Climate change: observations, projections, and general implications for viticulture and wine production[1]

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1 Climate Change, Viticulture, and Wine

The grapevine is one of the oldest cultivated plants that, along with the process of making wine, have resulted in a rich geographical and cultural history of development (Johnson, 1985; Penning-Roswell, 1989; Unwin, 1991). Today's viticultural regions for quality wine production are located in relatively narrow geographical and therefore climatic niches that put them at greater risk from both short-term climate variability and long-term climate change than other more broad acre crops. In general, the overall wine style that a region produces is a result of the baseline climate, while climate variability determines vintage quality differences. Climatic changes, which influence both variability and average conditions, therefore have the potential to bring about changes in wine styles. Our understanding of climate change and the potential impacts on viticulture and wine production has become increasingly important as changing levels of greenhouse gases and alterations in Earth surface characteristics bring about changes in the Earth's radiation budget, atmospheric circulation, and hydrologic cycle (IPCC, 2001). Observed warming trends over the last hundred years have been found to be asymmetric with respect to seasonal and diurnal cycles with greatest warming occurring during the winter and spring and at night (Karl et al., 1993; Easterling et al., 2000). The observed trends in temperatures have been related to agricultural production viability by impacting winter hardening potential, frost occurrence, and growing season lengths (Carter et al., 1991; Menzel and Fabian, 1999; Easterling et al., 2000; Nemani et al., 2001; Moonen et al., 2002; Jones, 2005c).

To place viticulture and wine production in the context of climate suitability and the potential impacts from climate change, various temperature-based metrics (e.g., degree-days, mean temperature of the warmest month, average growing season temperatures, etc.) can be used for establishing optimum regions (Gladstones, 1992). For example, average growing season temperatures typically define the climate-maturity ripening potential for premium quality wine varieties grown in cool, intermediate, warm, and hot climates (Jones, 2006; Figure 1). For example, Cabernet Sauvignon is grown in regions that span from intermediate to hot climates with growing seasons that range from roughly 16.5-19.5ºC (e.g., Bordeaux or Napa). For cooler climate varieties such as Pinot Noir, they are typically grown in regions that span from cool to lower intermediate climates with growing seasons that range from roughly 14.0-16.0ºC (e.g., Northern Oregon or Burgundy). 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 average temperature of 15ºC and the climate warms by 1ºC, then that region is climatically more conducive to ripening some varieties, while potentially less for others. If the magnitude of the warming is 2ºC or larger, then a region may potentially shift into another climate maturity type (e.g., from intermediate to warm). While the range of potential varieties 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. Furthermore, observations and modeling has shown that climate change will not just be manifested in changes in the mean, but also in the variance where there are likely to be more extreme heat occurrences, but still swings to extremely cold conditions. Therefore, even if average climate structure gets better in some regions, variability will still be very evident and possibly even more limiting than what is observed today.

Overall the wine quality impacts and challenges related to climate change and shifts in climate maturity potential will likely be evidenced mostly through more rapid plant growth and out of balance ripening profiles. For example, if a region currently experiences a maturation period (véraison to harvest) that allows sugars to accumulate to favorable levels, maintains acid structure, and produces the optimum flavor profile for that variety, then balanced wines result. In a warmer than ideal environment, the grapevine will go 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.

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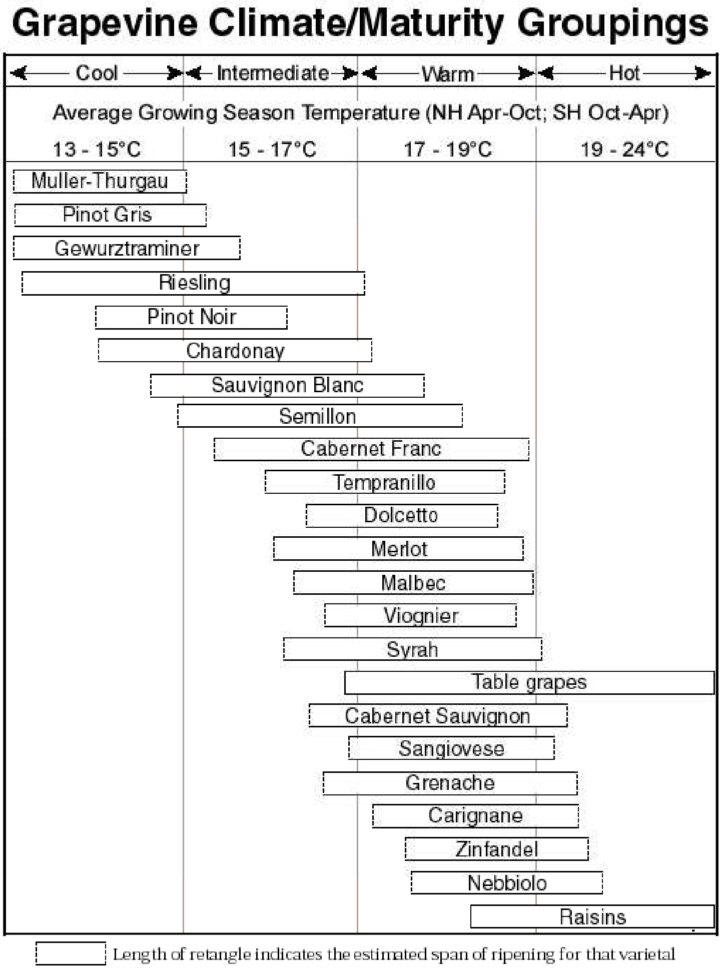

Figure 1. The climate-maturity groupings given in this figure are based on relationships between phenological requirements and climate for high to premium quality wine production in the world's benchmark regions for each variety. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than +/- 0.2-0.6℃ are highly unlikely. The figure and the resea rch behind it are a work in progress (Jones, 2006).

