WINE GROWING REGIONS GLOBAL CLIMATE ANALYSIS

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Abstract
We depict the main features of five viticulture agroclimatic indices for 626 wine growing regions within 41 countries. The indices are calculated using the WorldClim 30 sec arc (1 km) resolution database, updated for the period 2000-2014 using CRU3.2 database. The spatial limits of each region are given by the Vineyard Geodatabase, an electronic map elaborated from various sources (Atlases, wine region maps, land cover database...).

Keywords: Climate, viticulture, vineyard geodatabase, WorldClim, Growing season temperature, temperature extremes

1 INTRODUCTION

The relentless evolution of computer calculation and storage power together with GIS sciences have allowed climatologist to elaborate accurate databases and to share them with public. While research aiming at documenting and analyzing climate characteristics and variability within and between wine producing regions worldwide has been performed on the basis of station data in the past Gladstones 1992; Tonietto and Carbonneau 2004; many researches are being performed using gridded high spatial resolution data set Vaudour et al. 2015. Amongst available products, the WorldClim database (Hijmans et al. 2005) is a widely used source of climate data. It consists in a collection of grids of monthly temperature and rainfall averages on the period 1950-2000 at various resolutions, down to 30 arc seconds (about 1 km² at mid latitudes). Such resolution is very useful to investigate the climate diversity in viticulture, as vineyards are often located in complex terrain. WorldClim has already been used to depict the climate spatial variability in wine producing regions in Portugal (Jones and Alves), Europe (Bois et al. 2012) and a in few other regions of the world (Jones et al. 2009). These studies, as many others Anderson et al. 2012; Jones et al. 2010, describe climate conditions using data averages calculated for the late 20th century (e.g. 1950-2000, 1960-1990, 1970-2000, …). These period are considered as reference periods for climate description and are commonly choosen as historical references to compare climate projection thoughout the 21st century. However, one has to keep in mind that climate has already changed since the beginning of the 21st century, and these data are now outdated to depict current climate condition of wine producing regions. Yet, little high resolution data are available to update previous analysis of world vitivinicultural terroirs.

Another challenge to depict accurately climate conditions in wine producing region is the need for precise limits of wine regions. In Europe, very high spatial precision of wine regions limits can be reached with the Corine Land Cover database European Environment Agency 2007. In other parts of the world, geographical indications (GI) limits can be found, such as Australia's GI or USA's AVA (American Viticulture Areas). GI cover usually areas that are much larger than regions actually planted with vine, and might encompass zones that will probably never be suitable for grapevine cultivation (i.e. urban areas, lakes…).

The aim of this paper is to document the climate conditions of wine growing regions worldwide, by depicting temperature and rainfall averages 2000-2014. An update of the WorldClim data based on the early 21st century has been performed by downscaling the CRU TS database Harris et al. 2014 in its latest version (3.23). In parallel, we introduce the Vineyard Geodatabase (VGDB v1.1.2) which aims at delineating rather precisely most of the wine producing regions worldwide. By combining both datasets we compare the changes in growing season temperature and rainfall, as well as thermal risk indices from 1950-2000 to 2000-2014 periods.

2 MATERIALS AND METHODS

2.1 Climate data

Climate monthly rainfall (Prec), minimum (Tmin) and maximum (Tmax) temperatures averaged on the 1950-2000 period (hereafter referred to as HIST) were collected at 30 sec arc resolution from the WorldClim (WC) climate database Hijmans et al. 2005. To match current climate conditions, WorldClim data was updated to the 2000-2014 period (hereafter referred to as CURRENT). The CURRENT period is not available in the WorldClim database. We performed this update the latest available version (3.23) of Climate Research Unit

