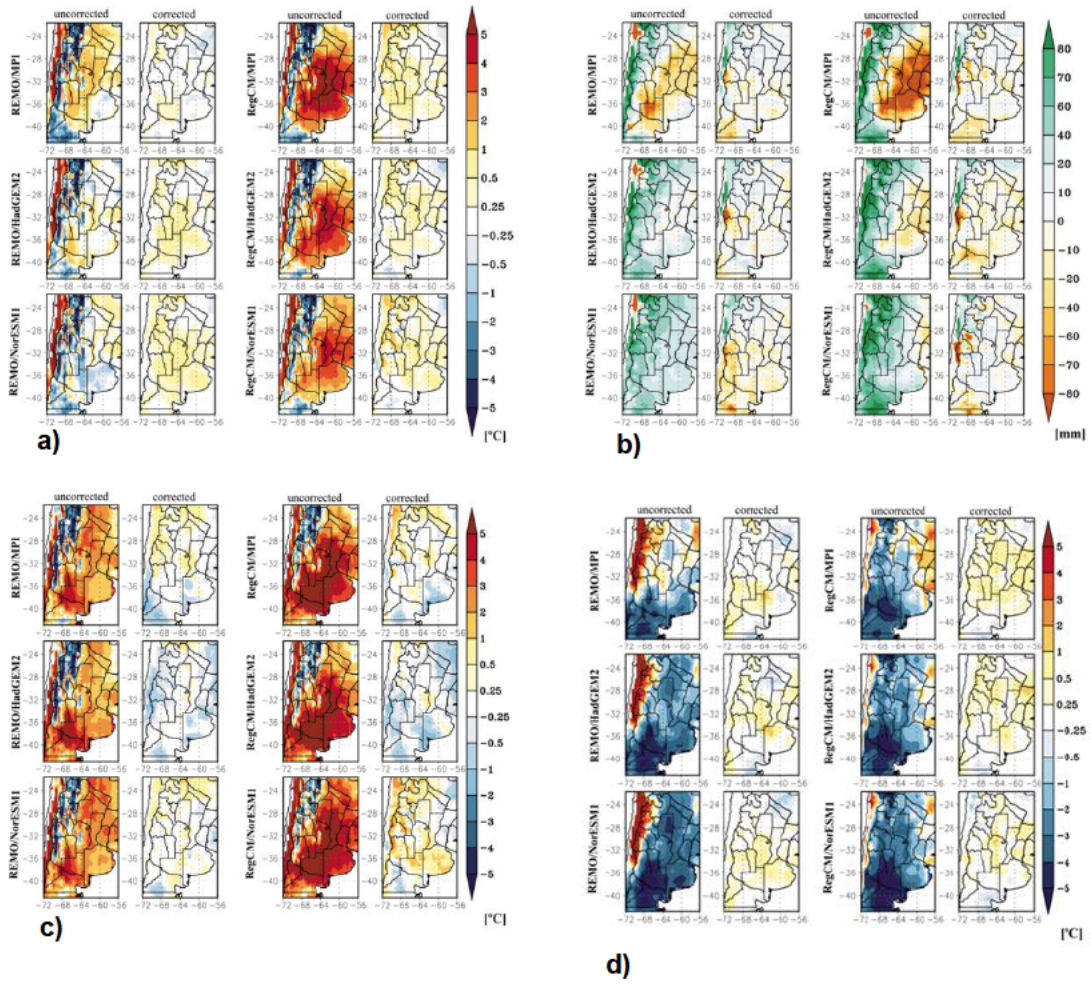

Figure 2. Spatial distribution of systematic error of GST (a), GSP (b), CN (c) and GSTA (d) for the CORDEX-CORE simulations, REMO and RegCM: raw (first and third column), corrected (second and fourth column)

Units: [°C] for GST, CN and GSTA and [%] for GSP.

For CN, in general, a greater predominance of positive (warm) bias is observed throughout the study region, indicating that the RCMs overestimate the magnitude of CN (4 °C for REMO and 5 °C for RegCM). This positive (warm) bias of CN is of greater geographical extension for the RegCM model compared with the REMO model. Negative (cold) bias of CN (up to -5 °C for both models) is observed over complex topography to the east of the Andes Mountains between Mendoza and Jujuy. This is a common behaviour of RCMs over the Andes and over any mountainous region of the world[31]. Regarding GSTA, a greater predominance of negative (cold) bias is observed throughout the study region, indicating that the RCMs underestimate the magnitude of GSTA. This negative (cold) bias is observed over most of central-eastern Argentina with a maximum (-5 °C) over southern Mendoza and the border area between La Pampa, Neuquén and Río Negro. This maximum seems to vary in geographic extension depending on the evaluated RCM/GCM combination, being of greater geographical extension for RegCM compared with REMO. Positive (warm) bias of GSTA is observed over complex topography areas in the border of Argentina-Chile, being of greater magnitude (5 °C) for the REMO model (**Figure 2** c, d). Summarizing, the bias correction's application reduces the range of the systematic error of CN and GSTA, finding: |bias CN corr| ≤ 1 ºC and |bias GSTA corr| ≤ 1 ºC, regardless of the RCM.