As a result higher alcohol levels have been observed in many regions, for example Duchêne and Schneider (2005) 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. Godden and Gishen (2005) summarize trends in composition for Australian wines,, and while not attributing any influence to the much warmer conditions experienced in Australia today (McInnes et al., 2003; Webb et al., 2005), they show increases in the alcohol content of 12.3% to 13.9% for red wines and 12.2% to 13.2% for white wines from 1984-2004. For Napa, average alcohol levels have risen from 12.5% to 14.8% from 1971-2001 while acid levels fell and the pH climbed (Vierra, 2004). While Vierra (2004) argues that this trend is due to the tendency for bigger, bolder wines driven by wine critics and the economics of vintage rating systems, Jones (2005d) and Jones et al. (2007c) find that climate variability and change are likely responsible for over 50% of the trend in alcohol levels. Besides changes in wine styles, one of the more germane issues related to higher alcohol levels is that wines typically will not age as well or as long as wines with lower alcohol levels. 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 harvested fruit and potentially desiccated fruit without greater irrigation inputs.

2 Historical Observations of Wine Region Climates

History has shown that winegrape growing regions developed when the climate was most conducive and that shifts in viable wine-producing regions have occurred due to climate changes, making production more difficult or easier (Le Roy Ladurie, 1971; Pfister, 1988; Gladstones, 1992). In Europe, records of dates of harvest and yield have been kept for nearly a thousand years (Penning-Roswell, 1989; Le Roy Ladurie, 1971), revealing periods with more beneficial growing season temperatures, greater productivity, and arguably better quality in some regions. Other evidence has shown that vineyards were planted as far north as the coastal zones of the Baltic Sea and southern England during the medieval "Little Optimum" period (roughly 900-1300 AD) when temperatures were up to 1℃ warmer (Gladstones, 1992). During the High Middle Ages (12^{th} and 13^{th} centuries) harvesting occurred in early September as compared to early to mid October today and growing season temperatures must have been at least 1.7℃ warmer than those experienced today (Pfister, 1988; Gladstones, 1992). However during the 14^{th} century dramatic temperature declines lead to the "Little Ice Age" (extending into the late 19^{th} century), which resulted in most of the northern vineyards dying out and growing seasons so short that harvesting grapes in much of the rest of Europe was difficult. In addition, research has used contemporary grape harvest dates from Burgundy to reconstruct spring-summer temperatures from 1370 to 2003 and, while the results indicate that temperatures as high as those reached in the warm 1990s have occurred several times in the region since 1370, the extremely warm summer of 2003 appears to have been higher than in any other year since 1370 (Chuine et al., 2004).

More recent research of the impacts of climate change on wine quality by Jones et al. (2005a) analyzed growing season temperatures in 27 of arguably the best wine producing regions in the world and found that average growing season temperatures warmed 1.3℃ over the last 50 years. However, the warming was not uniform across the regions with greater magnitudes in the western U.S. and Europe, and less warming in Chile, South Africa, and Australia. The greatest warming was seen in the Iberian Peninsula, Southern France, and parts of Washington and California with warming greater than 2.5℃. Figure 2 provides examples of the observed warming for the Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux regions with 1950-1999 warming trends ranging from 0.7-1.8ºC. The study also found that vintage ratings in these same regions (Sotheby's and the Wine Enthusiast: Stevenson, 2002; Mazur, 2002) have shown trends of increasing overall quality with less vintage-to-vintage variation and that growing season temperatures were important factors in vintage ratings across many regions, albeit not uniform across the regions and not always linear. Depending on the region and wine type, the marginal effects of the growing season temperatures show that a 1℃ warmer vintage can result in 10-22 ratings point increases (Jones et al., 2005a). However, the research also notes that the role of factors other than growing season temperatures such as technology and familiarity are important factors in vintage ratings. Furthermore, the research found that climate thresholds are evident in many regions where, once past a given growing season temperature, quality declines are seen. Therefore, the general rule of thumb "the warmer the better" does not apply for all wine regions where some are near or at the optimum growing season temperatures for achieving the highest quality wine.

