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Which climatic modeling to assess climate change impacts on vineyards?

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Abstract

Abstract: The impact of climatic change on viticulture is significant: main phenological stages appear earlier, wine characteristics are changing,... This clearly illustrates the point that the adaptation of viticulture to climate change is crucial and should be based on simulations of future climate. Several types of models exist and are used to represent viticultural climates at various scales. In this paper, we propose a review of different types of climate models (methodology and uncertainties) and then few examples of its application at the scale of wine growing regions worldwide.

Keywords: climate change, modelling, uncertainties, bioclimatic index, viticulture

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Introduction

The vine, like other perennial crops (fruit trees, forests), is particularly sensitive to climate change because its management and adaptation must be anticipated well in advance (van Leeuwen *et al.*, 2004, Carey *et al.*, 2008). The characteristics of vineyards and of the wines are the result of a combination of several factors (grape, soil, climate, agricultural practices) that produce wines with a typical style and quality that are distributed on specific territories (Webb *et al.*, 2007; Hall and Jones, 2010; Quénol *et al.*, 2014). The temperature increase over the last 50 years has led to the advance of the main phenological stages and a change of wine characteristics (sugar content and acidity) (Jones *et al.*, 2005; Webb *et al.*, 2008; van Leeuwen *et al.*, 2009). These main findings show that the adaptation of vineyards to climate change is crucial and should be based on simulations of future climate (Quénol et al, 2014; Moriondo et al, 2013, Hannah et al, 2013, Santos *et al.*, 2013).

Different types of model exist to represent climate on Earth at various scales. At the global scale, General Circulation Models (GCMs) are mainly used as the basis to build climate change scenarii that estimate trends in climate variables like temperature, rainfall and wind globally, at low spatial resolution (~300 km). Obviously, these kinds of models are not suitable for considering temperature variability at vineyard scale. Several studies have tried to improve the resolution of GCMs, leading to a range of different regional climate models, such as WRF (Weather Research and Forecasting, http://www.wrf-model.org/index.php). In the context of climate in vineyards, regional climate models have been used in the South African district of Stellenbosch to study effects of the local circulation (Bonnardot *et al.*, 2005; Bonnardot *et al.*, 2012; Soltanzadeh *et al.*, 2016), and are currently being used to characterize climate and model vine phenology in the Marlborough region, New Zealand (Sturman *et al.*, 2014) and in Burgundy (Xu *et al.*, 2012). In addition to regional models based on physics, downscaling techniques enable representation of climate at local scales on the basis of statistical relationships between global and local variables. However, the spatial resolution of these models is generally still not accurate enough to be used by winegrowers (Dunn *et al.*, 2015). To compensate for the difficulty that dynamic models have in accurately representing local temperature variability, some fine scale observation networks have been established to monitor temperatures. Their spatial distribution is designed on the basis of topographic features derived from Digital Elevation Models (DEMs). This relationship can be used to estimate temperatures at a very fine scale and then to provide a better analysis of plant response. In the context of vineyards, frost damage on grapevines can be very localized and is generally strongly connected to local topography (Quénol and Bonnardot, 2014; Irimia *et al.*, 2014; Madelin and Beltrando, 2005). Therefore, integration of high resolution monitoring networks and atmospheric models appears to be a promising approach.

As stated in Cautenet and Bonnardot (2014), climate models are complex computer programs that are able to simulate the climate of both the past and the future. Climate models and weather models use the same equations, which are the fundamental equations of atmospheric physics. Climate models include relatively simplified representations of the surface of the Earth and its atmosphere that take into account all the mechanisms that govern atmospheric circulation. They are able to predict the weather and to represent the climate, that is to say, the average state of the atmosphere over long periods. Depending on their applications, climate models have different spatial

Table 1. The spatial and time scales and areas of application of climate models (Cautenet and Bonnardot, 2014).

Climate models	Spatial resolution	Temporal resolution	Scale	Application
Global Circulation Models (GCM)	From 5° to 0.5° (500 to 50 km)	From 10 years to several hundred years	Global	Modeling of atmospheric general circulation Modeling of global warming
Global with varying resolution (VRGCM)	From 1° to 10-12 km	More than 10 years to several hundred years	Global and regional	Weather forecast Modeling of global warming
Regional Circulation Models (RCM)	From 50 km to 200 m (imbricated grids)	Hourly to several days	Regional and local	Weather forecast Meso-scale climate modeling

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and temporal resolutions. Table 1 describes the key attributes of global and regional climate models.

Regional climate modeling

As mentioned above, the global climate models do not have a fine enough resolution for local scale impact studies. This is why many studies are attempting to create models able to disaggregate the overall climate signal at regional scales. Regional circulation models of the atmosphere, or mesoscale models, can represent finer resolutions than global models, of the order of a kilometer or even a few hundred meters. The meshes used in these models are fine enough to allow consideration of the consequences of changing human activities.