Once the bias correction was applied, the spatial distribution of mean values of the UCI's components and the UCI itself computed with the bias-corrected model outputs is described.

With the aim of complementing the assessment of model performance given by the spatial analysis of the systematic errors of the UCI's components (**Figure 2**), the Mean Absolute Error (MAE) was included. **Table 1** displays a summary of the models' errors, by means of the MAE, computed spatially. This metric was calculated for the four UCI's components, GST, GSP, CN and GSTA. The table shows that for GST the MAE ranges from 1.58 to 3.19 in raw model outputs and is reduced to a range from 0.21 to 0.43 in the corrected model outputs. Regarding GSP, the MAE ranges from 33 to 58.7 in raw model outputs and is reduced to a range from 12.97 to 15.60 in the corrected model outputs. For CN the MAE ranges from 2.71 to 4.02 in raw model outputs and is reduced to a range from 0.31 to 0.59 in the corrected model outputs. For GSTA the MAE ranges from 1.94 to 3.46 in raw model outputs and is reduced to a range from 0.28 to 0.37 in corrected model outputs, as expected. Note also that large errors over the Andes mountains have a strong impact on the magnitude of the MAE. To conclude, the lower values of MAE from the corrected model outputs indicate a better model's performance after the application of bias correction, which justifies the use of the biased-corrected CORDEX-CORE simulations for this study.

Figure 3 shows the spatial distribution of GST (a) and GSP (b) computed from observations (CRU) and from the bias-corrected model outputs. According to Solman and others[20], the unfavourable climate conditions for Malbec vine's growth are represented by the lower and upper extreme ranges of GST (GST ≤ 16 ºC and GST > 27 ºC) and GSP (GSP ≤ 50 mm and GSP > 450 mm), and, consequently, these ranges correspond to levels of non climatic suitability. Between these extremes of non climatic suitability, favourable climate conditions are identified, which are classified in three degrees of climatic suitability levels. Regions with GST values between 16 ºC < GST ≤ 18 ºC and 25 ºC < GST ≤ 27 ºC and GSP values between 50 mm < GSP ≤ 80 mm and 300 mm < GSP ≤ 450 mm represent areas in which the climatic conditions for vine's growth are limiting (limiting climatic suitability). Regions with GST values between 18 ºC < GST ≤ 20 ºC and 23 ºC < GST ≤ 25 ºC and GSP values between 80 mm < GSP ≤ 120 mm and 220 mm < GSP ≤ 300 mm represent areas where the climatic conditions for vine's growth are suitable (adequate climatic suitability). Regions with GST values between 20 ºC < GST ≤ 23 ºC and GSP values between 120 mm < GSP ≤ 220 mm represent areas in which the climatic conditions for vine's growth are optimal (optimal climatic suitability).

Table 1. Mean Absolute Error (MAE) computed spatially for GST (a), GSP (b), CN (c) and GSTA (d) for the CORDEX-CORE simulations. RCMs REMO and RegCM: raw (first and third column), corrected (second and fourth column); GCMs: MPI (first row), HadGEM2 (second row), NorESM1 (third row)

a)	GST				b)	GSP			
	REMO		RegCM			REMO		RegCM	
	raw	corrected	raw	corrected		raw	corrected	raw	corrected
MPI	1.87	0.21	3.19	0.41	MPI	37.03	12.97	58.07	13.33
HadGEM2	1.58	0.30	2.84	0.32	HadGEM2	33.00	13.36	40.16	14.88
NorESM1	1.66	0.36	2.72	0.43	NorESM1	44.06	15.17	44.71	15.60

c)	CN				d)	GSTA			
	REMO		RegCM			REMO		RegCM	
	raw	corrected	raw	corrected		raw	corrected	raw	corrected
MPI	2.71	0.36	3.77	0.39	MPI	2.11	0.28	1.94	0.37
HadGEM2	2.79	0.33	3.73	0.41	HadGEM2	2.91	0.29	2.33	0.32
NorESM1	2.89	0.31	4.02	0.59	NorESM1	3.46	0.29	2.63	0.29

Units: [°C] for GST, CN and GSTA; [%] for GSP. Minimum and maximum values of MAE are highlighted in blue and red, respectively.

