Past and Future Impacts of Climate Change on Wine Quality

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Abstract

Climate change has the potential to greatly impact nearly every form of agriculture. History has shown that the narrow climatic zones for growing grapes for high quality wines are especially prone to variations in climate and long-term climate change. This analysis has detailed climate changes from 1950 to 1999 for arguably the world's highest quality wine-producing regions showing that the majority of the regions experienced warming trends during their respective growing seasons at the same time that vintage ratings increased significantly while year-to-year variation declined. The results find that climate is a more important factor in vintage ratings in Europe, while many New World regions have seen significant advances in production technology or recognition in their vintage ratings that mask climatic variations. For some regions, an optimum temperature-vintage rating was modeled indicating that many regions are at or near their ideal climate. While the observed warming of the last fifty years appears to have mostly benefited the quality of wine grown worldwide, the average predicted regional warming of 2°C in the next 50 years (2000-2049) has numerous potential impacts including – changes in grapevine phenological timing, disruption of balanced composition in grapes and wine, alterations in varieties grown, alterations in regional wine styles, and spatial changes in viable grape growing regions.

Key Words: climatology, climate change, viticulture, grapes, wine

Introduction

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 (Unwin, 1991; Penning-Roswell, 1989; Johnson, 1985). Today's viticultural regions for quality wine production are located in narrow climatic niches (Figure 1) that put them at particular risk from both short-term climate variability and long-term climate change. 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 therefore have the potential to bring about changes in wine styles. Our understanding climate change and the potential impacts on viticulture (the science of the cultivation of grapevines) and viniculture (the science of the making of wines) 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 (Houghton et al., 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). The observed trends in temperatures have been related to agricultural production viability by impacting winter hardening potential, frost occurrence, and growing season lengths (Menzel and Fabian, 1999; Carter et al., 1991; Easterling et al., 2000; Nemani et al., 2001; Moonen et al., 2002; Jones, 2004).

History has shown that winegrape growing regions developed when the climate was most conducive (Le Roy Ladurie, 1971; Pfister, 1988; Gladstones, 1992). Records of dates of harvest and yield for European viticulture have been kept for nearly a thousand years (Penning-Roswell, 1989; Le Roy Ladurie, 1971) revealing periods with more beneficial growing season temperatures and greater productivity. During the medieval "Little Optimum" period (roughly

900-1300 AD) the data indicate that temperatures were up to 1°C warmer with vineyards planted as far north as the coastal zones of the Baltic Sea and southern England (Gladstones, 1992). During the High Middle Ages (12th and 13th centuries) harvesting occurred in early September as compared to early to mid October today and that growing season temperatures must have been 1.7°C warmer than today (Pfister, 1988; Gladstones, 1992). Conversely, temperature declines during the 14th century were dramatic leading to the "Little Ice Age" (extending into the late 19th century) resulting in northern vineyards dying out and growing seasons so short that harvesting grapes in southern Europe was difficult.

Recent analyses of the impacts climate change on viticulture have suggested that growing seasons in Europe should lengthen and that wine quality in Champagne and Bordeaux should increase (Lough et al., 1983). 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 viable once again (Butterfield et al., 2000; Kenny and Harrison, 1992). Examining specific varieties (Sangiovese and Cabernet Sauvignon), Bindi et al., (1996) find that climate change in Italy will lead to shorter growth intervals but increases in yield variability. 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). Other studies of the impacts of climate change on grape growing and wine production reveal the importance of changes in 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).

Given the importance of climate to viticultural viability and its potential to impact wine styles and quality, Jones et al. (2005) has examined climates in 27 of the world's highest quality wine regions. The research examines the observed changes seen in growing season temperatures, variation and trends in vintage quality, the relationship between observed climate and vintage ratings; and the projected growing season temperature changes from a general circulation climate model. This analysis represents an overview of the Jones et al. (2005) results and provides an additional examination of the potential to predict the optimum growing season climates for the world's best wine producing regions.

Data and Methods

In their analysis, Jones et al. (2005) examine two climate data sets to determine the observed trends in climate and to project potential changes for the future. The research used a 0.5° x 0.5° gridded climatology of monthly mean air temperature to examine the effects on wine quality (Willmott and Matsuura, 2000). The gridded temperature data archive was produced from the Global Historical Climatology Network (GHCN version 2) and Legates and Willmott's (Legates and Willmott, 1990) station records of monthly and annual mean air temperature. Data from 1950-1999 and grids for the respective wine regions (Figure 1 and Table 1) were extracted and averaged over the growing season (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere) to create 27 time series. To examine the potential temperature changes in the wine regions, the authors used a 100-year run (1950-2049) of the HadCM3 coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre (Gordon et al., 2000; Pope et al., 2000) which has been used by numerous others in climate change studies (e.g., Butterfield et al., 2000; Winkler et al., 2002; Fischer et al., 2002; Forest et al., 2002; Palutikof et al., 2002 and others). The AOGCM was developed with a stable control climatology, does not use a flux adjustment, has 19 vertical levels, and has a 2.5° x 3.75°

horizontal resolution (comparable to a spectral resolution of T42). Similar to the 1950-1999 gridded climatology, grids where extracted, averaged over the growing seasons, thereby creating 25 time series for trend analysis (there are two less grids as four wine regions share two grids at the AOGCM resolution).

