

Climate, Grapes, and Wine: Structure and Suitability in a Changing Climate

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Abstract

Climate is a pervasive factor in the success of all agricultural systems, influencing whether a crop is suitable to a given region, largely controlling crop production and quality, and ultimately driving economic sustainability. Climate's influence on agribusiness is never more evident than with viticulture and wine production where climate is arguably the most critical aspect in ripening fruit to optimum characteristics to produce a given wine style. To understand climate's role in growing winegrapes and wine production one must consider 1) the weather and climate structure necessary for optimum quality and production characteristics, 2) the climate suitability to different winegrape cultivars, 3) the climate's variability in wine producing regions, and 4) the influence of climate change on the structure, suitability, and variability of climate. This survey article discusses our knowledge of these relationships and details the significance of climate change on the wine industry.

INTRODUCTION

Structure and Suitability

As a component of terroir, climate arguably exerts the most profound effect on the ability of a region or site to produce quality grapes and therefore wine. Worldwide, the average climatic conditions of wine regions determine to a large degree the grape varieties that can be grown there, while wine production and quality are chiefly influenced by site-specific factors, husbandry decisions, and short-term climate variability (Jones and Hellman, 2003). Historically there have been numerous temperature-based metrics (e.g., heat summation, degree-days, mean temperature of the warmest month, average growing season temperatures, etc.) that have been used for establishing optimum climates for the range of winegrape cultivars (Gladstones, 1992; Tonietto and Carbonneau, 2004; Jones, 2006). This is not to say that precipitation or any other weather/climate factor is not important, but that temperature is the most influential factor in overall growth and productivity of winegrapes. At the global scale the general bounds on climate suitability for viticulture are found between 12-22°C for the growing season in each hemisphere (Jones, 2007; Fig. 1). As seen in Figure 1 the 12-22°C climate bounds depict a largely midlatitude suitability for winegrape production, however many sub-tropical to tropical areas at higher elevations also fall within these climate zones. Furthermore, any general depiction of average temperatures will also include large areas that have not been typically associated with winegrape production. This is evident in Figure 1 where large areas of eastern Europe, western Asia, China, the mid-western and eastern United States, southeastern Argentina, southeastern South Africa, and southern Australia fall within the 12-22°C thresholds. While many of these regions may have the growing season temperatures conducive to growing winegrapes, other limiting factors such as winter minimum temperatures, spring and fall frosts, short growing seasons, and water availability would limit much of the areas mapped to the average conditions. Furthermore,

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while the vast majority of the world's wine regions are found within these average growing season climate zones, there are some exceptions. For example, there are defined winegrape growing areas in the United States (Texas, Oklahoma, and the Mississippi delta region), Brazil (São Francisco Valley), and South Africa (Lower Orange River in the Northern Cape) that are warmer than 22°C during their respective growing seasons. However, these regions have different climate risks, have developed viticultural practices to deal with the warmer climates (e.g., two crops per year, irrigation, etc.), or produce table grapes or raisins, and do not necessarily represent the average wine region.

Further refining the climate suitability for many of the world's most recognizable cultivars, Jones (2006) shows that high quality wine production is more realistically limited to 13-21°C average growing season temperatures (Fig. 2). The climate-maturity zoning in Figure 2 was developed based upon both climate and plant growth for many cultivars grown in cool to hot regions throughout the world's benchmark areas for those winegrapes. While many of these cultivars are grown and produce wines outside of the bounds depicted in Figure 2, these are more bulk wine (high yielding) for the lower end market and do not typically attain the typicality or quality for those same cultivars in their ideal climate. Furthermore, growing season average temperatures below 13°C are typically limited to hybrids or very early ripening cultivars that do not necessarily have large-scale commercial appeal. At the upper limits of climate, some production can also be found with growing season average temperatures greater than 21°C, although it is mostly limited to fortified wines, table grapes and raisins (up to 24°C).

