CLIMATE CHANGE AND GLOBAL WINE QUALITY

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Abstract. From 1950 to 1999 the majority of the world's highest quality wine-producing regions experienced growing season warming trends. Vintage quality ratings during this same time period increased significantly while year-to-year variation declined. While improved winemaking knowledge and husbandry practices contributed to the better vintages it was shown that climate had, and will likely always have, a significant role in quality variations. This study revealed that the impacts of climate change are not likely to be uniform across all varieties and regions. Currently, many European regions appear to be at or near their optimum growing season temperatures, while the relationships are less defined in the New World viticulture regions. For future climates, model output for global wine producing regions predicts an average warming of 2 °C in the next 50 yr. For regions producing high-quality grapes at the margins of their climatic limits, these results suggest that future climate change will exceed a climatic threshold such that the ripening of balanced fruit required for existing varieties and wine styles will become progressively more difficult. In other regions, historical and predicted climate changes could push some regions into more optimal climatic regimes for the production of current varietals. In addition, the warmer conditions could lead to more poleward locations potentially becoming more conducive to grape growing and wine production.

1. Introduction

Understanding climate change and the potential impacts on natural and human-based systems 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). In most cases, observed atmospheric warming trends are seasonally and diurnally asymmetric with greatest warming during winter and spring and at night (Karl et al., 1993). Enhanced hydrologic cycling (i.e., increase in evaporation rates and atmospheric water vapor) may influence this asymmetric warming (Raval and Ramanathan, 1989; Chahine, 1992; Dai et al., 1997). These observed temperature trends and potential future changes influence agricultural production viability due to changes in winter hardening potential, frost occurrence, and growing season lengths (Carter et al., 1991; Menzel and Fabian, 1999; Easterling et al., 2000; Nemani et al.,

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Figure 1. Wine region centroids used to extract the appropriate grid cells for both the 0.5° × 0.5° 1950–1999 observed climatology data and the 2.5° × 3.75° 1950–2049 HadCM3 climate model data.

2001; Moonen et al., 2002; Jones, 2005b). However, the overall impacts of climate change on agriculture will ultimately depend on the timing of plant physiological requirements and the spatial variations, seasonality, and magnitude of the warming (Butterfield et al., 2000; McCarthy et al., 2001).

The importance of understanding climate change impacts on agriculture is especially evident with viticulture (the science of the cultivation of grapevines). A long history of grape growing has resulted in the finest wines being associated with geographically distinct viticulture regions (Johnson, 1985; Penning-Rowsell, 1989; Unwin, 1991) found in the Mediterranean climates around the world (Figure 1). The weather and climate in these regions profoundly influence the production of quality grapes and therefore high-quality wine. In general, the types of grapes that can be grown and overall wine style that a region produces are a result of the baseline climate, while climate variability determines vintage-to-vintage quality differences (Jones and Hellman, 2003). While there are many individual weather and climate factors that can affect grape growth and wine quality (e.g., solar radiation, heat accumulation, temperature extremes, precipitation, wind, and extreme weather events such as hail), growing season length and temperatures are critical aspects because of their major influence on the ability to ripen grapes to optimum levels of sugar, acid, and flavor in order to maximize a given style of wine and its quality.

Temperatures during the growing season can affect grape quality and viability in at least three ways. First, prolonged temperatures above 10 °C initiates spring vegetative growth and thus determines the start of the growing season (Mullins et al., 1992). Second, during flowering and throughout the growth of the berries, extremes of heat can cause: premature véraison (change of color and start of the accumulation of sugars); high grape mortality through abscission; enzyme inactivation; and partial or total failure of flavor ripening (Mullins et al., 1992). Third, during the maturation stage, a high diurnal temperature range leads to the beneficial synthesis of grape tannins, sugars, and flavors (Gladstones, 1992).