More regionally specific and temporally resolved analyses concur with the global observations of wine region temperature trends (Jones and Davis, 2000; Jones et al., 2005b; Jones, 2005c). Overall, during the last 30-70 years many of the world's wine regions have experienced a decline in frost frequency, shifts in the timing of frosts, and warmer growing seasons with greater heat accumulation. In North America research has shown significant changes in growing season climates, especially in the western U.S. For example, during 1948-2002 in the main grape growing regions of California, Oregon, and Washington, growing seasons have warmed by 0.9℃, 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, 2005c). Temporal changes for the Napa Valley since 1930 (Jones et al., 2007c) show that heat accumulation is over 350 units higher (degree-days in ℃ units) and has been the result of significant warming at night where the minimum temperatures have climbed 3.0℃ while daytime temperatures have not changed significantly. Precipitation amounts and timing are highly variable in the western U.S., being more tied to larger scale climate variability mechanisms such as El Niño or the Pacific Decadal Oscillation than structural trends (Jones et al., 2007c). A focused study for Napa and Sonoma California, found that higher yields and quality over the last 50 years were influenced by asymmetric warming (at night and in the spring) where a reduction in frost occurrence, advanced initiation of growth in the spring, and longer growing seasons were the most influential (Nemani et al., 2001). In addition, recent analyses of wintertime extreme freeze events for two important growing regions in North America–eastern Washington and the Niagara Peninsula of Canada–reveal that although there has been some warming in moderate minimum temperature levels (days with temperatures less than 0℃), extreme low temperatures (-5℃ or less) have not changed in frequency over the last 75 years (Jones, 2007b). Furthermore, from the limited data available across the U.S., observed changes in grapevine phenology document changes on the order of 2-5 days earlier per decade over the last 25-35 years depending on variety and region (Wolfe et al., 2005; Jones, 2007b) and are strongly correlated to warmer springs and summers.

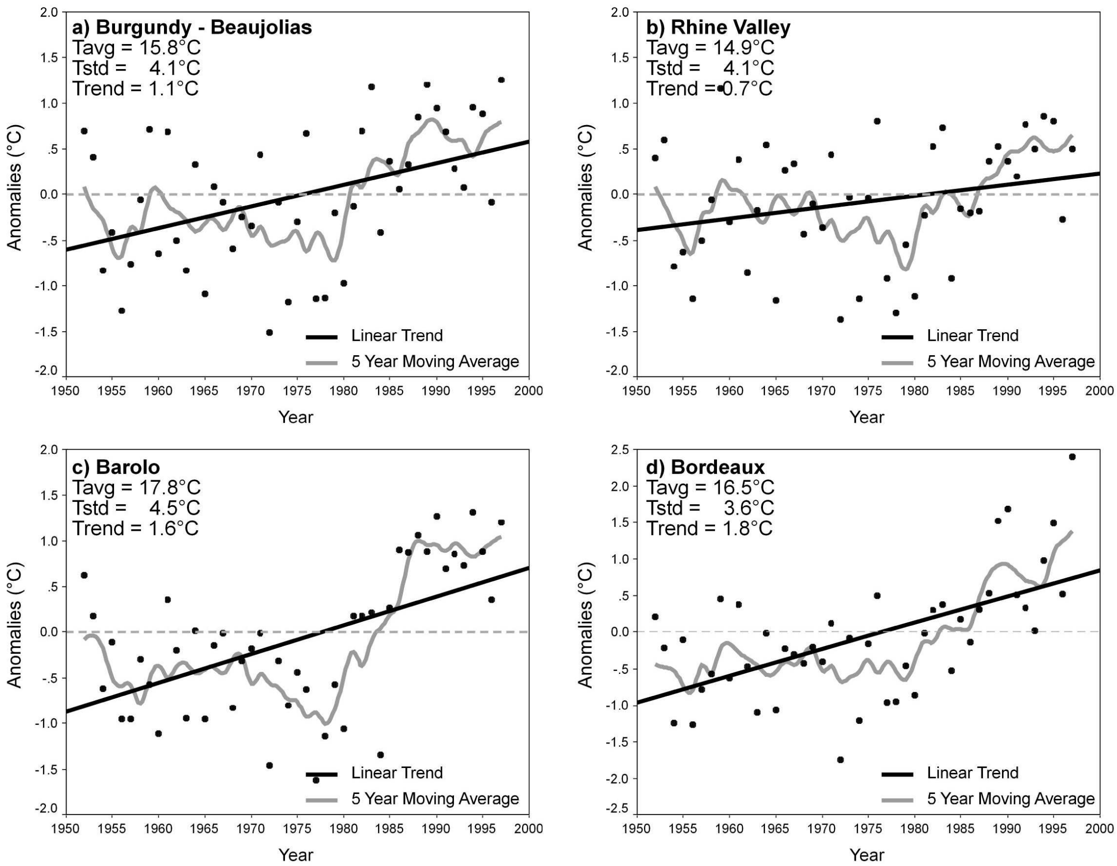

Figure 2. Observed growing season average temperature anomalies for a) the Beaujolais region of Burgundy, b) the Rhine Valley, c) Barolo, and d) Bordeaux as analyzed by (Jones et al., 2005a). The temperature data are monthly values extracted from a 0.5° x 0.5° grid centered over the wine producing regions for 1950-1999. Tavg is the average growing season temperature (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere), Tstd is the standard deviation of monthly temperatures during the growing season, and the Trend is over the 50-year period.