An example of cool climate suitability depicted in Figure 2 is found with the widely recognized "Pinot Noir" cultivar, which is typically grown in regions that span from cool to lower intermediate climates with growing seasons that range from roughly 14.0-16.0°C (e.g., Burgundy or northern Oregon). The coolest of these is the Tamar Valley of Tasmania, while the warmest is the Russian River Valley of California. Across this 2°C climate niche, "Pinot Noir" produces the broad style for which it is known with the cooler zones producing lighter, elegant wines and the warmer zones producing more full-bodied, fruit-driven wines. While "Pinot Noir" can be grown outside the 14.0-16.0°C growing season average temperature bounds it typically is unripe or overripe and readily loses its typicality. As examples of intermediate to warmer climate cultivars, the noble winegrapes "Cabernet Franc" and "Cabernet Sauvignon" are clearly two of the most widely recognized in the world. The spread of these two cultivars worldwide has produced an assortment of wine styles from quite diverse regions. Figure 2 shows this wide diversity with both "Cabernet Franc" and "Cabernet Sauvignon" having roughly 3.5°C climate ranges, nearly double that of "Pinot Noir". "Cabernet Franc" can be grown in intermediate to warm climates (15.4-19.8°C) as evidenced by its quality production in the Loire Valley of France. "Cabernet Sauvignon" on the other hand is grown in regions that span from intermediate to hot climates with growing seasons that range from roughly 16.8-20.2°C (e.g., Bordeaux or Napa). The lower climate limit for "Cabernet Sauvignon" suitability is found in Hawke's Bay, New Zealand while the upper climate limit is found in Robertson, South Africa.

Another example of both broad climate and wine styles diversification can be found with "Chardonnay" (Fig. 2). As "Chardonnay" production expanded worldwide it was found to be one of the most flexible and forgiving cultivars, producing a range of wine styles. "Chardonnay" can be grown in relatively cool climates (~14-16°C) creating an elegant, crisp style that is flavored more by apple, pear, and fig while in warmer climates (~16-18°C) it produces a bolder style with more peach to honey notes that could be enhanced via the use of oak barrel ageing. Cultivar diversification within regions is also evident in Figure 2 with two notable examples. The Piedmont region of Italy has become known for its red wines which are made from either "Dolcetto" or "Nebbiolo". While both cultivars are grown over a relatively narrow climate range, "Dolcetto" does better in a slightly cooler climate (16.4-18.4°C) while "Nebbiolo" does better in a warmer climate (17.8-20.4°C) with a long growing season. The Piedmont region has therefore diversified its production and quality potential in that during cool years "Dolcetto" ripens

best, during warm years Nebbiolo does better, and during average years they both do relatively well. Another example of cultivar-climate diversification is in Bordeaux where the average growing season temperatures of 16.8-17.8°C makes it ideal to Cabernet Franc, Cabernet Sauvignon, and Merlot, albeit with warmer years favoring higher Cabernet Sauvignon quality.

Climate Variability

While the average climate structure in a region determines the broad suitability of winegrape cultivars, climate variability influences issues of production and quality risk associated with how equitable the climate is vintage to vintage. Climate variability in wine regions influences grape and wine production through cold temperature extremes during the winter in some regions, frost frequency and severity during the spring and fall, high temperature events during the summer, extreme rain or hail events, and broad spatial and temporal drought conditions. Climate variability mechanisms that influence wine regions are tied to large scale atmospheric and oceanic interactions that operate at different spatial and temporal scales (Fig. 3). The most prominent of these is the large scale Pacific sector El Niño-Southern Oscillation (ENSO), which has broad influences on wine region climates in North America, Australia and New Zealand, South Africa, South America, and Europe (Jones, 2010; Fig. 2). While each of the known climate variability mechanisms reveals some temporal periodicity, increases in climate variability for many wine regions has been observed. Increases in climate variability in a given region would bring about greater risk associated with climate extremes, which in turn would strain the economic viability of wine production in any region (Schultz and Jones, 2010).

Evidence comes from both observations and models where climates have shown changes in both the mean and the variability of temperatures, and precipitation in some cases, in wine regions and elsewhere (Jones, 2007). For example, if the change response of a warming climate was only in the mean, then there would be less cold weather and more hot and record hot weather. On the other hand, increases in the temperature variance alone would result in more cold and hot weather and record conditions. However, evidence points to increases in both the mean and variance which would bring about less change for cold weather events and much more hot weather and record hot weather (IPCC, 2007). For example, Schär et al. (2004) demonstrate that the European summer climate might experience a pronounced increase in year-to-year variability in response to greenhouse-gas forcing. Such an increase in variability might be able to explain the unusual European summer 2003, and would strongly affect the incidence of heat waves and droughts in the future. Evidence of changing climate variability in wine regions was also found by Jones (2005) and Jones et al. (2005a) where the coefficient of variability in the growing season climates throughout the western US and many other wine regions globally has increased over the last 50 years. Jones et al. (2005a) also found that model projections through to 2050 show a continued increase in the coefficient of variability in 20 of 27 wine regions globally.