The spatial pattern of GST and GSP from the CRU observations shows the three climate suitability levels of favourable climatic conditions: optimal, adequate and limiting. Regardless of the evaluated RCM, a good spatial representation of the climate suitability levels of GST is reproduced (**Figure 3**a six bottom panels). The zone of optimal climatic suitability presents a narrow latitudinal strip between Jujuy and south of Mendoza, and an extensive longitudinal strip that crosses the centre of Argentina. The two RCMs show a good representation of this spatial pattern; however, they present some discrepancy in the latitudinal location and orientation of its southern limit when compared with CRU observations. For example, regardless of the driven GCM, both RCMs reproduce a small northwest-southeast diagonal area of optimal climatic suitability between the border area of Mendoza, La Pampa and San Luis and the border area of La Pampa, Rio Negro and Buenos Aires. Moreover, among the 6 evaluated RCM/GCM combinations, only REMO/MPI presents greater similarity with respect to CRU observations. South from the area of optimum climatic suitability, areas of adequate and limiting climatic suitability are found. They are well represented by both RCMs in terms of shape and geographic location (over Buenos Aires, Neuquén, Río Negro and north-western Chubut). Both RCMs adequately represent the geographical location of the southern extreme of the zone of adequate climatic suitability; however, the geographic location of the extreme north depends on the southernmost representation of the lower extreme of the zone of optimum climatic suitability, in connection with what was previously described. Both RCMs adequately represent the region of limiting climatic suitability located over the south-eastern part of Buenos Aires. However, the modelled geographical extension depends on the evaluated RCM/GCM combination, being of smaller area compared to the observed one (CRU). North from the area of optimum climatic aptitude, areas of adequate and limiting climatic suitability are found. Both RCMs show a good representation of these areas over central-eastern Argentina. In general, even though both RCMs adequately represent the northeast-southwest orientation of the zone of adequate climatic suitability and its minimum located over Sierras de Córdoba, its shape and extension depend on the RCM/GCM combination. All the RCM/GCM combinations, except one (the REMO/MPI), reproduce an area of limiting climatic suitability zone located over the border area between northeast La Rioja, south Catamarca and northwest Córdoba. However, its geographical extension varies depending on the evaluated RCM/GCM combination. Regarding this aspect, the REMO/MPI seems to be the only combination in better agreement with the observed CRU.

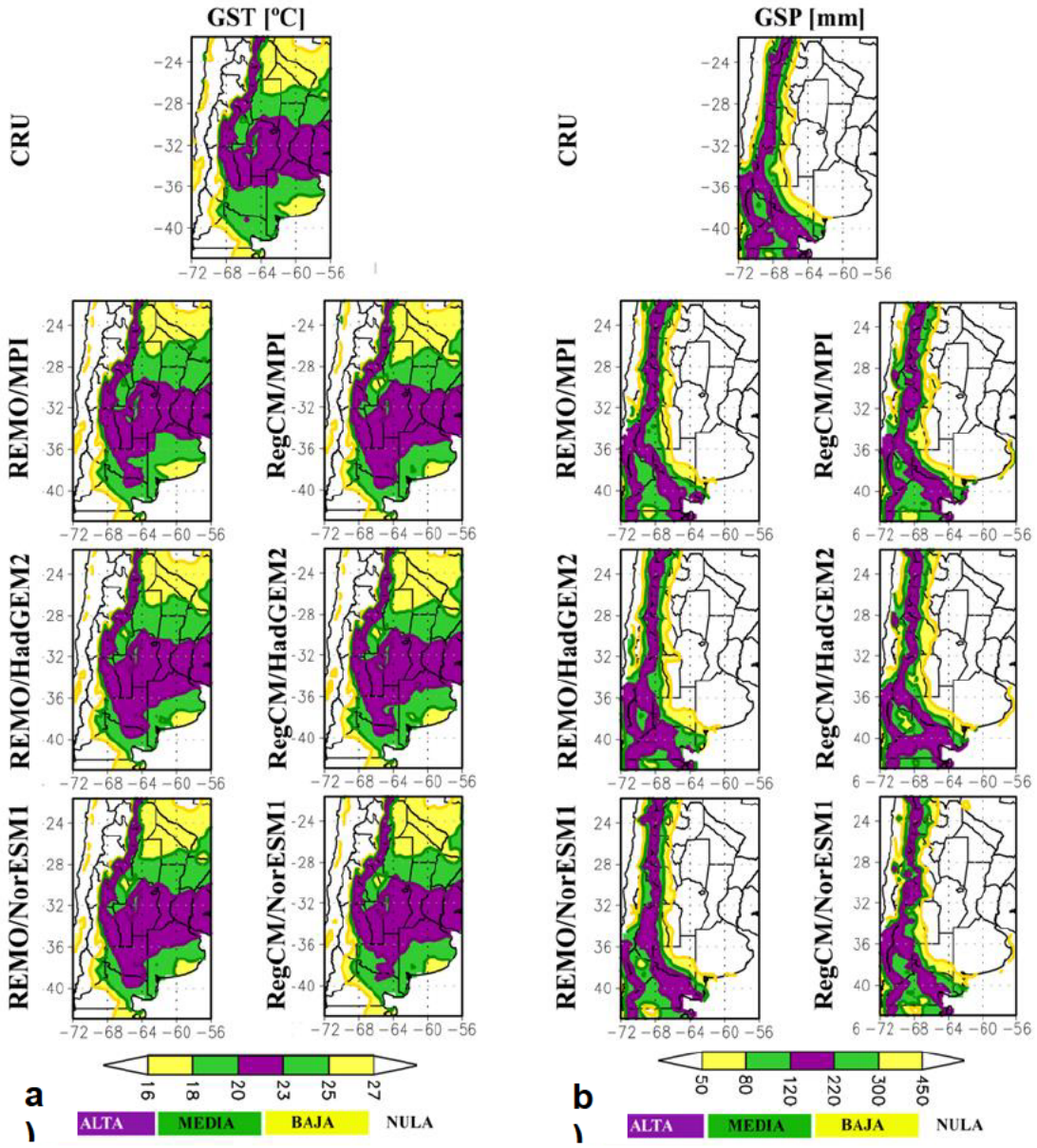

Figure 3. Spatial distribution of GST (a) and GSP (b): observed CRU (upper centre panel) and modelled (six bottom panels) for the corrected simulations CORDEX-CORE: REMO and RegCM, left and right column, respectively

Units: [°C] for GST, [mm] for GSP. According to Solman and others[20]: shaded colors represent different *climatic suitability levels*: optimum (violet); adequate (green), limiting (yellow) and null (white). The horizontal bar was included for visualizing the relationship between GST and GSTP ranges and climatic suitability levels.