To examine wine quality Jones et al. (2005) used the most recent published Sotheby's vintage ratings (Stevenson, 2001). Vintage ratings are a common benchmark by which years are compared and have long been a determinant of the annual economic success of a wine region (de Blij, 1983). While numerous rating systems, compiled over various time periods and by various sources (e.g., Penning-Roswell, 1989; Broadbent, 1980; Parker, 1985; Stevenson, 2001, and others), exist, correlations between the various sources are generally strong (r > 0.9) indicating that this subjective measure of quality is a good quantitative representation of a vintage (Jones, 1997). The Sotheby's ratings are scaled from 0-100 and are for 18 of arguably the best wine producing regions in the world (Table 2) and cover 28 categories of wine (some regions are divided into sub-regions with separate ratings and others are simply divided into ratings for red and white wines). The ratings are scaled theoretically from 0-100 (although a score of zero would probably never be given) with general categories of 0-39 Disastrous, 40-59 Very bad, 60-69 Disappointing, 70-79 Average to good, 80-89 Good to very good, 90-100 Excellent to superb. Lacking a vintage rating for both South Africa and Chile, two very important and growing wine regions, the Sotheby's data are supplemented with a similar scale of ratings from the Wine Enthusiast, a separate and widely respected monthly publication on wine (Mazur, 2002). Overall, 30 categories of wine are represented, covering 10-38 years during the 1967-2000 vintage year period (in some regions, Portugal and Champagne, vintages are often "undeclared" resulting in a discontinuous time series).

There are several analyses examining the relationship between climatic variables and wine prices (Ashenfelter et al., 1993; Byron and Ashenfelter, 1995; Jones and Storchmann, 2001) with the underlying hypotheses that beneficial climatic conditions will improve the wine's quality and, therefore, lead to higher prices in the short-run. Thus the authors modeled wine prices as dependent on seasonal temperatures and precipitation. However, Ashenfelter and Jones (2000) find that vintage ratings are not necessarily efficient predictors of the prices of Bordeaux wines, but that vintage ratings do "reflect qualitatively the same weather factors that have been documented to be determinants of wine quality." Therefore, this paper's purpose is to analyze the relationship between wine ratings and climate. In contrast to Ashenfelter et al., (1993), Byron and Ashenfelter (1995), and Jones and Storchmann (2001) we draw only on growing season temperatures as these are better represented in most regions (data availability) and much more easily modeled in future climates than is precipitation.

From Jones et al., (2005) it is found that vintage ratings have moderate covariance with growing season temperature; therefore this analysis component assumes the following model:

$$(1) \quad R_{i,t} = \alpha_0 + \alpha_1 temp_{i,t} + \beta_1 trend_i + \varepsilon_{i,t}$$

where $R_{i,t}$ and $temp_{i,t}$ represent the wine rating in points and the average growing season temperature in °C for vintage t in region i. In order to account for quality improvements that are independent of climatic changes we introduced a trend variable trend for each region i. The trend variable begins with the value one in 1950 and continues in one-unit–steps (i.e., taking on the value 51 in 2000). A positive value for β_1 would indicate better ratings over time, which can be explained by improvements in production technologies. However, a positive value for β_1 can also represents a time correlated bias of wine critics, i.e., "score inflation". The final term in the equation represents the stochastic error $\varepsilon_{i,t}$.

Equation (1) assumes a linear relationship between growing season temperatures and wine quality. Ashenfelter et al., (1993) and Jones and Storchmann (2001) drew on the same linear relationship and found a positive correlation between temperature and prices for Bordeaux wines. However, many wines are produced in much warmer areas where a further increase in temperature might produce unbalanced wines with high sugar content, resulting in high alcohol, lower acidity, too high of pH, and compromised flavor profiles. The hypothesis "warmer is better" may not be correct for these wine regions. In fact, the correlation of rating and temperature may be negative or non-linear. Our analysis takes this into account and estimates, in addition to equation (1), a quadratic relationship between wine rating and growing season temperatures. Equation (2) below assumes that increasing temperatures improve the grape and therefore the wine, but at a decreasing rate. Ultimately, if temperature is higher than a certain optimum, grape quality declines:

(2) $$R_{i,t} = \alpha_0 + \alpha_1 temp_{i,t} + \alpha_2 temp_{i,t}^{\ 2} + \beta_1 trend_i + \varepsilon_{i,t}$$

Taking the partial derivative and setting it equal to zero allows us to calculate the temperature optimum for each wine growing region:

(3) $$\frac{\partial R}{\partial\ temp} = \alpha_1 + 2\alpha_2 temp = 0 \quad \Rightarrow \quad temp_{opt} = \frac{-\alpha_1}{2\alpha_2}$$

Equation (1) and (2) are estimated by the ordinary least square method for each category of wine separately.

Results and Discussion

The multi-region analysis of the impacts of climate change on wine quality by Jones et al. (2005) analyzed growing season temperatures in 27 of arguably the best wine producing regions in the world (Figure 1). The authors used average growing season temperatures as these values typically define the climate-maturity ripening potential for varieties grown in cool, intermediate, warm, and hot climates (Figure 2; Table 1). For example, Pinot Noir is grown in regions that span from cool to lower intermediate climates with growing seasons that range from roughly 14-16ºC (e.g., Champagne, Northern Oregon, Burgundy). Results from the analysis during 1950-1999 revealed that all regions warmed during their respective growing seasons with 17 of the 27 wine regions experiencing statistically significant trends ($P<0.01$). Figure 3 provides examples of the warming for the Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux regions with 1950-1999 warming trends ranging from 0.7-1.8ºC. Also note that some regions have lower year-to-year variability than others (e.g., Burgundy and Bordeaux) due to the proximity to the coast. In addition, note the indication of a shift in climate that occurred in the mid-1970s with substantial warming since then. An examination of these potential shifts in mean growing season temperatures during 1950-1974 and 1975-1999 reveals for the Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux regions mean changes of 0.3-0.9ºC. Overall, Jones et al. (2005) found that a large majority of the U.S. and European wine regions saw significant increases while the majority of the Southern Hemisphere locations changes were not as significant. Averaged across all wine regions with significant trends, the warming trend was 1.26ºC. The most dramatic of these changes, confirmed by another observation-based climatology (Moisselin et al., 2002), occurred in the northern Rhone Valley of France where the growing season warmed by 4.07ºC.

Jones et al. (2005) then examined temporal changes in vintage ratings as given by Sotheby's and the Wine Enthusiast (Stevenson, 2002; Mazur, 2002). For 25 of the 30 wine regions or categories of wine, vintage ratings have shown trends of increasing overall quality with less vintage-to-vintage variation. Figure 4 depicts the vintage ratings for the red wines from the Beaujolais wines of Burgundy, the white wines of the Rhine Valley, the red wines of the Barolo, and the red wines from the Médoc and Graves region of Bordeaux showing a general trend over time to better quality with less variability. Also note the potential heteroscedasticity with early vintages having wider swings in quality and less variation in more recent vintages. This research then analyzed the relationships between average growing season temperatures and vintage ratings using a multiple regression approach.