Climate Change

At the global scale, trends in wine region climates have resulted in warmer growing season climates that have allowed many regions to produce better wine, while future climate projections indicate more benefits for some regions and challenges for others. The observed growing season warming rates for numerous wine regions across the globe during 1950-2000 averaged 1.3°C (Jones et al., 2005a), with the warming driven mostly by changes in minimum temperatures, with greater heat accumulation, a decline in frost frequency that is most significant in the dormant period and spring, earlier last spring frosts, later first fall frosts, and longer frost-free periods (Jones, 2005). However, climate model projections by 2050 for the same wine regions predict growing season warming of an additional 1.5-2.5°F on average. Furthermore, spatial analyses show the potential for relatively large latitudinal shifts in viable viticulture zones with increasing area on the poleward fringe in the Northern Hemisphere (NH) and decreasing area in the

Southern Hemisphere (SH) due to the lack of land mass (Fig. 4). Within regions, spatial shifts are projected to be toward the coast, up in elevation, and to the north (NH) or south (SH). Furthermore, climate variability analyses have shown evidence of increased frequency of extreme events in many regions, while climate models predict a continued increase in variability globally. In addition, phenological changes observed over the last 50 years for numerous locations and varieties globally indicate that grapevines have responded to the observed warming with earlier events (bud break, bloom, veraison, and harvest) and shorter intervals between events that range from 6-17 days depending on cultivar and location (Jones et al., 2005b). Numerous studies point from a 5 to 10 day earlier event response per 1°C of warming (Jones, 2007).

To further place viticulture and wine production in the context of climate suitability and the potential impacts from climate change, Figure 2 provides the framework for examining today's climate-maturity ripening potential for premium quality wine cultivars grown in cool, intermediate, warm, and hot climates (Jones, 2006). From the general bounds that cool to hot climate suitability places on high quality wine production, it is clear that the impacts of climate change are not likely to be uniform across all varieties and regions, but are more likely to be related to climatic thresholds whereby any continued warming would push a region outside the ability to produce quality wine with existing varieties. For example, if a region has an average growing season temperature of 15°C and the climate warms by 1°C, then that region is climatically more conducive to ripening some cultivars, while potentially less for others. If the magnitude of the warming is 2°C or larger, then a region may potentially shift into another climate maturity type (e.g., from intermediate to warm). While the range of potential cultivars that a region can ripen will expand in many cases, if a region is a hot climate maturity type and warms beyond what is considered viable, then grape growing becomes challenging and maybe even impossible.

DISCUSSION

From the discussion above on the climate structure, suitability, and variability associated with regional to global wine production it is clear that viticultural regions are located in relatively narrow geographical and climatic ranges. In addition, winegrapes have relatively large cultivar differences in climate suitability further limiting some winegrapes to even smaller areas that are appropriate for their cultivation. These narrow niches for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than more other more broad acre crops (Jones, 2007). The wine quality impacts and challenges related to climate change and shifts in climate maturity potential have been and will likely continue to be evidenced mostly through more rapid plant growth and out of balance ripening profiles (Jones and Webb, 2010). For example, if a region currently experiences a ripening period that allows sugars to accumulate to favorable levels, maintains acid structure, and produces the optimum flavor profile for that cultivar, then balanced wines result. In a warmer than ideal environment, the grapevine goes through its phenological events more rapidly resulting in earlier and likely higher sugar ripeness and, while the grower or winemaker is waiting for flavors to develop, the acidity is lost through respiration resulting in unbalanced wines without greater after-harvest inputs or adjustments in the winery. As a result of warming conditions to date, higher alcohol levels have been observed in many regions. For example research has found that potential alcohol levels of Riesling at harvest in Alsace have increased by 2.5% (by volume) over the last 30 years and was highly correlated to significantly warmer ripening periods and earlier phenology. For Napa, average alcohol levels have risen from 12.5 to 14.8% from 1971-2001^{1b} while acid levels fell and the pH climbed (Vierra, 2004). Similar changes have been quantified for wines from Australia (Godden and Gishen, 2005) and in Europe

¹ Note that alcohol levels in Napa have continued to rise with the average percent alcohol for all wines from California Crush District 4 (Napa) above 15% since 2002.