In general, regardless of the evaluated RCM, a good representation of the climate suitability levels of GSP is reproduced (**Figure 3**b six bottom panels). The two RCMs adequately represent the zone of optimum climatic suitability, delimited by the 120 mm and 220 mm isohyets. This zone consists of a latitudinal strip from Jujuy to centre Mendoza, and then divides into 2 branches: a western one that continues bordering the mountain range and an eastern one that crosses diagonally in northwestern-southeastern direction from southern Mendoza to Rio Negro-Chubut over the Atlantic coast. It seems that the REMO/HadGEM2 and RegCM/HadGEM2 combinations are the ones that show the best representation of this structure. These 2 branches delimit a zone of adequate climatic suitability located at Neuquén, Río Negro and Chubut. Eastern from the east branch of the optimal climatic suitability zone, the adequate and limiting climatic suitability zones are found, having been well represented by both RCMs.

Figure 4 shows the spatial distribution of CN (a) and GSTA (b) computed from observations (CRU) and from the bias-corrected model outputs. According to Solman and others[20], the unfavourable climate conditions for Malbec vine's growth are represented by the lower and upper extreme ranges of CN (CN ≤ 9 °C and CN > 20 °C) and GSTA (GSTA ≤ 10 °C and GSTA > 20 °C), and, consequently, these ranges correspond to levels of non climatic suitability. Regarding favourable climate conditions of CN and GSTA for Malbec vine growth, three degrees of climatic suitability were identified. Regions with CN values within 9 °C < CN ≤ 11 °C and 17 °C < CN ≤ 20 °C and GSTA values within 10 °C < GSTA ≤ 12 °C and 18 °C < GSTA ≤ 20 °C represent areas in which the climatic conditions for vine's growth are limiting (limiting climatic suitability). Regions with CN values between 11 °C < CN ≤ 13 °C and 15 °C < CN ≤ 17 °C and GSTA values between 12 °C < GSTA ≤ 14 °C and 16 °C < GSTA ≤ 18 °C represent areas in which the climatic conditions for vine's growth are adequate (adequate climatic suitability). Regions with CN values between 13 °C < CN ≤ 15 °C and GSTA values between 14 °C < GSTA ≤ 16 °C represent areas in which the climatic conditions for vine growth are optimal (optimal climatic suitability).