Table 3a and 3b give the results of the multiple regressions of equation (1) and equation (2), respectively. Since both specifications are likely to suffer from heteroscedasticity the equations were estimated with White's heteroscedasticity-consistent standard errors. Thus heteroscedasticity consistent t-values are given in parenthesis. The results of the linear specification (Table 3a) reveal great differences between wine regions. While some (northern) European wine regions, such as the Mosel and Rhine Valleys, show a goodness to fit of about 0.6, other wine regions show an R^2 of close to zero. In most of the estimates, the temperature variable is significant and has positive sign indicating a positive relationship between growing season temperatures and wine ratings. The marginal effects are given directly by the parameter. Thus, a temperature increase by 1°C will improve the rating of Rhine Valley wines by 21.5 points. Similarly, Mosel Valley wines will improve by 20.8, red Burgundies by 12.7, and Saint Émilion and Pomerol wines by 10.4 points. In contrast, most wine regions of the New World (e.g., the U.S. and Australia) show no relationship or even a slight (however insignificant) negative relationship between temperature and wine ratings. The role of factors other than growing season temperatures, especially in South Africa and Australia, is also underpinned by the existence of serial correlation indicated by the Durbin Watson statistic. Therefore, the results hint that the European vintners at the northern frontier of professional viticulture are likely to benefit more from rising temperatures. The trend variable shows the reverse pattern; it is insignificant for most Old World wine regions but significant and positive for almost all New World wine regions. Especially emerging wine regions, such as Australia, Chile, and South Africa appear to have experienced an improvement in wine ratings which is not climate driven (e.g., wine originating from the Barossa Valley and Margaret River regions have experienced score increase of more than one point per year). Given the comparatively long estimation period from for the rating/climate analysis, it is assumed that substantial technological advances and accumulating experience of these regions are causal for the positive trend.

The linear specification is significantly refined by the results of the quadratic specification as given in Table 3b. First, for most wine regions the estimates of equation (2) lead to substantially higher R^2 values than does the linear specification. For instance, the goodness to fit for the Rhine Valley improves from 0.56 to 0.72; and for Saint-Émilion and Pomerol the increase is from 0.39 to 0.54. Therefore, the general rule of thumb "the warmer the better" does not even apply for cool climate wine regions. Figure 5 shows examples of predicted optimum growing season average temperatures for the Rhine Valley, the Loire Valley (sweet white wines), Bordeaux, and Barolo as derived from Table 3b. For the four regions depicted, the predicted optimum growing season temperatures for wine quality, according to equation (3), range from 15.6ºC for the Rhine Valley, 16.7ºC for the Loire Valley, 17.3ºC for Bordeaux, to 18.6ºC for Barolo (explained variances range from 0.48-0.72). The importance of these predictions becomes obvious when compared to the long-term (1950-1999) mean growing season temperatures for the regions (Table 4). The regions range from being at their optimum (Barossa Valley white wines) to being 1.4ºC from their optimum (Loire Valley red wines) with an average across all twelve regions of 0.8ºC from the predicted optimum. However, Table 4 shows that the average from 1950-1999 is well below the average of 1990-1999, when growing season temperatures in almost all wine regions have increased dramatically. If one compares the average growing season temperature of 1990-1999 with the optimum it can be seen that many wine regions are even closer to their optimum. For a few regions the 1990s were even too warm (e.g., Alsace, Médoc and Graves).

To examine future climate change, Jones et al. (2005) analyzed output from the HadCM3 general circulation model from 1950-2049 for 25 grid cells encompassing the same wine regions

(Table 1). A comparison of the two periods, 1950-1999 and 2000-2049, suggests that mean growing season temperatures will warm by an average 1.24ºC over the wine regions studied and for Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux the differences range from 0.9-1.4ºC (Figure 6). 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 (Table 1 and Figure 2). The projected changes are greater for the Northern Hemisphere (1.31ºC) than the Southern Hemisphere (0.93ºC). Examining the rate of change projected for 2000-2049 reveals significant changes in each wine region with trends ranging from 0.18ºC to 0.58ºC per decade. Overall trends during the 2000-2049 period average over 2ºC across all regions with the smallest warming in South Africa (0.88ºC/50 years) and greatest warming in Portugal (2.85ºC/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 6). In addition, Table 4 shows that many of the wine regions/categories of wine are at or near their optimum growing season temperature and further increases, as predicted by changes between the 1950-1999 and 2000-2049 means, will place some regions outside their theoretical optimum growing season climate.

Conclusions

From 1950-1999 growing season average monthly temperatures have increased for many of the world's high quality wine producing regions. During the same time period, vintage ratings in the majority of these regions have increased. Given that wine quality is reflected by expert's ratings and mainly determined by climatic factors, a linear econometric approach can be used to explain vintage ratings for many world's wine regions using annual growing season temperatures. While some of the trend in better quality can undoubtedly be attributed to better viticultural and vinicultural practices, climate variations exert profound influences in year-to-year variations in quality (Gladstones, 1992; Jones and Davis, 2000). However, in order to account for potential rating improvements over time, which are not climate-driven, we introduced a trend variable. From the linear modeling the results show that vintage ratings for nearly all European wine regions are positively related with growing season average temperatures. The trend variable was always insignificant indicating that climate is very important in vintage ratings variations. However, the relationship between wine ratings and temperature in the New World is not as significant (very few locations), whereas the trend variable is always significantly positive indicating improving production technologies or increasing recognition over time in the ratings. In addition to the linear approach we estimated a quadratic specification, which in most cases produce better models. Twelve wine regions/categories of wine are predicted to have significant optimum growing season temperatures, whereby warmer growing seasons result in lower vintage ratings. The results suggest that the simple rule of thumb "the warmer the better" does not necessarily hold for every region, especially the cool climate wine regions of Europe. Most of the wine regions with significant quadratic models are close to their optimum, while some are already beyond the predicted optimums. We speculate that other ratings-dependent issues may be confounding the results for many of the insignificant regions. For example, broad vintage rating categories (i.e., Pacific Northwest, California, Chile, South Africa, etc.) that reflect numerous varieties and not one wine style, may mask the variability contained in any more defined wine category. In addition, climate may mean different things to different regions and varieties and a simple measure, such as growing season average temperatures, while significant in some regions may not have the same influence for others.