(CRU) TS gridded data at 0.5° resolution Harris et al. 2014. The CRU TS 3.23 database provides monthly interpolated climate data from 1901 to 2014. To downscale CRU TS 3.2 data at WorldClim resolution for CURRENT period (i.e. "updating" WorldClim data), we used a so called "delta approach". First, averages on HIST and CURRENT periods for each month and each climate variable (Prec, Tmin and Tmax) were calculated (36 grids at 0.5 resolution for each HIST and CURRENT periods). Then we calculated the difference (DELTA) of each monthly averages between CURRENT and HIST periods : $CRU\_DELTA_{i,j} = CRU\_CURRENT_{i,j} - CRU\_HIST_{i,j}$; where CRU_ is the CRU TS 3.23 0.5° resolution gridded dataset for each i variable of the month j averaged on the HIST or CURRENT periods. CRU_DELTA grids were downscaled to match WorldClim (WC) 30 sec arc resolution using bilinear interpolation. The resulting WC_DELTA, was then added to WorldClim 1950-2000 (HIST) grids : $WC\_CURRENT_{i,j} = WC\_HIST_{i,j} + WC\_DELTA_{i,j}$; where WC_ is the WorldClim 30 sec arc resolution dataset for each i variable of the month j.

Using WC_HIST and WC_CURRENT monthly grids, we calculated 5 agroclimatic indices for viticulture:

- The growing season temperature average Jones 2006 ; hereafter referred to as GST, widely used in climate-viticulture related literature. This corresponds to the average temperature from April to October on the north hemisphere and October to April for the south Hemisphere;
- The growing season rainfall (hereafter referred to as GSR), which correspond to cumulated rainfall on the same period as for GST:
- The Winter Freeze Index (WFR), calculated as the minimum temperature of January (July) in the North (South) hemisphere Benjamin Bois et al. 2014;
- The Spring Frost Index (SFR), calculated as the minimum temperature of April (October) in the North (South) hemisphere Benjamin Bois et al. 2014;
- The heat stress index (HSI), calculated as the maximum temperature of July (January) in the North (South) hemisphere Benjamin Bois et al. 2014.

Those indices are relevant only for non-tropical viticulture regions (i.e. where one vegetative cycle is possible each year, usually taking place in the growing season period presented above and where HSI, SFR and WFR are valid). No reference exists to identify from climate data whether a given area offers tropical or non-tropical conditions from viticulture, i.e. the possibility to the grower to produce grapes throughout the year, with more possibly more than one harvest a year. Conceiçao et al 2012 proposed to identify tropical regions where there is 20% frequency or lower to have a month a year which minimum temperature is below -2°C. This frequency could not be calculated using WC long term averages. We limited therefore the current study to regions located at latitude higher than 23.5°N or S (the approximate latitude of Cancer and Capricorn tropics lines).

2.2 The vineyard geodatabase

Since 2009, we've been building a numeric map of wine producing region called the Vineyard Geodatabase (VGDB) which preliminary version has been used in a previous paper B. Bois et al. 2012. The VGDB has been established using wine atlases mostly the World Atlas of Wine by Johnson and Robinson 2013 and maps to locate the major wine producing regions worldwide. This database has been greatly improved in 2015 (Gavrilescu, 2015) when many vitivinicultural regions limits have been adjusted by analyzing aerial photographs as displayed in Google Earth©. In Europe, the CORINE Land Cover 2006 version European Environment Agency 2007 was used to restrict wine regions to areas actually planted with vines. The current version of VGDB (v1.1.2) references 626 wine growing regions worldwide (figure 1). It will shortly be made available online.
The removal of regions located in the intertropical area basically led to eliminate all winegrowing regions located in Bolivia, Peru, and Northern Brazil (Sao Francisco valley region).

Within VGDB, we gathered worldwide wine producing areas in 9 sub-regions:
We extracted each WorldClim HIST and CURRENT agroclimatic indices pixel at 30 sec arc resolution located within the each region limits, and we calculated basic descriptive statistics. In this paper, we focus mostly on regions median values of each agroclimatic index. Extreme (min and max) values are not analyzed, as, despite a thorough delimitation of vineyards limits within VGDB, some regions might still contain some specific topographical features (direct sea proximity, high elevation) which might be either not relevant for grape cultivation or subject to interpolation errors within the WorldClim database.