Recent research for Europe has shown similar results as those found in North America detailed above (Jones et al., 2005b). An examination of climate and phenology trends over the last 30-50 years for eleven locations across a range a climate types in Europe (cool to warm) and for 16 varieties shows that warming has occurred across most seasons, but is strongest in the spring and summer. Growing seasons over the studied locations have warmed by 1.7°C on average with most of the warming coming at night. Heat accumulation has increased as well with degree days rising by 250-300 units (°C units) while precipitation frequency and amounts have not changed significantly. Specifically for Spain, Jones et al. (2005b) find growing seasons that have warmed on average by 0.8-1.2°C for the Galicia and Valladolid regions with the warming being much more significant at night (minimum temperatures increasing 1.1-2.1°C) than during the day (not significant). Heat accumulation, either measured by the Huglin Index or Winkler Index (see below), has increased inland but has not changed significantly in the more coastal region of Galicia. Furthermore, grapevine phenological timing in Europe has showed strong relationships with the observed warming with trends ranging 6-25 days earlier over numerous varieties and locations (Jones et al., 2005b). Changes are greatest for véraison and harvest dates which typically show a stronger, integrated effect of a warmer growing season. Interval lengths between the main phenological events have also declined with bud break to bloom, véraison, or harvest dates shortening by 14, 15, and 17 days, respectively. Averaged over all locations and varieties, grapevine phenology shows a 3-6 day response per 1°C of warming over the last 30-50 years.

3 Model Projections of Wine Region Climates

Projections of future climates are produced through models based upon knowledge of how the climate system works and used to examine how the environment, in this case viticulture and wine production, are likely to respond to these changes. These climate models are complex 3-D, mathematical representations of our Earth/Atmosphere system that represent spatial and temporal analyses of the laws of energy, mass, moisture, and momentum transfer in the atmosphere and between the atmosphere and the surface of the Earth. Additionally, climate models are based upon IPCC emissions scenarios (IPCC, 2001) which reflect estimates of how humans will emit CO_2 in the future. The many models in use today, combined with the fact that they are modeling a non-linear system and using different emission scenarios, result in a range of potential changes in temperature and precipitation for the planet (IPCC, 2001). Work over the last three decades using model projections show that the observed warming trends in wine regions worldwide are predicted to continue. From one of the early analyses of the impacts climate change on viticulture, it was suggested that growing seasons in Europe should lengthen and that wine quality in Champagne and Bordeaux should increase (Lough et al., 1983). These results have largely been proven correct. Furthermore, spatial modeling research has also indicated potential shifts and/or expansions in the geography of viticulture regions with parts of southern Europe predicted to become too hot to produce high quality wines and northern regions becoming more stable in terms of consistent ripening climates and/or viable once again (Kenny and Harrison, 1992; Butterfield et al., 2000). Examining specific varieties (Sangiovese and Cabernet Sauvignon), Bindi et al. (1996) found that climate change in Italy should lead to shorter growth intervals but increases in yield variability. Other studies of the impacts of climate change on grape growing and wine production reveal the importance of changes in the geographical distribution of viable grape growing areas due to changes in temperature and precipitation, greater pest and disease pressure due to milder winters, changes in sea level potentially altering the coastal zone influences on viticultural climates, and the effect that increases in CO_2 might have on grape quality and the texture of oak wood which is used for making wine barrels (Tate, 2001; Renner, 1989; Schultz, 2000; McInnes et al., 2003).

At the broadest scale of global suitability for viticulture, it has long been considered that viticulture zones are found between either the mean annual 10-20℃ isotherms (de Blij, 1983; Johnson, 1985) or the growing season 12-22℃ isotherms (Gladstones, 2005; Jones, 2006), however Jones (2007a) found that the growing season criteria is more valid as the 12-22℃ isotherms more completely encompasses the world's viticulture regions (not shown). To examine the global latitudinal bounds of viticulture suitability due to climate, Jones (2007a) used output from the Community Climate System Model (CCSM) on a 1.4°x1.4° latitude/longitude resolution and B1 (moderate), A1B (mid-range), and A2 (high) emission scenarios to depict the 12-22℃ isotherms shifts for three time periods 1999, 2049, and 2099. Changes from the 1999 base period show both shifts in the amount of area suitable for viticulture and a general latitudinal shift poleward (Figure 3). By 2049, the 12℃ and 22℃ isotherms shift 150-300 km poleward in both hemispheres depending on the emission scenario (see Figure 3 for the mid-range A1B scenario). By 2099, the isotherms shift an additional 125-250 km poleward. The shifts are marginally greater on the poleward fringe compared to those on the equatorial fringe in both hemispheres. However, the relative area of land mass that falls within the isotherms across the continents expands in the Northern Hemisphere while contracting in the Southern Hemisphere due to land mass differences (Figure 3). Similar shifting is seen by 2099 for all scenarios (not shown).