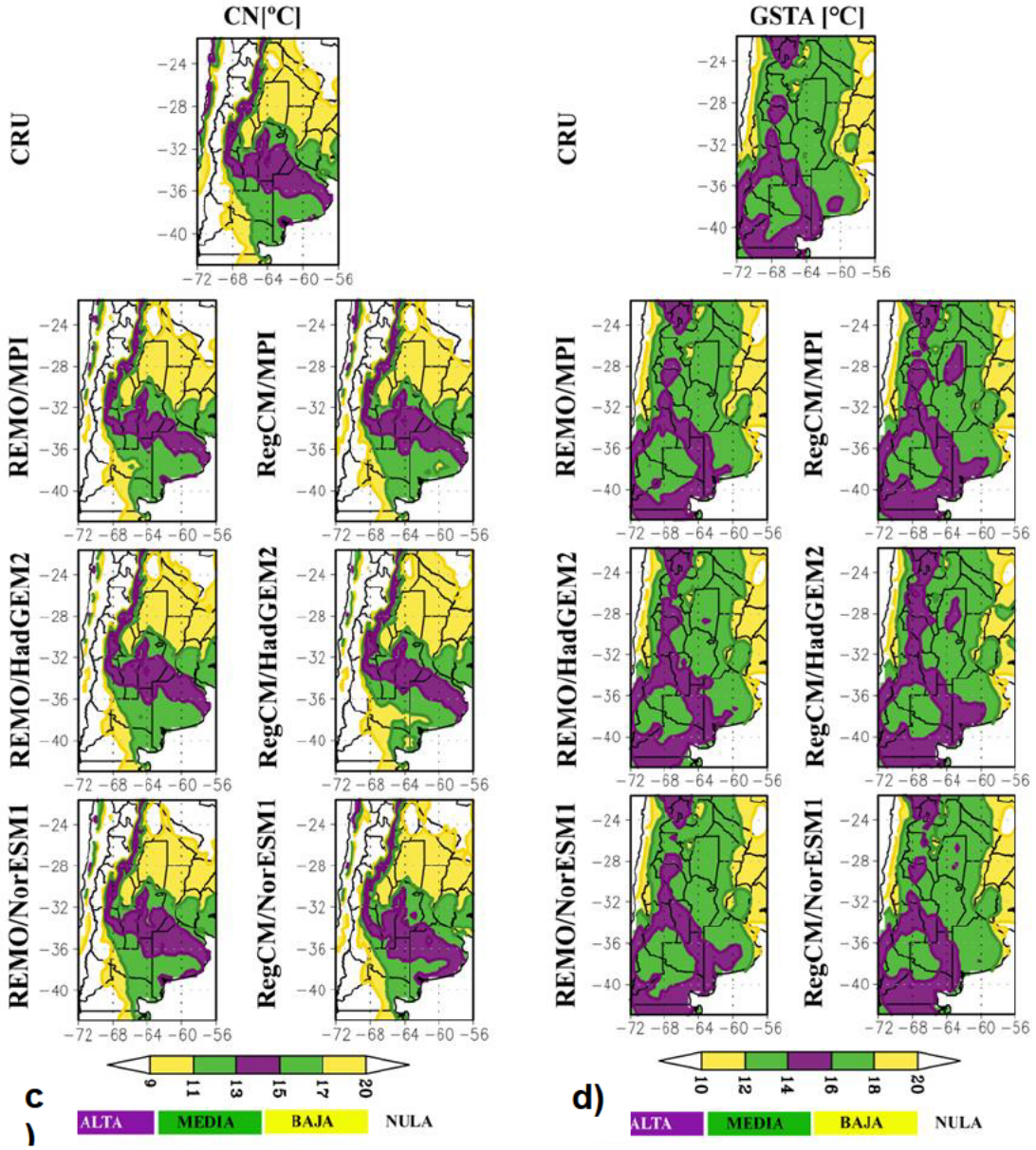

Figure 4. Spatial distribution of CN (a) and GSTA (b): observed CRU (upper centre panel) and modelled (six bottom panels) for the corrected simulations CORDEX-CORE: REMO and RegCM, left and right column, respectively

Units: [°C] for CN and GSTA. According to Solman and others[20]: shaded colours represent different *climatic suitability levels*: optimum (violet); adequate (green), limiting (yellow) and null (white). The horizontal bar was included for visualising the relationship between CN and GSTA ranges and climatic suitability levels.

The observed spatial pattern of CN shows the three climate suitability levels well defined. The optimal climatic suitability zone is located over eastern Andes Mountains in a north-south direction between Jujuy and northern Mendoza, and from there crossing Argentina in northwest-southeast direction arriving at the Atlantic coast of Buenos Aires (with a very small geographical area over southern Buenos Aires). Regardless of the evaluated RCM, a good representation of this spatial pattern is found, except for some small discrepancy over southern Buenos Aires, which is only represented by REMO/MPI, REMO/NorESM1 and RegCM/NorESM1 combinations (6 lower panels of **Figure 4**a). Moreover, the optimal climatic suitability zone limits upper and lower with the adequate climatic suitability zone. The northern branch of the adequate climate suitability zone is of smaller geographical extension compared to the southern branch. A feature very well represented by both RCMs, which is in agreement with CRU. Besides, the zone of adequate climatic suitability delimits upper and lower with the zone of limiting climatic suitability; being its (upper/lower) branch of (greater/lesser) geographical extension. This feature is also well reproduced by both RCMs, in agreement with CRU. In connection with the above, it is worth mentioning the geographical location of the isotherms of 17 °C and 11 °C, the limits between the adequate and limiting climatic suitability zones. In general, the geographical location of the 17 °C isotherm is very well represented by the 6 RCM/GCM combinations. However, some differences in the representation of the 11 °C isotherm's location are found over centre La Pampa and southwest Buenos Aires with the REMO/MPI and RegCM/HadGEM2.

The observed spatial distribution of GSTA shows an optimal climatic suitability zone located over the traditional wine-growing area with a ring-shaped area over northern Patagonia, enclosing over there the adequate climatic suitability zone that is centred over south Mendoza, centre-west La Pampa, northwest Río Negro and Neuquén. Moreover, another small area of optimal climatic suitability, located over south-western Buenos Aires province, is represented by the CRU observations. Regarding the adequate climatic suitability zone, most of the area of the study domain belongs to it. In general, a good representation of the spatial distribution of GSTA is reproduced by the two RCMs, regardless of the driven model (six bottom panels of **Figure 4**b). Particularly, both climatic suitability zones are satisfactorily represented by the 6 RCM/GCM combinations, which is in agreement with CRU. However, some small discrepancies may be mentioned. For example, even though all RCM/GCM combinations seem to reproduce the described spatial pattern, the small optimal climatic suitability area over Buenos Aires is not represented by the RegCM/NorESM1 combination. And, even more, for those RCMs/GCMs that do simulate this zone, it seems to be represented as an eastward extension of the optimum climatic suitability area, not as an isolated area as represented by CRU. Moreover, regarding the ring-shape area of northern Patagonia, it is worth noting that its extension and shape seem to have small variations depending on the evaluated RCM/GCM combination, finding that REMO/HadGEM2 and REMO/NorESM1 are the closest to CRU's representation. Besides the adequate climatic suitability zone located over northern Patagonia in a ring-shaped area, the centre-east of Argentina belongs also to this climatic aptitude level. Finally, the limiting climate suitability zone, located over the easternmost part of the study domain as well as very small isolated areas over Tucuman, eastern Jujuy and Salta, is also well represented by both RCMs.