However, it has been found that simple growing season temperature parameters can be used effectively to define spatial variations in varietal potential and growing season climates (see Jones, 1997 for a review). For example, Amerine and Winkler (1944) developed a heat summation index for California (growing degree days from April–October in the Northern Hemisphere with a base of 10 °C) to place a region into one of five climate types capable of adequately ripening certain grape varieties. In addition, Jones (2005a) showed that grape growing climates can be ordered into cool, intermediate, warm, and hot groupings based on average growing season temperatures (April–October in the Northern Hemisphere) and varietal ripening potential. Since warmer growing seasons have been related to longer growing seasons (e.g., Menzel and Fabian, 1999), climate warming would theoretically bring about conditions more conducive to ripening fruit and producing quality wine.

Historical evidence supports the connection between temperature and wine production where winegrape-growing regions developed when the climate was most conducive (Le Roy Ladurie, 1971; Pfister, 1988). Records of dates of harvest and yield for European viticulture have been kept for nearly a thousand years (Penning-Rowsell, 1989) revealing periods with more beneficial growing season temperatures and greater productivity. During the medieval "Little Optimum" period (roughly 900–1300 AD) vineyards were planted as far north as the coastal zones of the Baltic Sea and southern England, and during the High Middle Ages (12th and 13th centuries) harvesting occurred in early September as compared to early to mid October today (Pfister, 1988; Gladstones, 1992). Conversely, dramatic temperature declines during the "Little Ice Age" (14–19th centuries) resulted in most of the northern vineyards dying out and growing seasons that were so short that harvesting grapes in southern Europe was difficult.

Climate change impacts on viticulture have been and are likely to be highly variable, both geographically and varietally. An early analysis suggested that in Europe, growing seasons should lengthen and that precipitation would increase in the North and decrease in the South (Lough et al., 1983). The research also found strong relationships between wine quality (vintage ratings) and climate, indicating that vintage quality, especially in Bordeaux and Champagne, should improve under the simulated future climates. Spatial modeling research has indicated potential geographical shifts and/or expansion of viticultural regions with parts of southern Europe becoming too hot to produce high-quality wines and northern regions becoming viable once again (Kenny and Harrison, 1992; Butterfield et al., 2000). An analysis of Sangiovese and Cabernet Sauvignon to climate change in Italy revealed that warmer conditions will lead to shorter growth intervals but increases in yield variability (Bindi et al., 1996). In Napa and Sonoma, California, Nemani et al. (2001) found that higher yields and quality over the last 50 yr were influenced by a reduction in frost occurrence, advanced initiation of growth in the spring, and longer growing seasons associated with asymmetric warming. Other studies of the impacts of climate change on grape growing and wine production reveal 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 (Renner, 1989; Schultz, 2000; Tate, 2001; McInnes et al., 2003).

In addition to the above effects on quality wine production, climate generally constrains a given variety's optimum ripening conditions to a narrow geographic zone, putting the grapevines at a greater potential risk from climatic variations and change than crops with a broader geographic range. Furthermore, wine has developed as a key economic sector with broad historical, social, and cultural identity derived from grape growing and production (e.g., Bordeaux, France). Based on the cultural and economic importance of viticulture, extensive evidence of historical responsiveness to climate change, and the potential impacts that may come from future climate change, this research studies the nature and trends of climate and wine quality for 27 of the most prominent wine growing regions in the world. The analysis differs from earlier studies in that it includes multiple regions and covers a greater length of time. The research examines: 1) the observed changes seen in growing season temperatures; 2) the variation and trends in vintage ratings; 3) the relationship between observed climate and vintage ratings; and 4) the projected growing season temperature changes from a climate model.