Using Hadley Centre climate model (HadCM3) output and an A2 emission scenario (Pope et al., 2000) to 2049 for 27 of the world's top wine producing regions, Jones et al. (2005a) compared the average climates of two periods, 1950-1999 and 2000-2049. The results suggest that mean growing season temperatures will warm by an average 1.3ºC over the wine regions studied with Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux differences ranging from 0.9-1.4ºC (Figure 4). Also, the projected changes are greater for the Northern Hemisphere (1.3ºC) than the Southern Hemisphere (0.9ºC). Examining the rate of change projected for the 2000-2049 period only reveals significant changes in each wine region with trends ranging from 0.2ºC to 0.6ºC per decade. Overall trends during the 2000-2049 period average 2ºC across all regions with the smallest warming in South Africa (0.9ºC/50 years) and greatest warming in Portugal (2.9ºC/50 years). For the Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux regions, decadal trends are modeled at 0.3-0.5ºC while the overall trends are predicted to be 1.5-2.4ºC (Figure 4). In addition, Jones et al. (2005a) showed that many of the wine regions may be at or near their optimum growing season temperature for high quality wine production and further increases, as predicted by the differences between the means of the 1950-1999 and 2000-2049 periods, will place some regions outside their theoretical optimum growing season climate. The magnitude of these mean growing season changes indicate potential shifts in climate maturity types for many regions at or near a given threshold of ripening potential for varieties currently grown in that region. Referring back to Figure 1, where Bordeaux's growing season climate of the last 50 years averaged 16.5ºC and add to it the overall trend in projected warming in Bordeaux of 2.3ºC by 2049. An 18.8ºC average growing season would place Bordeaux at the upper end of the optimum ripening climates for many of the red varieties grown there today and outside the ideal climates for the main white varieties grown. Still more evidence of these impacts come from Napa, where a 17.5ºC historical average is projected to warm by 2.2ºC to 19.7ºC by 2049. This would place Napa at the upper end of optimal ripening climates for nearly all of the most common varieties (Figure 1). Finally, the results also show warming during the dormant periods which could influence hardening potential for latent buds, but observations and models indicate continued or increased seasonal variability which could spell problems in freeze or frost prone regions.

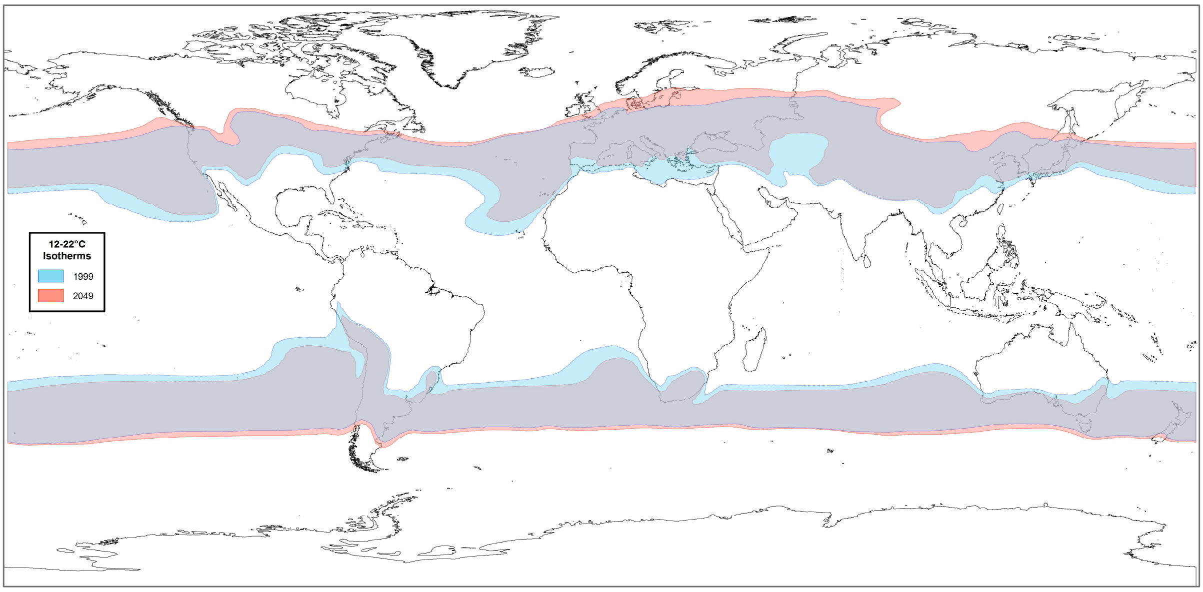

Figure 3. Map of the 12°-22°C growing season average temperature isotherm zones (Northern Hemisphere, Apr-Oct; Southern Hemisphere, Oct-Apr) for 1999 and 2049 derived from observations and model runs from the Community Climate System Model (CCSM). Future projections are driven by the A1B emission scenario (moderate future consumption). The isotherms zones represent the latitudinal limits of the majority of the world's grape growing areas (Gladstones, 2005; Jones, 2006).

For the United States as a whole, White et al. (2006) used a high-resolution (25 km) regional climate model forced by an IPCC A2 greenhouse gas emission scenario and estimated that potential premium winegrape production area in the conterminous United States could decline by up to 81% by the late 21st century. The research found that increases in heat accumulation will likely shift wine production to warmer climate varieties and/or lower-quality wines. Additionally the models show that while frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) in the growing season are projected to completely eliminate winegrape production in many areas of the United States. Furthermore, grape and wine production will likely be restricted to a narrow West Coast region and the Northwest and Northeast, areas where excess moisture is already problematic (White et al., 2006).