This analysis reveals 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 a climatic threshold whereby any continued warming would push a region outside the ability to ripen varieties that are already established. For example, note that a wine region, on average, can be positioned within the range of the climate maturity types based on its average growing season average temperature (Figure 2). 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. The wine quality issues related to climate change and shifts in climate maturity potential are evidenced mostly through a more rapid plant growth and out of balance ripening profiles. If a region currently experiences a maturation period (véraison to harvest) that allows sugars to accumulate, maintains acid levels, 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 sugar ripeness and, while the grower or winemaker is waiting for flavors to develop, the acidity is lost through respiration resulting in "flabby" wines (high alcohol with little acidity retained for freshness). In addition, 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 hot and potentially desiccated fruit without greater irrigation inputs.

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Table 1 – Wine region average growing season temperatures as analyzed by Jones et al. (2005) sorted into their respective climate maturity groupings as depicted in Figure 2.

Region	Growing Season[a] Tavg (°C)	Climate Maturity Grouping[b]
Mosel Valley	13.0	COOL
Alsace	13.1	
Champagne	14.5	
Rhine Valley	14.9	
Northern Oregon	15.2	INTERMEDIATE
Loire Valley	15.3	
Burgundy-Côte	15.3	
Burgundy-Beaujolais	15.8	
Chile	16.3	
Eastern Washington	16.5	
Bordeaux	16.5	
Central Washington	16.6	
Rioja	16.7	
Southern Oregon	16.9	
Coastal California	17.0	WARM
South Africa	17.1	
Northern California	17.4	
Northern Rhône Valley	17.6	
Northern Portugal	17.7	
Barolo	17.8	
Southern Rhône Valley	18.2	
Margaret River	18.6	
Chianti	18.8	

Hunter Valley	19.8	**HOT**
Barossa Valley	19.9	
Southern Portugal	20.3	
Southern California	20.4	

Note that the growing season average temperatures depicted here are derived from a 0.5° x 0.5° grid and not from any one station (see Jones et al., 2005 for details).
[a] The growing season is Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere.
[b] The climate maturity groupings are based upon the average growing season temperatures and the ability to ripen a given variety (see Figure 3 and Jones et al., 2005 for details).

Table 2 – Wine regions and categories of wine as given by Sotheby's (Stevenson, 2001) and analyzed by Jones et al. (2005). The wine regions correspond to the locations (black dots) depicted in Figure 1.

Region	Categories of Wines in Sotheby's Vintage Ratings
C. Washington E. Washington N. Oregon S. Oregon	**US - Pacific Northwest Red US - Pacific Northwest White**
N. California C. California S. California	**US - California Red US - California White**
N. Portugal	**Vintage Port**
S. Portugal	**No Specific Rating Provided**
Rioja	**Rioja Red**
Barolo	**Barolo Red**
Chianti	**Chianti Red**
Rhine Valley	**Rhine Valley White**
Mosel Valley	**Mosel-Saar-Ruwer Valley White**
N. Rhône Valley	**N. Rhône Valley Red**
S. Rhône Valley	**S. Rhône Valley Red**
Loire Valley	**Loire Valley Red Loire Valley Sweet White**
Alsace	**Alsace White**
Champagne	**Vintage Champagne**
Burgundy-Côte Burgundy-Beaujolais	**Burgundy - Côte D'Or Red Burgundy - Côte D'Or White Burgundy - Beaujolais Red**
Bordeaux	**Bordeaux - Médoc and Graves Bordeaux - St. Émilion and Pomerol Bordeaux - Sauternes and Barsac**
Hunter Valley	**Hunter Valley Red Hunter Valley White**
Margaret River	**Margaret River Red Margaret River White**
Barossa Valley	**Barossa Valley Red Barossa Valley White**
South Africa[a] Chile[a]	**Overall Vintage Overall Vintage**

[a] Rating data for South Africa and Chile are from a different source than the other locations (see text for details).

Table 3a – Linear Specification: Regression coefficients and test statistics for the 30 categories of wine or regions. The regressions are run with heteroscedasticity consistent t-statistics as show in parenthesis below each coefficient.

Region	Constant	Growing Season Tavg	Trend Variable	R^2	Adj. R^2	DW
Germany - Mosel-Saar-Ruwer Valleys	-191.11*** (-5.33)	20.75*** (7.38)	0.11 (0.55)	0.62	0.60	2.09