(Duchêne and Schneider, 2005) Issues with higher alcohol wines are that they are typically "hotter" and less food friendly and will not age as well or as long as wines with lower alcohol levels. While many may argue that this trend is due to the tendency for bigger, bolder wines driven by wine critics and the economics of vintage rating systems (Vierra, 2004), research has shown that that climate variability and change are responsible for over 50% of the trend in alcohol levels (Jones et al., 2010). Furthermore, the climates of wine regions today allow growers to hang the fruit on the vine longer - this could not be done in the climates of as little as 30-50 years ago when later spring frost, earlier fall frosts, and shorter growing seasons occurred. Finally, harvests that occur earlier in the summer, in a warmer part of the growing season (e.g., August or September instead of October in the Northern Hemisphere) will result in hotter fruit being harvested (which readily loses flavor and aroma compounds) with the potential for greater fruit desiccation, without greater irrigation inputs (Webb et al., 2007).

CONCLUSIONS

Overall, winegrapes are a climatically sensitive crop whereby quality production is achieved across a fairly narrow geographic range. In addition, winegrapes are grown largely in mid-latitude regions that are prone to high climatic variability that drive relatively large vintage differences in quality and productivity. However, while understanding the climate structure and variability in wine regions worldwide provides more exacting varietal selections and vintage to vintage production management, the projected rate and magnitude of future climate change will likely bring about numerous potential impacts for the wine industry, including - added pressure on increasingly scarce water supplies, additional changes in grapevine phenological timing (Bindi et al., 1996), further disruption or alteration of balanced composition in grapes and wine, regionally-specific needs to change the types of varieties grown, necessary shifts in regional wine styles, and spatial changes in viable grape growing regions. While uncertainty exists in the exact rate and magnitude of climate change in the future, it would be advantageous for the wine industry to be proactive in assessing the impacts, invest in appropriate plant breeding and genetic research (Bisson et al., 2002), be ready to adopt suitable adaptation strategies (Jones and Webb, 2010), be willing to alter varieties and management practices or controls (Schultz and Jones, 2010), or mitigate wine quality differences by developing new technologies.

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Figures

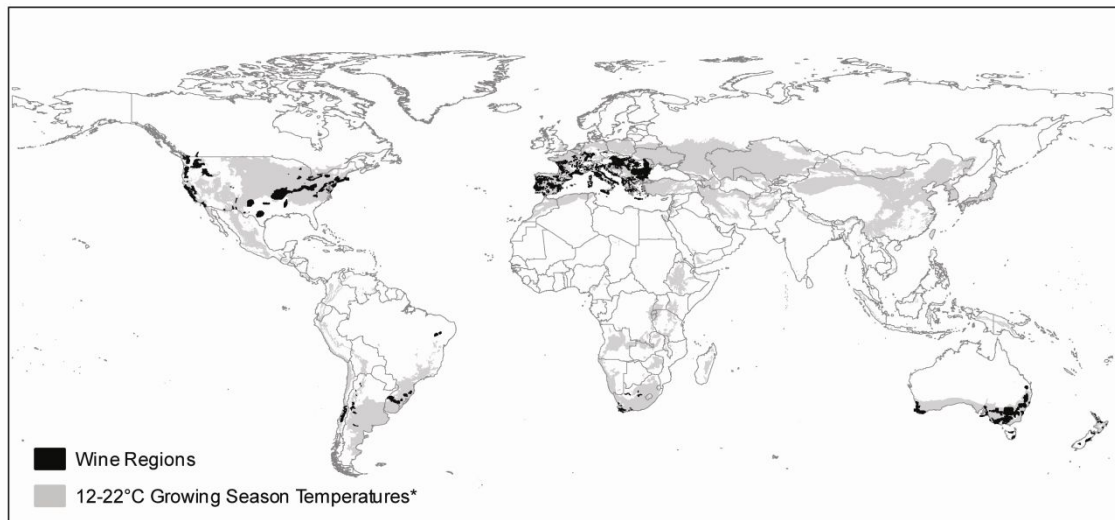


Fig. 1. Global wine regions and 12-22°C growing season temperature zones (Apr.-Oct. in the Northern Hemisphere and Oct.-Apr. in the Southern Hemisphere) as derived from WorldClim (Hijmans et al., 2005). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, Geographic Indicators in Australia and Brazil, and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina, and New Zealand).