It is concluded that both RCMs reproduce to a greater or lesser extent the main features (magnitude; spatial pattern) of GST, GSP, CN and GSTA required for the zoning of MGP in Argentina.

Figure 5 shows the spatial distribution of UCI, which represents the current Malbec grapevine zoning in Argentina, computed from CRU observations (upper middle central panel) and from the bias-corrected CORDEX-CORE simulations (six lower panels). This zoning is located in a northwest-southeast strip of Argentina ranging from La Rioja (in the north) to the border between Río Negro and Chubut (in the south). Within this area, three viticultural suitability levels are well defined: (a) high located in centre-east San Juan and Mendoza provinces; (b) medium located over south Mendoza, south La Pampa, north-eastern Río Negro and southern extreme of Buenos Aires province; (c) low bordering the area of medium viticultural suitability to the east and west. In general, regardless of the driven GCM, both RCMs adequately represent the current observed Malbec grapevine zoning in Argentina. However, some small differences can be identified

mainly related to the geographical location and/or areal extension of viticultural suitability zones. As an example, few of them can be mentioned. As it was previously described, the current observed spatial distribution of UCI only shows the high viticultural suitability level located over the Argentinean traditional viticultural area (central-north Mendoza and San Juan). Even though this feature is reproduced by the 6 RCMs/GCMs combinations (presenting smaller geographical longitudinal extension in RegCM than in REMO), most combinations except for REMO/MPI simulate a new area of high viticultural suitability over eastern Río Negro. All the MCR/MCG combinations show a good representation of the medium viticultural suitability zone, except the REMO/MPI and RegCM/MPI combinations. These two combinations seem to show some geographical discontinuity over southern Mendoza and western La Pampa. All the MCR/MCG combinations show a good representation of the low viticultural suitability zone, except for the REMO/NorESM1 and RegCM/NorESM1 combinations. These two seem to not represent the observed low viticultural suitability zone in the border area between eastern Neuquén and northwestern Río Negro.

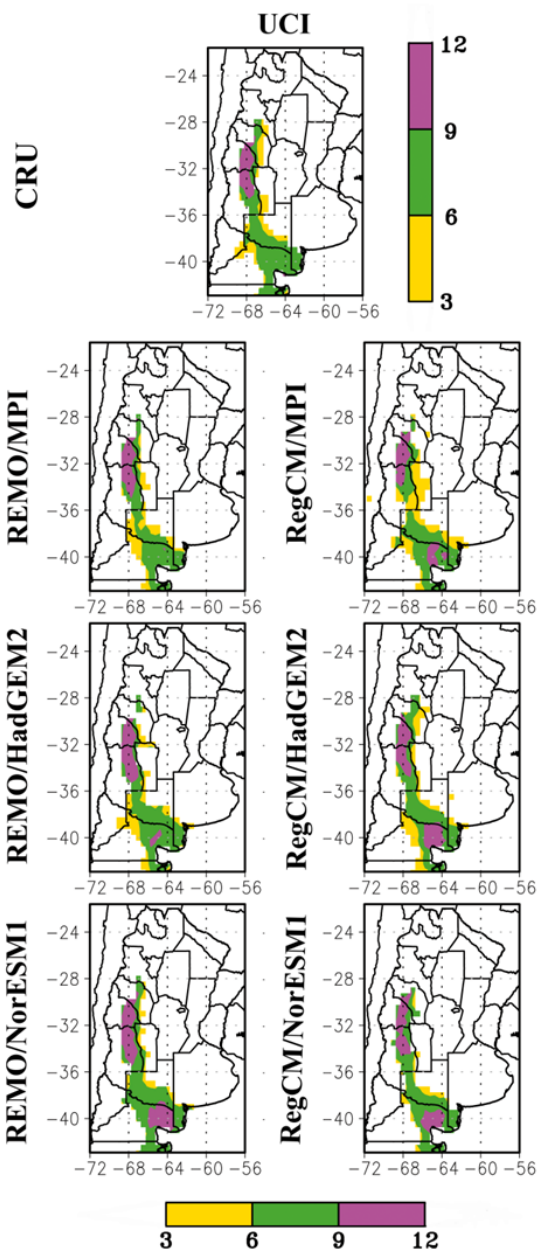

Figure 5. Spatial distribution of UCI calculated with the observed CRU database (upper middle panel) and modelled by the set of corrected CORDEX-CORE simulations (six lower panels): REMO and RegCM, left and right column, respectively

Units: dimensionless. According to Solman and others[20]: shaded colours represent different *viticultural suitability levels:* high (9 < UCI ≤ 12; purple); medium (6 < UCI ≤ 9; green) and low (3 < UCI ≤ 6; yellow); non (UCI ≤ 3; white).

In spite of the small differences mentioned above, both RCMs show a good representation of the spatial pattern of UCI. This is consistent with the current observed zoning of MGP, locating the area of best suitability over northern Mendoza, where most Malbec grapes are produced (shown in Solman and others[20]).