From a more regional analysis, Jones (2007d) examined suitability for viticulture in the western U.S., which has long been based on a standard heat summation formulation originally proposed by Amerine and Winkler (1944). Winkler regions are defined by growing degree-days using a base of 10°C over the growing season of April-October. The resulting five regions show broad suitability for viticulture across cool to hot climates and the varieties that grow best in those regions. Using recent historical data at a 1 km resolution (Daymet; Thornton et al. (1997)) depicts that the cooler region I is found higher in elevation, more coastal, and more northerly (e.g., the Willamette Valley) while the warmest region V areas are mostly confined to the central valley and further south in California (e.g., the San Joaquin Valley; Figure 5). Averaged over the 1980-2003 time period, 34% of the western U.S. falls into regions I-V with 59% being too cold (< 1111 °C units) and 7 % too hot (>2778 °C units). Separated into individual regions finds that region I encompasses 34.2%, region II 20.8%, region III 11.1%, region IV 8.7%, and region V 25.2%. Therefore the western U.S. is predominately at the margins of suitability with 59.4% in the coolest and hottest regions (regions I and V, respectively). Using projections for increases in average growing season temperatures from the Community Climate System Model (CCSM) of 1.0-3.0°C for 2049 results in a range of increases in growing degree-days of 15-30% (Figure 5). At a +1.0°C warming (roughly a 15% increase in growing degree days) by 2049, the area of the western U.S. in regions I-V increases 5% from 34% to 39% and at +3.0°C warming (roughly a 30% increase in growing degree days), increases by 9% to 43%. Overall the changes show a reduction in the areas that are too cold from 59% to 41% while the areas that are too hot increase from 7% to 16% in the greater warming scenario (Jones, 2007d). Similarly, by individual region there are shifts to predominately more land in region I (34.2% to 40.6%), smaller changes to region II (20.8% to 23.4%), region III (11.1% to 14.2%), and region IV (8.7% to 10.1%), and a reduction of region V area from 25.2% to 11.6%. Spatially the shifting of regions occurs toward the coast, especially in California, and upwards in elevation (most notably in the Sierra Nevada Mountains). Other regions show large scale shifting from one Winkler region to another (e.g., Willamette Valley shifting from predominately region I to region II).

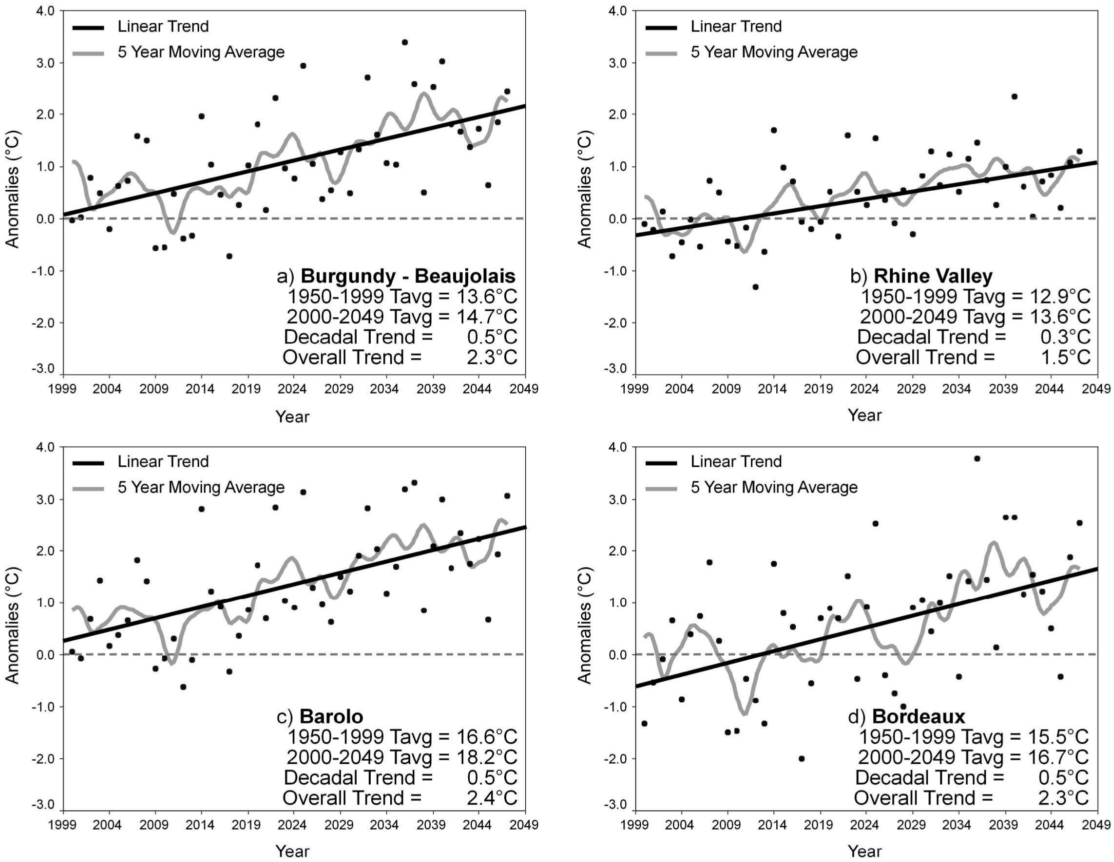

Figure 4 – Modeled growing season average temperature anomalies for a) the Beaujolais region of Burgundy, b) the Rhine Valley, c) Barolo, and d) Bordeaux as analyzed by (Jones et al., 2005a). The modeled temperature data are from the HadCM3 climate model on a monthly time scale extracted from a 2.5° x 3.75° grid cent ered over the wine producing regions for 2000-2049. The anomalies are referenced to the 1950-1999 base period from the HadCM3 model. Trend values are given as an average decadal change and the total change over the 50-year period.