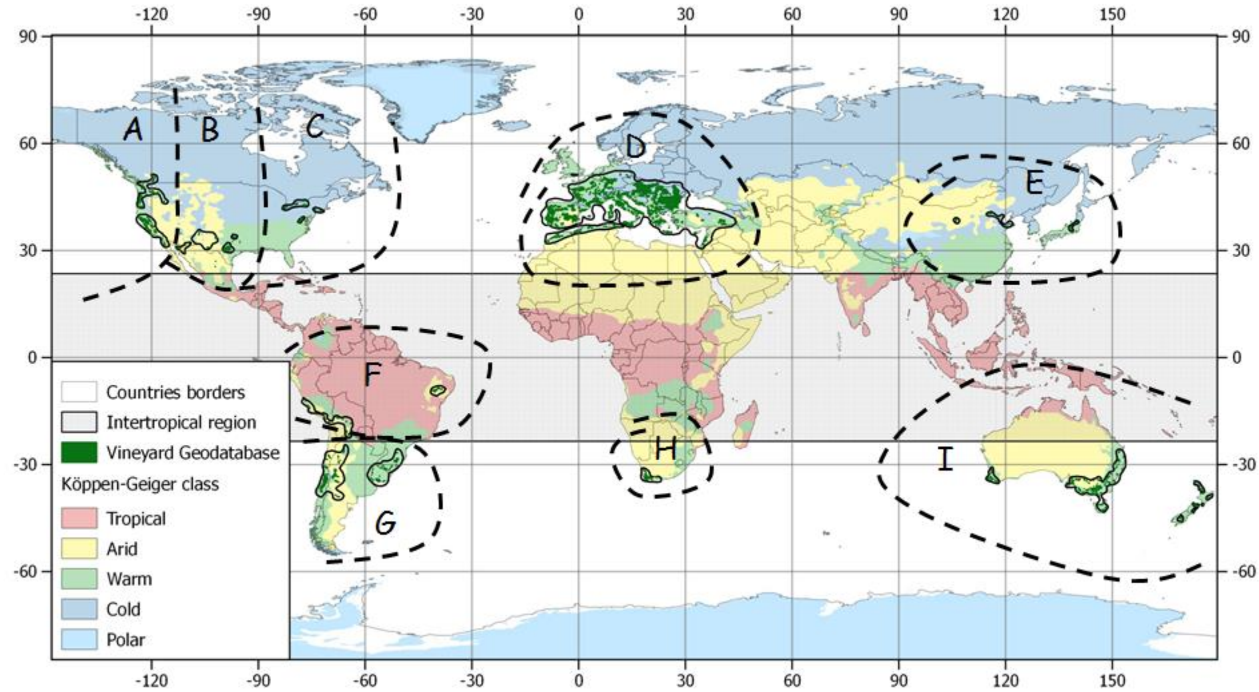

Figure 1: A map of the Vineyard Geodatabase, version 1.1.2. The background colors indicate the Köppen-Geiger classification map from Peel at al. 2007. The dashed lines delimits 9 world regions of wine production : A : Western North America ; B : Central North America, C : Eastern North America, D : Europe and Mediterranean, E : Eastern Asia ; F : Northern South America, G : Southern South America H : South Africa, I: Australia and New Zealand.

3 RESULTS AND DISCUSSION

3.1 Recent climate change in wine regions

Considering all 30 sec arc pixels located within wine regions delimited in the vineyard geodatabase, average growing season temperature (GST) of wine growing regions worldwide ranges from 15.5°C to 24.5°C (0.05 and 0.95 quantiles, table 1). The median is 19.8°C (table 1). GST median has risen of 0.8°C from CURRENT to HIST. The largest increase can be seen in Europe and Mediterranean, with the highest rise in Tunisia (median = +1.8°C) and the lowest in in Portugal (+0.63°C). Little increase in GST is observed in Western North America (+0.1°C), though some specific regions exhibit clear temperature increase such as in Applegate Valley (Southern Oregon; +0.8°C). In contrast, GST has decreased in Temeluca region (Southern California; -0.4°C). GST increase is also moderated in Australia and New Zealand. In New Zealand, no change in GST median value is observed, consistently to Sturman and Quénol 2013 earlier reports in Malbourough valley (where thermal amplitude has risen, but not average annual temperature).