1. Regional atmospheric models

Regional atmospheric models aim to regionalize the outputs of global models by using nesting of model grids of increasing levels of resolution. The first grid is thus forced at its boundaries by atmospheric fields at low resolution, often from the global climate models, while the last grid contains the data with the finest resolution. These fine grids represent the regional circulation of the atmosphere models. With the improvement of the resolution of model outputs, topography, vegetation, hydrography and soil characteristics are better taken into account. Meteo-France uses the ARPEGE-Climate model as a global model, which has a variable resolution of 50 km over the Mediterranean and 450 km over the Pacific (Déqué *et al.*, 2007). To disaggregate the ARPEGE signal to finer scales, they use the regional ALADIN model down to a resolution of 10 km, which is also called a «limited-area model.» On the scale of Europe, the EuroCordex model output enables a resolution of a few kilometers (Vautard *et al.*, 2013) In terms of regional climate modeling, many studies have demonstrated the value of using different regional atmospheric models with increased resolution for characterizing climate variability and the potential climate risks in a wine-producing environment. The so-called physical atmospheric models is used to grasp the complexity of the environment (e.g. Earth-atmosphere models). The development of these models has grown strongly in recent years thanks to the increased computing capacity that allows improvements in both their resolution and complexity. The RAMS model (Regional Atmospheric Modeling System) (Pielke *et al.*, 1992)) was used to study the local circulations in the wine district of Stellenbosch in South Africa (Bonnardot *et al.*, 2005; Bonnardot and Cautenet, 2009; Soltanzadeh and al., 2016), Champagne and the Loire Valley (Briche *et al.*, 2014; Bonnefoy, 2012). Similar modeling studies have been conducted in Australia (Lyons and Considine, 2007). The WRF model (Advanced Research Weather Research and Forecasting) has been used to investigate the spatial variability of climate in Burgundy (Bonnefoy *et al.*, 2010. Cuccia, 2013; Xu *et al.*, 2012), as well as New Zealand (Sturman *et al.*, 2014). But, these models at very fine scales require a strong computing capacity.

2. Statistical modeling by data interpolation

The use of mesoscale atmospheric modeling allows a scalar disaggregation of spatial patterns obtained from global models, but the need for significant computing capacity makes it difficult to achieve satisfactory results at a very fine scale. The interweaving of various atmospheric phenomena in terms of the overlapping of scales (from local to synoptic) makes this type of modeling impracticable at a very detailed level. To overcome these limitations, advanced statistical methods are used to perform spatial interpolation of climate data obtained at fine scales. These methods are based on establishing the relationship between surface characteristics (e.g. landscape morphology and land use) and weather variables. In this type of study, the existence of a link between climate elements and topographic characteristics is then evaluated spatially across a study site using a Geographic Information System (GIS). Mesoscale numerical modeling and spatial interpolation of climate data have specific advantages and disadvantages. Numerical modeling at the mesoscale can take into account the synoptic scale weather as well as the overlapping scales, but it is difficult to use at fine scales particularly because of computing time and parameterization problems. Spatial interpolation using multiple regression has the advantage of being adapted to local scales, but the results are only a partial explanation because the model is static (with reference to a fixed time frame).

3. Uncertainties using climate data

In order to consider the uncertainties related to climate data several methods have been developed in the literature during last years:

- Anomalies method which calculates the difference between two periods (current and future conditions) for different climatic variables (ie. temperature, rainfall, wind) and apply it to the current conditions. This method is easy to be used but does not allow to introduce a change in variability

- Weather types method is a statistical method which classifies each day into a category of weather type

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(with its own structure). The main concern is then to be sure that the method generates correctly the future distribution of weather types. This method is very time consuming and needs very long observed past datasets;

- Quantile-quantile method is a statistical method. «*It consists in correcting the values of the model's quantiles by those computed from observations... This method has in particular the advantage of correcting the model bias*.» (DRIAS, *www.drias-climat.fr* ; Déqué, 2007).

The uncertainty in regional climate modeling in climate change context is complex because downscaling methods are all based on simulations of global climate model («cascade of uncertainties» from Boe, 2007). In order to illustrate this uncertainty, a multi-models approach for each RCP scenario was used about a regional climate study in France (Ouzeau *et al.*, 2014).

Climate modeling at the scale of wine regions

First studies of the impact of climate change on the grapevine have been conducted at multi-local scale. This approach has been used initially because of the past limitations on computing resources. Several studies in recent years have used this method to characterize the changing climatic conditions and production of European vineyards (Garcia de Cortazar Atauri-2006; Levrault and Brisson, 2010, Cuccia *et al.*, 2014). These studies describe changes in only some grid points across France (i.e. 8-20 points). Even if the methodology does not allow to represent spatial distribution of changes, it allows to multiply the number of hypotheses (different soil types, varieties and cropping systems) to achieve a more detailed analysis of the future impacts and to define adaptation strategies.