In another regional analysis for the west coast of the U.S., Lobell et al. (2006) examined the impacts of climate change on yields of perennial crops in California. The research combined the output from numerous climate models (testing climate uncertainty) with multiple statistical crops models (testing crop response uncertainty) for almonds, walnuts, avocados, winegrapes, and table grapes. The results show a range of warming across climate models of ~1.0-3.0℃ for 2050 and 2.0-6.0℃ for 2100 and a range of changes in precipitation from -40 to +40% for both 2050 and 2100. Winegrapes showed the smallest yield declines compared to the other crops, but showed substantial spatial shifts in suitability to more coastal and northern counties. The authors also note that yield trends have low attribution to climate trends and are more due to changes in technology (mostly) and an increase in CO_2 (likely).

Other regional work in both Europe (Kenny and Harrison, 1992; Butterfield et al., 2000; Stock, 2005), Australia (McInnes et al., 2003; Webb et al., 2005), and South Africa (Carter, 2006) has examined climate change through different modeling approaches but has come up with similar results. Kenny and Harrison (1992) did some of the early spatial modeling of future climate change impacts on viticulture in Europe and indicated potential shifts and/or expansions in the geography of viticulture regions with parts of southern Europe predicted to become too hot to produce high quality wines and northern regions becoming viable once again. Examining changes in the Huglin Index of suitability for viticulture in Europe (Huglin, 1985), Stock (2005) shows increases of 100-600 units that result in broad latitudinal shifts with new areas on the northern fringes becoming viable, changes in varietal suitability in existing regions, and southern regions becoming so hot that overall suitability is challenged. Specifically in Spain, Rodriguez et al. (2005) examine different emission scenarios to place lower and upper bounds on temperature and precipitation changes and find trends of 0.4-0.7ºC per decade with summer warming greater than in the winter. Overall the changes result in warming by 2100 of between 5-7ºC inland and 3-5ºC along the coast. Concomitant with these temperature projections, Rodriguez et al. (2005) show much drier springs and summers and lower annual rainfall which is less homogeneous across Spain than is temperature. Furthermore, to examine grapevine responses to climate change, Lebon (2002) used model output to show that the start of Syrah ripening (véraison) in Southern France would shift from the second week of August today to the third week of July with a 2ºC warming and to the first week of July with a 4ºC warming. Additionally the research found that significant warming during maturation and especially at night would disrupt flavor and color development and ultimately the wine's typicity (Lebon, 2002).

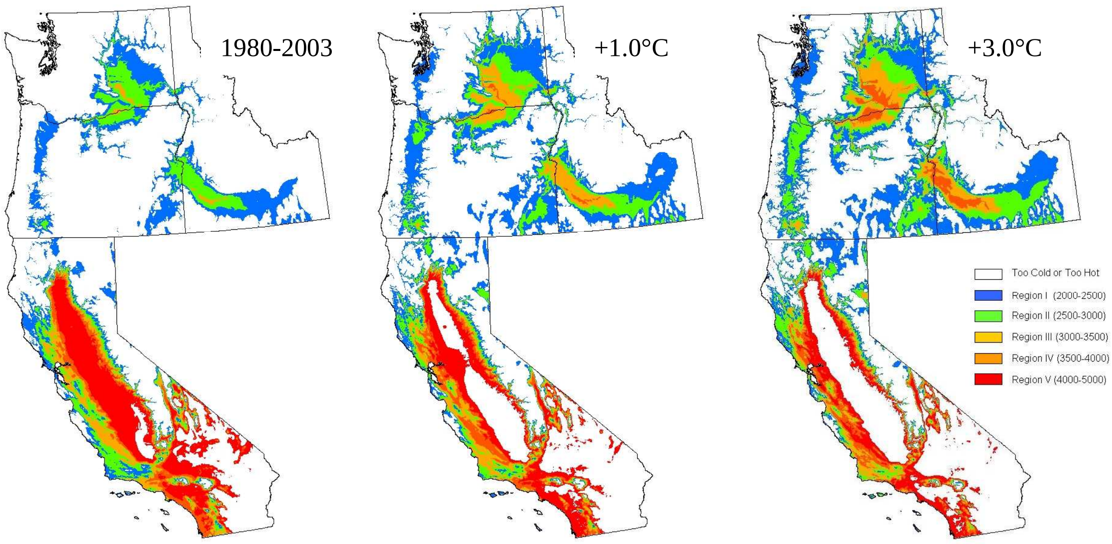

Figure 5 – Winkler Regions for the western U.S. based on Daymet (Thornton et al., 1997) daily 1 km resolution daily temperature data (growing degree-days, base 10℃ over Apr-Oct). The left panel is the average ov er the 1980-2003 time period. The middle panel is a projection of a +1.0℃ increase over 1980-2003 (low range of projected climate change by 2049). The right panel is a projection of a+3.0℃ increase over 1980-2003 (high range of projected climate change by 2049).