Growing season rainfall 2000-2014 VGDB median is 269 mm. It ranges (0.05 to 0.95 quantiles) from 48 to 787 mm. Eastern North America exhibit a wetter early 21st century, especially in the Finger Lakes region (+117 mm in the Cayuga Lake region). This part of the world gathers wine producing regions with very high rainfall amounts during the growing season (median = 598 mm), as in Central North America (median GSR = 510 mm), where the largest region is this part of the world, Texas Hill Country, has a median GSR of 526 mm. In Eastern Asia (especially North East China) median rainfall during the growing season has decreased (CURRENT – HIST) from -13 (Ningxia region) to -60 mm (Beijing region).

Cold risk related indices decline in most of the region, except in South America, where the winter freeze index (WFR) has fall by 0.2°C, without consequences for cold damage risk, as WFR remains much higher than 4°C upper limit from cold damage as proposed by Benjamin Bois et al. 2014. Heat stress has considerably increased in wine regions worldwide (HSI median +0.9 higher for CURRENT climate), except in North America. The highest increases are found in Eastern Asia (+1.1°C) and in Europe (+1°C, especially Eastern Europe and central Spain), Turkey, Israel and Turkey. 25% of the wine regions as depicted by the vineyard geodatabase exhibit HSI over 33.6°C (table 1). When HSI equals 30°C, 1 to 12 hot days during the fruit development period are expected daily maximum temperature > 35°C ; Benjamin Bois et al. 2014. Over HSI = 30°C, the number of hot days raises rapidly to reach 100 hot days to reach 100 hot days when HSI equals 40°C. White et al. 2006 observed that premium wines regions in the US were located where the number of hot days during grape growing season was below 14, on 1980-2003 period. With a median heat stress index of 31.3°C (results not shown), Napa Valley currently exhibits increased probability to reach such hot days frequency. In Central North America, the extreme heat frequency becomes challenging, as within the Valdepeñas region in Spain (median HSI = 34.8°C, data not shown) or San Juan in Argentina (median HSI = 34.9°C, data not shown).

Table 1: Agroclimatic indices (2000-2014) statistics of wine producing areas depicted by the vineyard geodatabase (version 1.1.2). Columns with +/- signs indicate the changes in statistics (CURRENT minus HIST). See text for acronyms definitions. Statistics in percent are quantiles.