Germany - Rhine Valley	-240.92*** (-5.55)	21.51*** (7.37)	-0.02 (-0.12)	0.60	0.57	2.04
Spain – Rioja	-56.11 (-0.80)	8.98+ (1.72)	0.02 (0.05)	0.19	0.14	1.66
Portugal - Vintage Port	26.65 (0.33)	3.28 (0.71)	0.09 (0.40)	0.06	0.07	2.39
Italy – Barolo	-175.22* (-2.11)	15.09*** (3.04)	-0.42 (-1.57)	0.40	0.36	1.92
Italy – Chianti	8.62 (0.17)	2.18 (0.61)	0.83*** (2.88)	0.32	0.28	1.39
Alsace	-126.79^{+} (-1.80)	14.04* (2.30)	0.50 (1.38)	0.35	0.31	1.94
Bordeaux - Médoc and Graves	-78.70 (-1.30)	8.11* (2.07)	0.62^{+} (1.71)	0.39	0.35	2.02
Bordeaux - Sauternes and Barsac	-149.52*** (-3.60)	13.29*** (4.67)	0.07 (0.21)	0.40	0.37	1.87
Bordeaux - St. Émilion and Pomerol	-111.20^{+} (-1.82)	10.44** (2.58)	0.42 (1.08)	0.39	0.35	2.21
Loire Valley – red	-216.31*** (-3.08)	18.68*** (4.11)	-0.02 (-0.04)	0.32	0.28	2.12
Loire Valley - sweet white	-249.07*** (-3.62)	21.36*** (4.82)	-0.27 (-0.79)	0.41	0.37	2.36
Burgundy - Beaujolais (red)	-78.09^{+} (-1.70)	9.09*** (2.96)	0.33^{+} (1.86)	0.47	0.44	2.29
Burgundy - Côte D'Or (red)	-147.70^{+} (-1.78)	12.68* (2.43)	0.89** (2.61)	0.32	0.28	2.43
Burgundy - Côte D'Or (white)	-99.21 (-1.28)	9.83* (2.06)	0.87*** (2.76)	0.36	0.32	2.43
Northern Rhône Valley	-74.63^{+} (-1.72)	9.19*** (3.83)	-0.33^{+} (-1.72)	0.28	0.24	2.44
Southern Rhône Valley	-75.84 (-1.24)	8.51** (2.68)	-0.00 (-0.02)	0.19	0.15	2.48
Champagne	5.83 (0.12)	6.02^{+} (1.87)	-0.22 (-1.47)	0.17	0.10	2.52
Australia - Hunter Valley (red)	30.44 (0.42)	1.58 (0.43)	0.52^{+} (2.01)	0.13	0.08	1.84
Australia - Hunter Valley (white)	-0.32 (-0.01)	3.66 (1.60)	0.27 (0.96)	0.09	0.03	2.03
Australia - Barossa Valley (red)	53.89 (0.83)	-0.85 (-0.29)	1.22* (2.08)	0.28	0.22	0.93
Australia - Barossa Valley (white)	58.21 (1.08)	-0.89 (-0.36)	1.12* (2.10)	0.26	0.20	0.83
Australia - Margaret River (red)	22.83 (0.22)	0.32 (0.07)	1.43* (2.38)	0.45	0.40	0.94
Australia - Margaret River (white)	162.53 (1.30)	-6.46 (-1.13)	1.00 (1.62)	0.43	0.40	0.96
South Africa	12.59 (0.37)	2.23 (1.08)	0.84*** (4.23)	0.39	0.22	2.93
Chile	40.37^{+} (1.82)	1.38 (1.09)	0.57*** (3.97)	0.47	0.38	1.92
US - Pacific Northwest (white)[b]	100.41*** (2.98)	-0.87 (-0.42)	-0.03 (-0.24)	0.01	0.07	2.32
US - Pacific Northwest (red)[b]	38.69 (0.43)	2.63 (0.48)	0.14 (1.19)	0.06	0.03	2.97
US - California (red)[b]	96.76*** (3.24)	-1.11 (-0.64)	0.28*** (3.02)	0.17	0.13	1.93

US - California (white)[b]	100.27*** (3.62)	-1.26 (-0.76)	0.22* (2.32)	0.12	0.07	2.26

[a] Rating data for South Africa and Chile are from a different source than the other locations (see text for details).
[b] Only the most significant model for the Pacific Northwest and California is presented here.
Heteroscedasticity consistent t-statistics in parenthesis; significance level: ***>1%, ** > 2%, * >5%, +>10%.

Table 3b – Quadratic Specification: Regression coefficients and test statistics for the 30 categories of wine or regions. The regressions are run with heteroscedasticity consistent t-statistics as show in parenthesis below each coefficient. The estimated optimum growing season average temperature is calculated from the fitted multiple regression (see Figure 5 for examples).

Region	Constant	Trend Variable	Growing Season Tavg	Growing Season $Tavg^2$	R^2	Adj. R^2	DW	Estimated Optimum Growing Season Tavg (°C)
Germany - Mosel-Saar-Ruwer Valleys	-1681.53*** (-4.36)	0.14 (0.81)	254.63*** (4.19)	-9.15*** (-3.84)	0.71	0.68	2.01	13.92
Germany - Rhine Valley	-3009.67*** (-5.58)	0.14 (0.82)	397.27*** (5.45)	-12.74*** (-5.20)	0.72	0.69	2.04	15.59
Spain - Rioja	-1304.23* (-2.10)	0.20 (0.58)	178.33* (2.20)	-5.75* (-2.17)	0.27	0.21	1.79	17.50
Portugal - Vintage Port	-11.15 (-0.01)	0.09 (0.39)	7.54 (0.04)	-0.12 (-0.02)	0.06	-0.16	2.39	NS
Italy - Barolo	-2504.87* (-2.31)	-0.02 (-0.07)	279.60* (2.31)	-7.53* (-2.24)	0.48	0.43	1.74	18.57
Italy - Chianti	0.76*** (2.81)	8.62 (0.17)	-88.19 (-0.92)	2.47 (0.95)	0.33	0.27	1.37	NS
Alsace	-2868.08*** (-4.34)	0.76+ (2.01)	437.57*** (4.18)	-16.36*** (-3.93)	0.48	0.43	1.78	13.41
Bordeaux - Médoc and Graves	-2091.10*** (-4.10)	0.66+ (1.99)	248.71*** (4.19)	-7.18*** (-4.16)	0.53	0.49	1.81	17.33
Bordeaux - Sauternes and Barsac	980.15 (1.63)	0.09 (0.26)	112.6 (1.60)	-2.96 (-1.44)	0.43	0.38	1.80	NS
Bordeaux - St. Émilion and Pomerol	-2188.61*** (-4.10)	0.46 (1.33)	258.80*** (4.18)	-7.41*** (-4.13)	0.54	0.50	1.99	17.47
Loire Valley – red	-2052.92+ (-1.98)	-0.04 (-0.11)	256.52+ (1.96)	-7.68+ (-1.85)	0.37	0.31	1.96	16.71
Loire Valley - sweet white	-2589.73*** (-3.33)	-0.23 (-0.71)	323.40*** (3.29)	-9.72*** (-3.13)	0.50	0.45	2.15	16.63
Burgundy - Beaujolais (red)	-641.21 (-0.39)	0.37* (2.27)	80.83 (0.87)	-2.29 (-0.78)	0.48	0.44	2.31	NS
Burgundy - Côte D'Or (red)	-482.36 (-0.26)	0.89** (2.52)	56.47 (0.24)	-1.43 (-0.19)	0.32	0.25	2.44	NS
Burgundy - Côte D'Or (white)	-1197.32 (-0.75)	0.85** (2.69)	153.52 (0.74)	-4.69 (-0.70)	0.37	0.31	2.43	NS
Northern Rhône Valley	197.26 (0.41)	-0.36+ (-1.72)	-22.00 (-0.40)	0.89 (0.56)	0.28	0.22	2.53	NS
Southern Rhône Valley	-2754.94+ (-1.78)	-0.08 (-0.47)	300.55+ (1.80)	-7.94+ (-1.76)	0.27	0.20	2.33	18.93
Champagne	-1625.32* (-2.17)	-0.19 (-1.36)	229.75* (2.28)	-7.66* (-2.26)	0.33	0.25	2.11	14.99
Australia - Hunter Valley (red)	-93.38 (-0.05)	0.52+ (1.97)	13.86 (0.07)	-0.3 (-0.07)	0.13	0.05	1.85	NS
Australia - Hunter Valley (white)	249.47 (0.32)	0.27 (0.95)	-21.13 (-0.27)	0.61 (0.32)	0.09	0.00	1.99	NS
Australia - Barossa Valley (red)	-1231.52 (-0.51)	1.28+ (2.00)	127.96 (0.52)	-3.22 (-0.52)	0.28	0.19	0.95	NS