4. Discussion and Conclusions

The objective of this study was to evaluate if the bias-corrected CORDEX-CORE simulations are reliable enough to represent the current observed zoning of Malbec grapevine in Argentina. The clear contribution of this work to the field of viticultural zoning is the utilization of the CORDEX-CORE simulations for representing Argentinean viticultural areas based on a given grapevine variety, as is the Argentinean Malbec. In order to achieve this objective a sequence of activities were carried out.

Firstly, a systematic model error assessment was performed to the UCI's components provided by the two RCMs from the CORDEX-CORE simulations, the REMO and the RegCM, analysis carried out in terms of their spatial distribution of mean values. From the results, it was concluded that the raw CORDEX-CORE simulations are affected by systematic errors of great magnitude over the study region. Therefore, in order to reduce them, it was necessary to apply an error correction method to the variables provided by both RCMs, because the use of climate models raw outputs as input for climate impact assessments could often give unrealistic results which should be interpreted with caution. Then, with these corrected variables, the UCI's components were again calculated to be compared with the observed ones, being the latter the closest representation to reality. To summarize, the systematic model error assessment showed a noticeable magnitude reduction of the model's systematic error after the bias-correction application. This magnitude reduction introduces an improvement in information processing, and, as a consequence, it was expected that bias-corrected variables provided more reliable information to represent the current spatial distribution of mean values of the UCI's components and the UCI index.

Second, the bias-corrected CORDEX-CORE simulations were evaluated in terms of the spatial distribution of the UCI's components and the UCI index. Regarding the UCI's components, it was shown that both RCMs reproduce to a greater or lesser extent the main features (spatial pattern; location and magnitude) of GST, GSP, CN and GSTA. With regard to the UCI index, in spite of the small differences related to geographical location and/or areal extension of viticultural suitability zones, both RCMs (regardless of the driven GCM) adequately represent the current observed Malbec grapevine zoning in Argentina, in agreement with Solman and others[20]. This is a very encouraging starting point in the evaluation of the reliability of the CORDEX-CORE models for representing the geography of Malbec in Argentina, not only in the present but also in the future.

However, strengths and weaknesses were identified during the research process. Regarding strengths, the first one is related to the use of two RCMs, the REMO and RegCM, instead of a single climate model. In addition, two RCMs driven by three GCMs that give rise to a set of six RCMs/GCMs combinations, which allows us to evaluate how each model reproduces the current geographical distribution of MGP in Argentina having the possibility of identifying in which aspects they agree and/or disagree (e.g. location and degree of viticultural aptitude). Moreover, this will allow evaluating the reliability of the results for a better understanding of the current modelled viticultural zoning. As this is the first study in Argentina derived from the CORDEX-CORE simulations and focused on Malbec grapevine variety, a strict comparison with previous bibliography is not possible. However, its general findings for the current reference climatology of GST and GSP are consistent with previous studies[44][45] carried out with a single climate model, RCM and GCM, respectively. Unfortunately, as the two above-mentioned works were based on a single climate model, they did not have the possibility of incorporating the issue of uncertainty in future climate projections. Therefore, this constitutes another relevant strength in the experiment design of this work. This is of utmost relevance because climate change projections

at regional scale are affected by multiple sources of uncertainty[46][47]. Therefore, the quantification of climate change requires the identification of uncertainty levels in order to provide a range of potential impacts of climate change on viticulture. Besides, in addition to using two RCMs, it is necessary to use the RCMs of highest spatial resolution available in the region (0.22° × 0.22°), as in this case. This necessity is due to an area of complex topography, such as the traditional Argentine grapevine growing region; it is better to work with the models of highest spatial resolution. Therefore, both implemented aspects, (a) the use of two RCMs, and (b) the use of available RCMs with the highest spatial resolution available over the study region, constitute the enhancement of this experiment design. Another important strength is related to the double dimension of UCI interpretation: the climatic suitability level and the viticultural suitability level, concepts derived from Solman and others[20], related to the analysis of the spatial distribution of mean values of UCI's components and the UCI index (the first is associated with each UCI's component, while the second is associated with the UCI itself). The climatic suitability level should be thought as the needed climatic conditions in each UCI component for allowing Malbec vine's growth in its different levels: optimal, adequate, limiting and null. These climate suitability levels are associated with certain GST, GSP, CN and GSTA ranges that represent favourable and unfavourable climatic conditions, that are represented by 4 categorical values (3, 2, 1, 0), from maximum to minimum. Both concepts, the climatic and viticultural suitability levels, are intertwined and converge on the UCI index interpretation, giving to UCI a climatic and viticultural dimension. Some clarifications in this respect will be given below. The climatic dimension is represented by its magnitude, indicating how favourable the climatic conditions are for MGP. The viticultural dimension is represented by its components (GST, GSP, CN, GSTA), because its degree of viticultural suitability depends on the categorical value assigned to them. The UCI interpretation brings together several aspects that basically will depend on the larger or smaller influence of GST, CN and GSP. The GST index provides the basis for placing latitudinal boundaries on viticulture zone[48][49] and is an essential factor in grapevine maturation as well as a useful indicator of the properly ripen requirements of different varieties in terms of sugar accumulation in berries[50]. The CN index provides information about the mean minimum temperatures when ripening usually occurs and is useful for evaluating the qualitative potential assessment of wine-growing regions, in relation to secondary metabolites (polyphenols, aromas) in grapes. It refers to the colour and aroma of both grapes and wines[51][52]. The GSP index provides information on how precipitation during the growing season can impact the phenology and the berry maturation, which also impacts on grape quality and on the incidence and/or severity of grapevine diseases. Therefore, as stated by Solman and others[20], the added value of this regional index, specifically designed for the Malbec variety in Argentina, is its capability of expressing a degree of suitability, which in turn depends on the (greater/lesser) influence of climate conditions on MGP, that are represented by GST, GSP, CN and GSTA. Summarizing, the use of both the CORDEX-CORE simulations having the RCMs with the available highest spatial resolution over the region and the UCI index are the two key-strengths of the experiment design that highlight the relevance of outcomes obtained in this work compared with previous Argentinean viticultural zoning studies.