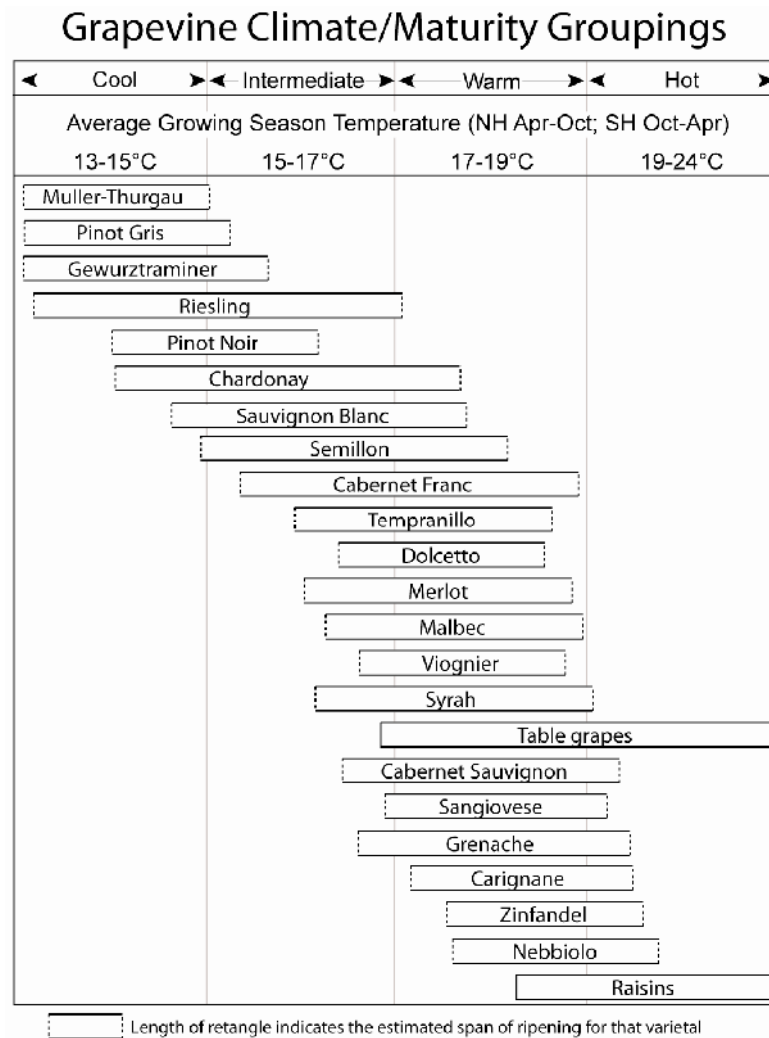


Fig. 2. Climate-maturity groupings based on relationships between phenological requirements and growing season average temperatures for high to premium quality wine production in the world's benchmark regions for many of the world's most common cultivars. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than $\pm 0.2-0.5^{\circ}\text{C}$ are highly unlikely (Jones, 2006).