Australia - Barossa Valley (white)	-3278.6 (-1.70)	1.25* (2.18)	333.47+ (1.72)	-8.38+ (-1.72)	0.29	0.20	0.83	19.89
Australia - Margaret River (red)	-204.29 (-0.26)	1.44* (2.39)	24.41 (0.29)	-0.64 (-0.28)	0.45	0.37	0.91	NS
Australia - Margaret River (white)	-1454.9 (-1.48)	1.09 (1.69)	165.09 (1.59)	-4.55 (-1.65)	0.46	0.38	0.88	NS
South Africa	848.57 (0.95)	0.92*** (4.08)	-100.86 (-0.91)	3.16 (0.92)	0.46	0.18	2.95	NS
Chile	-493.95 (-0.76)	0.57*** (3.65)	65.58 (0.84)	-1.93 (-0.83)	0.51	0.36	1.81	NS
US - Pacific Northwest (white)[b]	-1030.38 (-0.86)	0.02 (0.13)	134.43 (0.94)	-4.05 (-0.95)	0.06	-0.06	2.23	NS
US - Pacific Northwest (red)[b]	-967.08 (-0.66)	-0.02 (-0.06)	133.45 (0.72)	-4.22 (-0.72)	0.10	-0.02	2.69	NS
US - California (red)[b]	70.35 (0.07)	0.26*** (2.75)	1.45 (0.01)	-0.06 (-0.02)	0.17	0.09	1.94	NS
US - California (white)[b]	1572.66 (1.31)	0.22** (2.53)	-168.62 (-1.24)	4.75 (1.24)	0.17	0.09	2.27	NS

[a] Rating data for South Africa and Chile are from a different source than the other locations (see text for details).
[b] Only the most significant model for the Pacific Northwest and California is presented here.
Heteroscedasticity consistent t-statistics in parenthesis; significance level: ***>1%, ** > 2%, * >5%, +>10%.

Table 4 – Actual, estimated optimal, and predicted growing season average temperatures for those wine regions and categories of wine with significant models from Table 3b. Note that the 1950-1999 and 2000-2049 climate data come from different size grids (see text for details) and are not directly comparable. The values represented here for 2000-2049 are for the predicted change in average growing season temperature relative to 1950-1999.

Region and Category of Wine	**Average Growing Season Temperature (°C)**			**Estimated Optimum Growing Season Tavg (°C)**	**Difference between Optimum and Tavg (°C)**	**Modeled Change in Growing Season Tavg (°C)**
	1950-1999	1950-1989	1990-1999	**Modeled**	1990-1999	2000-2049[a]
Alsace – white wines	13.1	12.9	13.8	13.4	-0.4	0.94
Mosel Valley – white wines	13.0	12.9	13.4	13.9	0.5	0.93
Champagne	14.5	14.3	15.0	15.0	0.0	0.87
Rhine Valley – white wines	14.9	14.7	15.5	15.6	0.1	0.93
Loire Valley – sweet white wines	15.3	15.2	15.8	16.6	0.8	1.01
Loire Valley – red wines	15.3	15.2	15.8	16.7	0.9	1.01
Bordeaux: Médoc & Graves – red wines	16.5	16.2	17.5	17.3	-0.2	1.20
Bordeaux: St. Émilion & Pomerol – red wines	16.5	16.2	17.5	17.5	0.0	1.20
Rioja – red wines	16.7	16.3	18.1	17.5	-0.6	1.33
Barolo – red wines	17.8	17.5	18.8	18.6	0.2	1.41
Southern Rhône Valley – red wines	18.2	18.1	18.8	18.9	0.1	1.24
Barossa Valley – white wines	19.9	20.0	19.6	19.9	0.3	0.95

[a] Note that the 1950-1999 and 2000-2049 climate data come from different size grids (see text for details) and are not directly comparable. The values represented here are for the predicted 2000-2049 change in average growing season temperature relative to 1950-1999.