	Statistics	ELV [m]	GST [°C]		GSR [mm]		WFR [°C]		SFR [°C]		HSI [°C]	
All wine regions	5%	**23**	**15.5**	*+0.6*	**48**	*-6*	**-6.1**	*+1.0*	**3.4**	*+0.5*	**25.2**	*+0.5*
	25%	**104**	**17.7**	*+0.6*	**151**	*-7*	**0.4**	*+0.5*	**6.8**	*+0.7*	**28.4**	*+0.9*
	Median	**236**	**19.8**	*+0.8*	**269**	*+9*	**2.4**	*+0.4*	**8.6**	*+0.7*	**30.7**	*+0.9*
	75%	**509**	**22.1**	*+0.8*	**462**	*-15*	**4.7**	*+0.2*	**11.5**	*+1.0*	**33.6**	*+0.6*
	95%	**957**	**24.5**	*+0.5*	**787**	*+50*	**8.2**	*+0.3*	**13.2**	*+0.6*	**35.9**	*+0.2*
Europe and Mediterranean	Median	**195**	**19.3**	*+1.1*	**316**	*+11*	**2.0**	*+0.7*	**7.9**	*+1.0*	**29.6**	*+1.0*
Eastern North America	Median	**185**	**16.1**	*+0.5*	**598**	*+58*	**-8.1**	*+0.6*	**2.3**	*+0.4*	**27.4**	*+0.0*
Central North America	Median	**465**	**24.1**	*+0.5*	**510**	*-3*	**1.1**	*+0.5*	**12.2**	*+0.5*	**34.2**	*-0.2*
Western North America	Median	**106**	**19.0**	*+0.1*	**76**	*+0*	**2.5**	*+0.3*	**7.1**	*+0.5*	**32.9**	*+0.0*
Southern South America	Median	**355**	**19.8**	*+0.4*	**194**	*+6*	**3.6**	*-0.3*	**10.7**	*+0.9*	**30.6**	*+0.6*
South Africa	Median	**199**	**21.0**	*+0.9*	**153**	*-35*	**6.4**	*+0.6*	**11.0**	*+0.9*	**30.5**	*+0.7*
Australia and New Zealand	Median	**115**	**18.0**	*+0.3*	**245**	*-11*	**4.8**	*+0.4*	**8.2**	*+0.0*	**28.2**	*+0.8*
Eastern Asia	Median	**609.5**	**19.1**	*+1.0*	**333**	*-57*	**-11.5**	*+1.5*	**5.9**	*+2.0*	**30.8**	*+1.1*

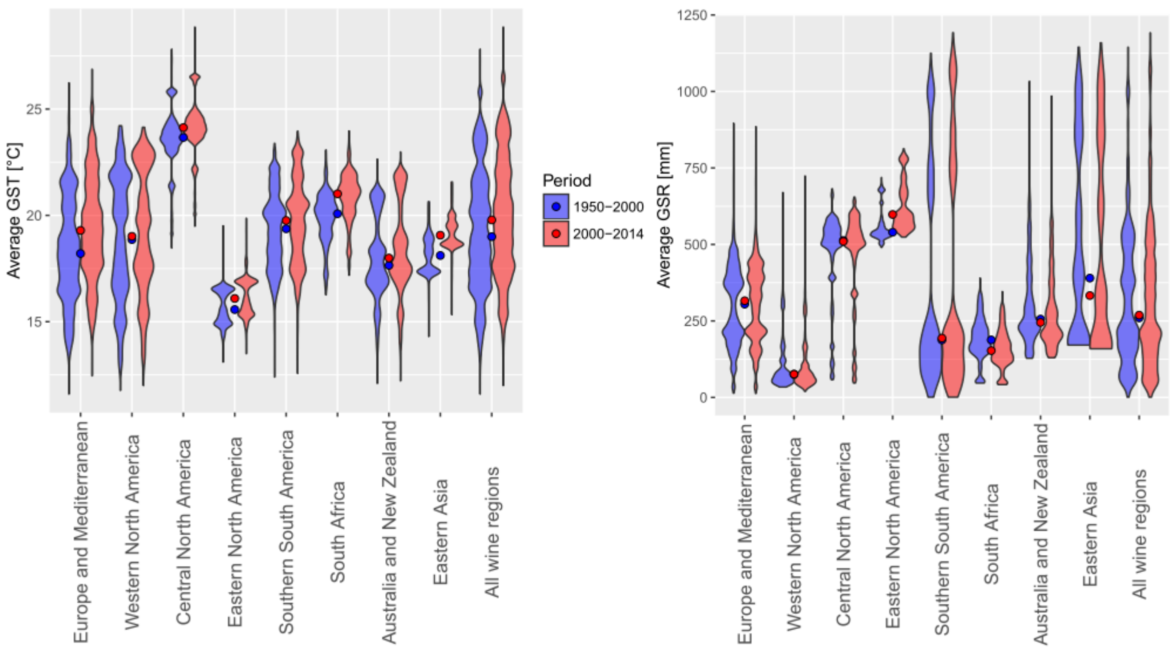

Figure 2: HIST (1950-2000) and CURRENT (2000-2014) GST (right) and GSR (left) distributions (kernel density estimates) within wine regions worldwide. The dots indicate the median values for HIST (blue) and CURRENT (red) periods.