The provision of regionalized climate data from climate models of the latest IPCC reports (2014) (Coupled Model Intercomparison Project, CMIP 4 and 5), has allowed to map climate variability in connection with the evolution of the potential viticulture areas (past, present and future).

Most recent work has been based on calculations of bioclimatic indexes based on different climatic models and scenarios of climate change (Moriondo *et al.*, 2013; Santos *et al.*, 2013, Hannah *et al.*, 2013). These studies showed significant potential changes on the distribution of vineyards.

The warming trend is often reflected by increased bioclimatic indices, which may involve a change in the classification of wine climate types from one category to the next. For example, Santos *et al.* (2013) analyzed past climatic conditions mapping several bioclimatic index (Huglin, Winkler, Dryness indices) between the 1980-2009 and 1950-1979 periods across all of Europe and North Africa. In some regions, particularly the north and east of Europe, an increase in the values of these indices is favorable and allows these regions to benefit from improved conditions for growing vines, while in other regions (mainly southern Europe) the increase in index values is more detrimental.

Recent studies also evaluate these trends under future climatic conditions (Moriondo *et al.*, 2013; Hannah *et al.*, 2013). These studies suggest three quite different trends in Europe until 2050. First, wine production in the southernmost Mediterranean regions could be adversely affected by 2020. Second, there is an intermediate zone for which the different studies show fairly divergent and sometimes contradictory results. This area is from the vineyards of northern Spain, Italy and Greece to the vineyards of the Loire Valley, Alsace and Germany. Third, to the north of these vineyards a general improvement of climatic conditions for the cultivation of vines is predicted. This could allow an expansion of the current production area if it is worthwhile from an economic point of view. By 2050, the various scenarios studied do not show strong differences, and the three trends described above are partly independent of the socio-economic model chosen by the industry. In contrast, over the period 2070-2100 wine producers can expect a significant change, resulting in a major transformation of European vineyards, and a sharp reduction in production areas in Mediterranean wine producing area.

All these results are confirmed by a recent study realized in France by the LACCAVE project. In this study, the Huglin index[1] (Figure 1) was mapped using data from the Aladin regional model (spatial resolution of 8 km). The maps were produced for the periods 1986-2005, 2031-2050 and 2081-2100 based on three Representative Concentration Pathways (RCPs) for four greenhouse gas concentrations (2.6, 4.5 and 8.5). Over the period 1986-2005, the northernmost wine regions (Loire Valley, Champagne, Alsace, Burgundy) correspond to the «cold» class. Bordeaux vineyards are in the «temperate» class and southern vineyards are mainly in the «warm temperate» class. For the 2031-2050 period, according to the RCP2.6, 4.5 and 8.5 scenarios, we can see a northward shift of the classes over France with the transition to the next class in southern wine regions. This is the case for the

[1] Huglin index is related to the thermal requirements of grape varieties, and to potential sugar content of grapes (Huglin and Schneider, 1998).

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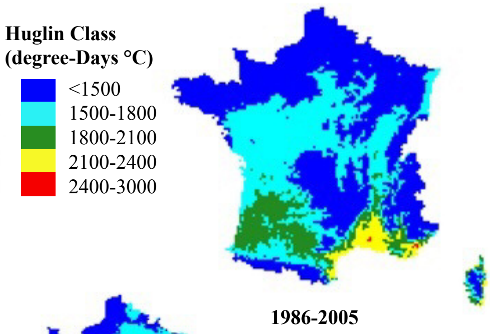
Bordeaux region that will theoretically increase from the «temperate» class to «warm temperate»; Burgundy, the Loire Valley and Alsace from the «cold» class to the «temperate» class and Languedoc from «temperate/temperate warm» to «temperate warm/warm». For the 2081-2100 periods, this potential migration (of zones of specific wine style) will become more important through the transition to the «warm» class for most wine regions, according to the RCP6.5 and 8.5 scenarios. Although these maps were made from modeled data, the results illustrate the range of possible trends (depending on the scenario) in the evolution of French viticulture and can help stakeholders to make decisions about future strategies.