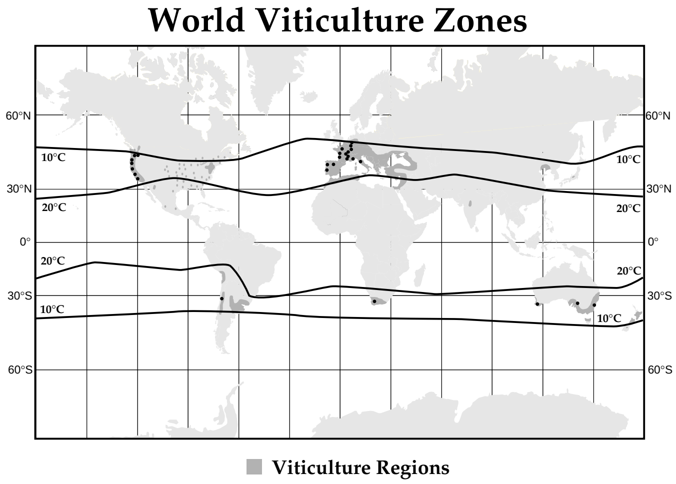

Figure 1 – General geographical extent of the world's viticulture regions (adapted from De Blij, 1983). Contours represent the mean annual 10°C and 20°C isotherms as a proxy for the latitudinal limits of the majority of the world's grape growing areas. The solid dots represent the wine regions studied by Jones et al. (2005).

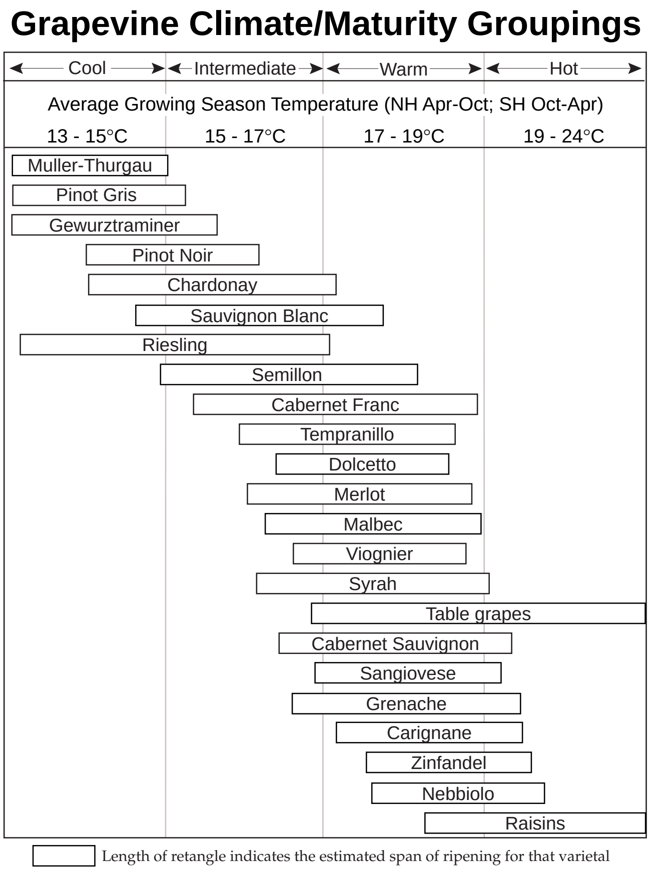

Figure 2 – Climate maturity groupings based on average growing season temperatures and the estimated span of varietal ripening potential that occurs within and across the groups. Note that the climate data is depicted in Table 1 and is derived from grids, not station data therefore the values given may deviate slightly from any one station in a given region (Jones et al., 2005).

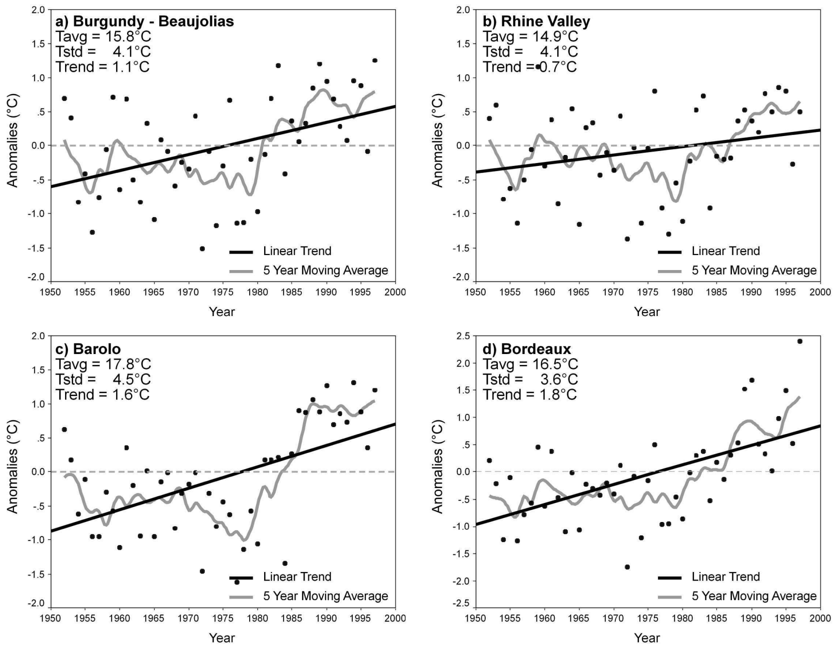

Figure 3 Observed growing season average temperature anomalies for a) the Beaujolais region of Burgundy, b) the Rhine Valley, c) Barolo, and d) Bordeaux as analyzed by (Jones et al., 2005). The temperature data are monthly values extracted from a 0.5° x 0.5° grid centered over the wine producing regions 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.