HIST and CURRENT GST and GSR distributions have little changed (figure 2). Europe/Mediterranean and Western North America exhibit the largest ranges of average temperature during the growing season. 90% of GST values (0.05 to 0.95 quantile) in Europe and Mediterranean (Western North America) are between 15.5

(14.5) to 23.5°C (23.2°C). In contrast, Central North America exhibits a narrow and warm inter-quantile range (21.8°C to 26.5°C) and Eastern North America exhibits a narrow and cool (14.9°C to 17.6°C) GST inter-quantile range. GSR distribution in Europe and Mediterranean exhibits two modes (240 and 320 mm approx.). 75% of Western North America wine regions collect less than 138 mm during the growing season, consistently to the wide use of irrigation for viable wine production. In Southern South America, GSR distributions show two groups: a first group (Chile and Argentina) with less than 300 mm approx. and a second group receiving considerable rainfall amounts from October to April, in Uruguay and Southern Brazil (figure 3). Considerable rainfall amounts are also found in Japan (figure 3, GSR median from 844 to 1062 mm).

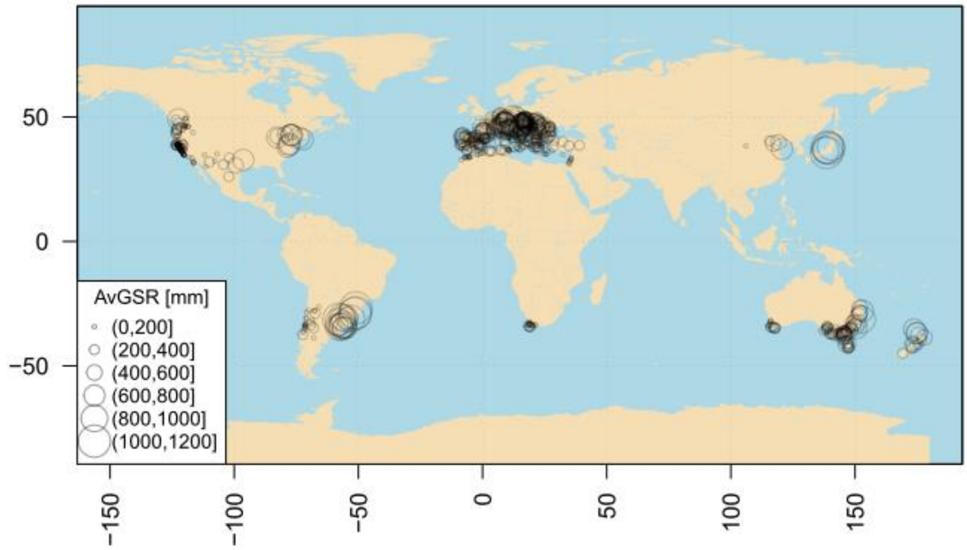

Figure 3: CURRENT (2000-2014) median GSR values of wine producing regions worldwide. Each circle corresponds to each wine producing region documented in VGDB v1.1.2.

4 CONCLUSION

While large scientific literature document the climate of the second half of the 20th century in many wine producing regions worldwide, none (to our knowledge) evaluates the early 21st century vitivinicultural terroir climate. The current paper fills this gap, and shows that significant changes in temperature are found in most of the wine producing regions worldwide. The elaboration of both updated high resolution gridded data for 2000-2014 together with a fine delineation of wine producing region should find many applications to better understand vitiviniculture and climate relationships. The ranges of current climate conditions of wine producing regions are useful references to evaluate the potentialities of areas where grapevine is currently not cultivated. It is also useful to evaluate the future opportunities and challenges of vitiviniculture in the 21st century using projected climate data. Finally, comparing climate conditions between regions could help to better assess the "climate plasticity" (adaptability) of grapevine cultivars for wine production.

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