Finally, Santos *et al.* (2016) have used recent data from Euro-cordex project to simulate the future phenology, production and water and nitrogen stress of grapevine systems in Europe using the STICS crop model (Brisson *et al.*, 2009). Authors only used a mean year (average year of 30 years of data) of



Class	°C	Examples
Very warm	IH > 3000	São Francisco Valley (Brazil)
warm	2 400 ≤ IH ≤ 3000	Malaga (Spain) Marsala (Italy)
Warm temperate	2 100 ≤ IH ≤ 2400	Napa (USA) Montpellier (France)
temperate	1 800 ≤ IH ≤ 2100	Pau, Bordeaux (France)
cold	1 500 ≤ IH ≤ 1800	Colmar, Angers (France)
Very cold	IH ≤ 1500	Québec (Canada) London (England)

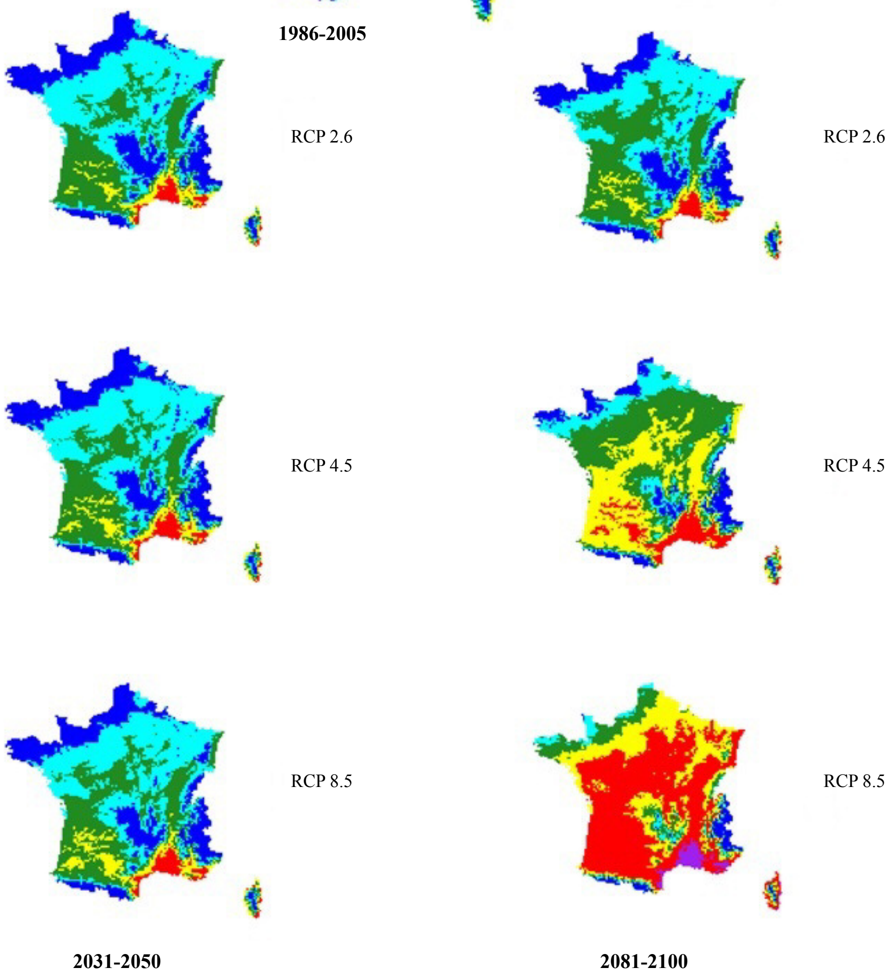


Figure 1. Mean Huglin Index classes through RCP scenarios. (sources: DRIAS)

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each variable to simulate future conditions and they highlighted the importance to use several scenarios and methods to characterize these impacts. Several crop models simulating grapevine systems have been developed during the last years (Moriondo *et al.*, 2015) and will be useful in the future to describe and test adaptation strategies. In this context, the quality and the availability of climatic variables required (radiation, wind, humidity, water potential) to simulated plant processes will be very important.

Discussion and conclusion

The various studies describing the calculation of bioclimatic indices based on different models and scenarios of climate change should allow estimation of the future state of viticulture in different parts of the world, although not without some uncertainties. First, the model predictions themselves have a significant amount of uncertainty in that it is not possible to validate future results (only validation on past data). Second, the indices are merely bioclimatic indicators but not the only factors affecting the development of the vine. In response to the article by Hannah *et al.* (2013) showing a large decrease in the ability to continue viticulture in the well-established wine-producing regions of the world over the next forty years, van Leeuwen *et al.* (2013) argued that it was necessary to be very careful when drawing definitive conclusions from this type of analysis. These studies on the impact of climate change address potential changes in the major global wine regions, but few have attempted to observe and simulate the climate at the scale of a terroir (at the local scale). Little research has addressed the future impacts of climate change on agro-climatic potential at fine scales. Yet in some soils (especially in complex terrain), changes in atmospheric parameters are very important over relatively small areas (of the order of a few kilometers to a few meters) and the quality of grapes and wine is often related to these local characteristics (slope, soil, etc.). Observation and modeling at the fine scale must therefore be considered in the development of strategies for adapting to climate change impacts on vineyard and interactions with terroir (Quénol *et al.*, 2014).

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