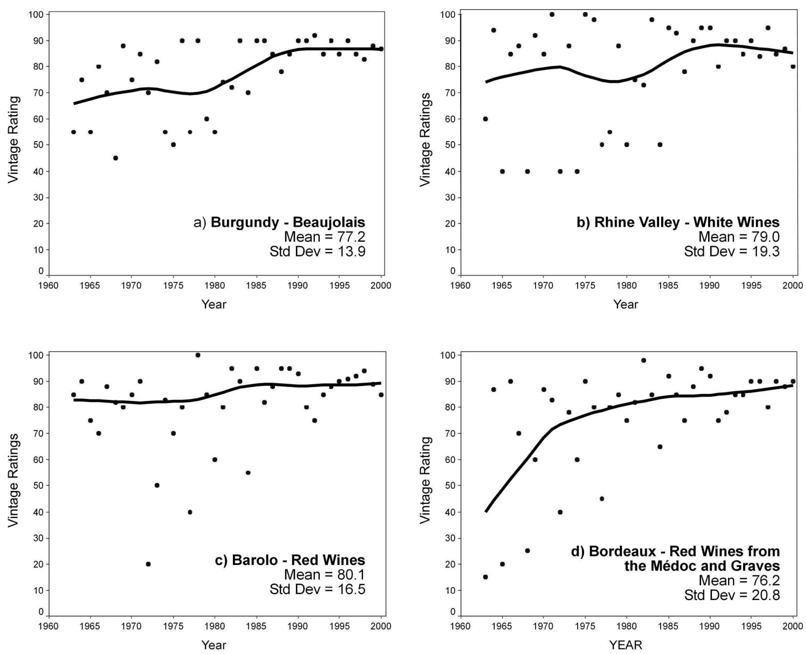

Figure 4 – Vintage ratings for a) red wines from the Beaujolais region of Burgundy, b) white wines from the Rhine Valley, c) red wines from Barolo, and red wines from the Médoc and Graves in Bordeaux as analyzed by (Jones et al., 2005). The ratings are from Sotheby's (Stevenson, 2001) and are based on a 0-100 scale. A LOWESS filter is applied to indicate the underlying pattern in the ratings.

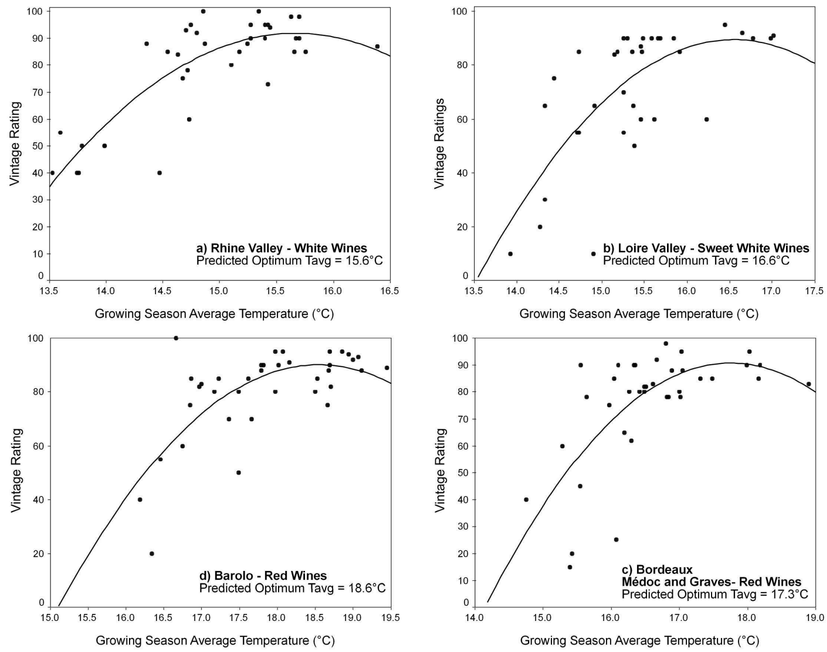

Figure 5 – Predicted vintage ratings from the multiple regression models for a) the Rhine Valley white wines, b) the Loire Valley sweet white wines, c) the red wines from the Médoc and Graves of Bordeaux, and d) the red wines of Barolo. The quadratic specification predicts optimum growing season temperatures for each region as given in the key.

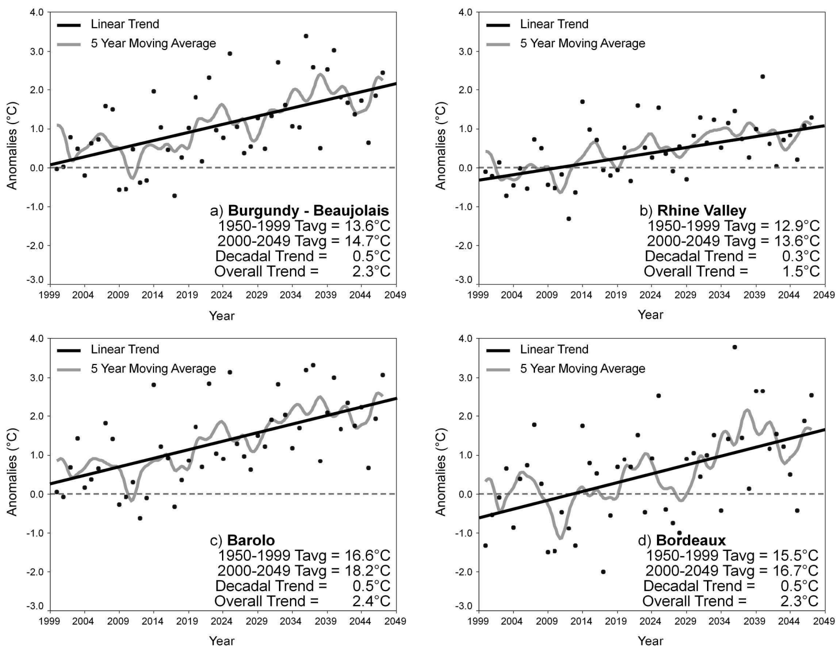

Figure 6 – Modeled growing season average temperature anomalies for a) the Beaujolais region of Burgundy, b) the Rhine Valley, c) Barolo, and d) Bordeaux as analyzed by (Jones et al., 2005). The modeled temperature data are from the HadCM3 climate model on a monthly time scale extracted from a 2.5° x 3.75° grid centered over the wine producing regions for 2000-2049. The anomalies are referenced to the 1950-1999 base period from the HadCM3 model. Note that the difference in the growing season average temperature in Figure 4 and those depicted here are due to the size of the grid square. Trend values are given as an average decadal change and the total change over the 50-year period.