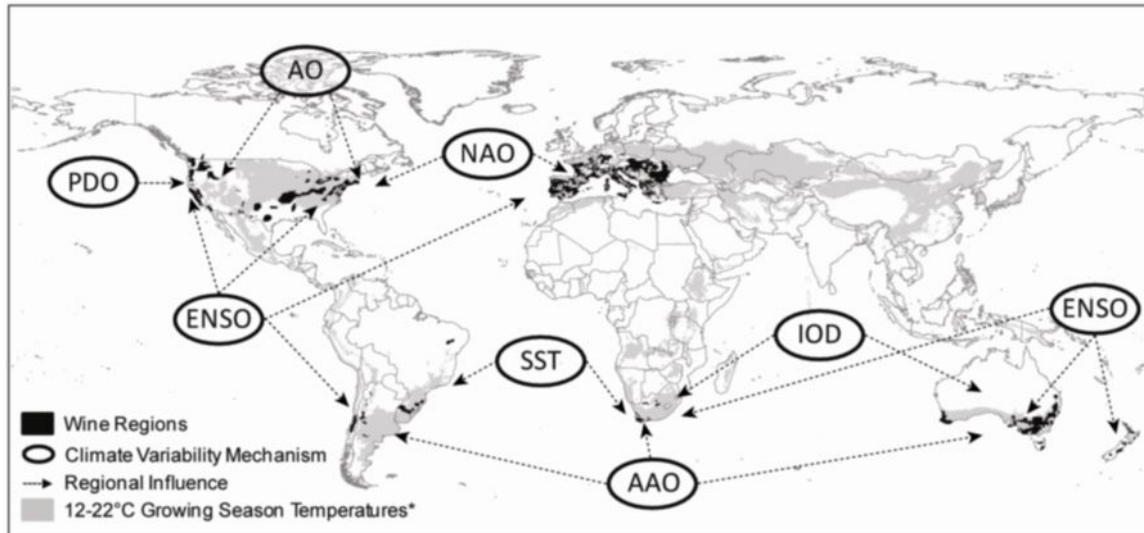


Fig. 3. Global wine regions, general climate zones, climate variability mechanisms, and their areas of known influences as described in the text. The climate data are from WorldClim (Hijmans et al., 2005). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, Geographic Indicators in Australia and Brazil, and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina, and New Zealand). The general climate zones are given by the 12-22°C growing season (Apr.-Oct. in the Northern Hemisphere and Oct.-Apr. in the Southern Hemisphere) average temperatures derived from the WorldClim database (Hijmans et al., 2005). ENSO - El Niño Southern Oscillation, PDO - Pacific Decadal Oscillation, NAO - North Atlantic Oscillation, IOD - Indian Ocean Dipole, AO - Arctic Oscillation, AAO - Antarctic Oscillation, SST - Sea Surface Temperatures.

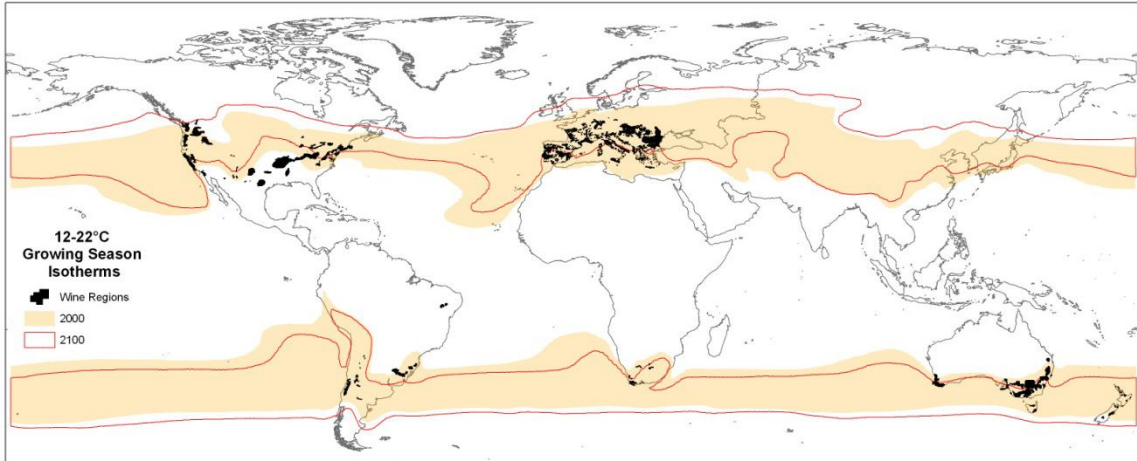


Fig. 4. Map of contiguous growing season average temperature isotherm regions (Northern Hemisphere Apr.-Oct., Southern Hemisphere Oct.-Apr.) derived from observations and model runs from the Community Climate System Model (CCSM). Future projections are driven by the A1B emission scenario (moderate future consumption). The wine regions are as described in Figure 1.