In Australia, Webb et al. (2005) analyzed climate change scenarios for viticulture showing that temperatures by 2070 are projected to warm in Australia by 1.0-6.0ºC increasing the number of hot days and decreasing frost risk, while precipitation changes are more variable but result in greater growing season stress on irrigation. The changes projected for Australia has tied future temperature regimes to reduced wine quality with southerly and coastal shifts in production regions being the most likely alternative to maintaining viability. In South Africa, regional projections of rising temperatures and decreased precipitation are projected to put additional pressure on both the phenological development of the vines and on the necessary water resources for irrigation and production (Carter, 2006). The research implies that the practice of winemaking in South Africa is likely to become riskier and more expensive with the most likely effects being shifts in management practices to accommodate an increasingly limited water supply. The author notes that the situation will likely exacerbate other economic issues such as increases in the price of wine, a reduction in the number of wine growers, and need for implementation of expensive and yet unknown adaptive strategies (Carter, 2006). Together these studies, and those detailed previously, indicate that the challenges facing the wine industry include more rapid phenological development, changes in suitable locations for some varieties, a reduction in the optimum harvest window for high quality wines, and greater management of already scarce water resources.

4 Overview and Implications

It is clear from recorded history and proxy records that the climates of the Earth have varied and changed on both long and short timescales (Le Roy Ladurie, 1971; Pfister, 1988). These variations have driven viability in many agricultural systems including viticulture and wine production where in general, and even more specifically for individual varieties, there are narrow climatic optimums that provide limited geographical zones of suitability. The observed warming over the last 50 years appears to have been largely beneficial for viticulture in many regions through longer and warmer growing seasons with less risk of frost. However, the trends have been shown to more influential on the poleward fringes by providing more consistent ripening climates for existing varieties, making warmer climate varieties more viable or opening up once forgotten regions again. On the other extreme, already hot regions have experienced warmer and generally drier conditions that have produced challenges in ripening balanced fruit. Concomitant with the warming trends have come better technology, better plant material, and better vineyard management and these adaptations have allowed growers to meet some of these challenges. However, the projections for future climate change will likely be more rapid and to a greater magnitude than our ability to adapt without increased understanding of the impacts and advances in plant breeding and genetics (Bisson et al., 2002; Vivier and Pretorious, 2002).

Overall climate change is one of the most studied and debated scientific issues of our day. While it is clear from historical evidence that changing climates are a part of the Earth's natural adjustments to both internal and external forces, more and more evidence is pointing to increasing human impacts on our climate. From processes such as desertification, deforestation, and urbanization where the global energy balance is disrupted, to changes in atmospheric composition, which enhances the greenhouse effect beyond its natural equilibrium, our role in climate change is increasing. From the latest Intergovernmental Panel on Climate Change "Summary for Policymakers" (IPCC, 2007), the following statements express our current state of knowledge:

> *"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."*

> *"Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns."*

> *"Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized."*

Given this knowledge, society's role should now shift from one of uncertainties, blame, or attribution, to one of mitigation and adaptation. While the wine industry has some leeway to mitigate fossil fuel use and sequester carbon through more efficient processes both in the vineyard and winery, the bulk of the response will likely be through adaptation. Because we know that winegrapes can only be grown across a fairly narrow range of climates for optimum quality and production, it all depends on where a region is today in terms of climate and the magnitude and rate of the future warming. Observations show and models predict that one of the most important issues for the wine industry will be whether or not achieving optimum varietal ripeness and wine balance will occur in the warmer environment or will we be forced to change varieties or shift regions to achieve the same wine styles. Referring back to Figure 1, note that varietal suitability has a window of only 2-3ºC and that the projections of temperature changes for wine regions around the world range from 1-7ºC. Changes of these magnitudes have the potential to bring about large shifts in suitability.

While most of the discussion has been focused on temperature-related impacts, other potential issues affecting grape and wine quality include changes in vine growth due to a higher CO_2 concentration in the atmosphere, added moisture stresses in water-limited regions, and changes in the presence or intensity of pests and vine diseases. Even with our current state of knowledge, much uncertainty still exists in the exact spatial and temporal nature of changes in climate, therefore the wine industry will need to be proactive in assessing the impacts, be ready to implement appropriate adaptation strategies, be willing to alter varieties and management practices or controls, or mitigate wine quality differences by developing new technologies. However, probably the greatest adaptation challenge will be how we respond culturally to changes in regional identities due to variety changes or wine style changes.

While the <u>exact</u> spatial changes in the magnitude and rate of climate in the future are speculative at this point, what is absolutely clear from historical observations and modeling is that the climates of the future, both over the short term and over the long term, will be different than those today. Can we remain steadfast in our approaches to growing winegrapes or any crop for that matter, likely not. It will be those sectors of agriculture that are the most aware, that experiment with both methods and technology–in plant breeding and genetics, in the field, and in processing–that will have the greatest latitude of adaptation.

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