However, in spite of the above-mentioned key strengths, the experiment design presents some weaknesses and limitations, which undoubtedly might have implications on the interpretation of the results. We acknowledge that a horizontal resolution of 0.22° × 0.22° and a monthly temporal scale of climatic variables may be considered not enough for the needed spatial detail in vineyard scale studies, and even more for representing the vine phenological and physiological processes. This could influence the decision-making process of adaptation strategies and planning for designing managements practices in vineyards[53][54]. However, as this MGP zoning is at regional scale, the spatial and temporal resolution used here provides very valuable information for our purpose. Furthermore, this zoning only considers climatic variables, and performing complementary zoning studies based on other variables could also be carried out for having an integrated climate-soil-topographic-edaphic analysis[55]. Thus, this would provide valuable information for enhancing the geographic characterization of winegrowing areas.

Nevertheless, although such limitations may affect in a greater or lesser extent the interpretation of our findings, the applied methodology obviously remains valid (e.g. with the use of RCMs of highest spatial resolution available, monthly temporal scale of the climatic variables and the selected bioclimatic indices according to the zoning purpose) and is endorsed by the guidelines for viticultural zoning methodologies on a climate level from the International Organization of Vine and Wine (OVI)[56][57]. Summarizing, we consider that the outcomes of this work are very valuable and encouraging because they allow us to understand how the set of bias-corrected CORDEX-CORE simulations represents the current zoning of MGP in Argentina. And this is precisely the starting point for assessing how this set of simulations projects the MGP areas in Argentina over the forthcoming decades.

Accordingly, regarding future perspectives, we are adapting the experimental design of this work for evaluating the projected changes in MGP areas in Argentina in a context of climate change. This means using this set of simulations, the bias-corrected CORDEX-CORE, for representing future MGP areas in Argentina under a climate change scenario (Representative Concentration Pathways, RCP 8.5 under two global warming levels, 1.5 °C and 2.0 °C[58]). This is endorsed by the established OIV guidelines for studying the effects of climate variability on viticulture in a climate change context[59]. It is worth mentioning that what differentiates this work from previous ones carried out over the region is that it is the first in using the CORDEX-CORE simulations focused on a single grapevine variety and a given winegrowing region, Malbec and Argentina, respectively. Therefore, the main goal is to understand how climate change impacts the current zoning of MGP in Argentina to later identify which of the usually available adaptation measures might be applied. This information would gain relevance for supporting the decision making process regarding the designing of long-term planning and/or adaptation strategies, mainly either changes in vineyard site relocation or changes in training systems.

Regarding future implications of the results in a climate change context, we could think about how the results may support the decision making process and contribute to the sustainable development of the activity in the future. Even though a wide range of works focused on possible mitigation/adaptation measures and their relation with the sustainable development of viticulture are found mainly in the Mediterranean region[60][62], few studies are found in Argentina[63]. Therefore, the connection between our results and sustainable viticulture in a climate change context might be thought as follows. The idea is to understand how climate change impacts the current zoning of MGP in Argentina to later identify which of the available adaptation measures might be applied. Particularly, it might be very useful information for supporting the decision making process regarding the design of long-term planning and/or adaptation strategies, mainly concerning either changes in vineyard site relocation or changes in training systems. Undoubtedly, this would be the study's contribution to the sustainability development of the winemaking sector in a climate change context in Argentina.

To summarize, results obtained here are encouraging because they allow us to evaluate the reliability of the bias-corrected CORDEX-CORE simulations for representing the current viticultural zoning of Malbec grape production in Argentina, information that might be potentially useful for climate change adaptation studies in the coming decades.

Acknowledgements

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Transparency of data

Available Data: The observed gridded dataset is available at *https://services.ceda.ac.uk/*. CORDEX-CORE RCMs datasets used are available at *https://cordex.org/data-access/*.

Author contribution statement

	MF Cabré	SA Solman	MN Nuñez
Conceptualization	■	■	■
Data curation	■		
Formal analysis	■		
Investigation	■	■	
Methodology	■	■	
Resources		■	
Supervision		■	
Visualization	■		
Writing – original draft	■		
Writing – review and editing	■	■	

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