2. Data and Methods

Year-to-year comparisons of wine quality are typically made with either prices or vintage ratings (Ashenfelter et al., 1995; Ashenfelter and Byron, 1995; Jones and Storchmann, 2001). Analyses of the relationship between climatic variables and wine prices are based on the underlying hypothesis that beneficial climatic conditions will improve the wine's quality and, therefore, lead to higher prices in the short-run. However, long-term consistent price data for multiple regions and wine types over many years is not readily available. Vintage ratings, on the other hand, are easily obtained for many wine styles, regions, and years and are a strong determinant of the annual economic success of a wine region (de Blij, 1983). For example, an analysis of price data from the *Wine Spectator* for Napa wines from the 1995 vintage showed that an average rating increase of 10 points (on a 0–100 scale) translated to a 220% price increase per bottle (Nemani et al., 2001). In addition, while Ashenfelter and Jones (2000) found that vintage ratings are not necessarily efficient predictors of the prices of Bordeaux wines, the authors determined that vintage ratings do "reflect qualitatively the same weather factors that have been documented to be determinants of wine quality." Furthermore, while numerous rating systems, compiled over various time periods and by various sources (e.g., Broadbent, 1980; Parker, 1985; Penning-Rowsell, 1989; 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). Vintage ratings are usually based upon a collection of estimates from one to five or seven classes (from exceptional to bad) and quality scores or ratings that range from 0–20 or 0–100 (with higher values indicating higher quality). Ratings may represent the score for an individual wine from a single winery or châteaux, or a general region-wide average score. Wines are typically rated by single judges or a panel, which attempt to qualify the vintage-to-vintage nuances of flavor, aroma, and color and the wine's balance of alcohol and acidity that together best represent that variety's wine style.

To examine the climatic effects on vintage ratings, the most recent published Sotheby's vintage ratings were used (Stevenson, 2001). The ratings are for 18 of arguably the best wine producing regions in the world and cover 28 categories of wine made from the dominant *v. vinifera* varieties grown in each region (some regions are divided into sub-regions or varietal categories with separate ratings and others are simply divided into ratings for red and white wines). For example, in the Sotheby's ratings the Bordeaux region has three separate ratings: (1) for the Médoc and Graves, typically a blend of 2–4 varieties dominated by Cabernet Sauvignon; (2) St. Émilion and Pomeral, a blend of mostly Merlot and Cabernet Franc; and (3) Sauternes and Barsac, typically a sweet white wine blend of Semillon and Sauvignon Blanc. Other ratings, such as those for California red wines, are generalized for all red wines produced from the region during a given vintage. The ratings are scaled theoretically from 0–100 (although a score of zero is probably never 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 expanding wine regions, the Sotheby's data were supplemented with a similar scale of ratings from the Wine Enthusiast, a separate and widely respected monthly publication on wine (Mazur, 2002). An examination of similar regional ratings in a 13-yr overlap period in these two indices (1988–2000) indicated moderate to strong correlation between the two ($0.7 < r < 0.9$). Overall, 30 categories of wine were represented in this analysis, covering 18–38 yr for the Sotheby's ratings and 10–14 yr for the Wine Enthusiast's ratings during the 1963–2000 vintage year period (in some regions, Portugal and Champagne, vintages are often "undeclared" resulting in a discontinuous time series).

While many daily and seasonal weather and climate factors can impact wine production and quality (Gladstones, 1992), average growing season temperatures were used in this analysis as these values typically define the climate-maturity ripening potential for high-quality wines made from varieties grown in cool, intermediate, warm, and hot climates (Jones, 2005a; Jones et al., 2004). For example, the highest quality Pinot Noir wines come from grapes that are grown in regions spanning cool to low intermediate climates with growing seasons that range 14.0–16.0 °C (e.g., Champagne, Northern Oregon, Burgundy), while the highest quality Cabernet Sauvignon wines come from grapes grown in warmer regions that span from intermediate to hot climates with growing seasons that range 16.5–19.5 °C (e.g., Bordeaux or Napa). While micro-climatic variations clearly play roles in wine-grape growth and quality; the assumption in this study is that the macroclimate is the mean of the microclimates of a given region. Therefore, a regional climatology of the growing season macroclimate should match well with the regional vintage ratings as they are typically based upon a region's ability to ripen fruit to produce a given wine style.

Owing to the fact that high quality and spatially appropriate long-term climate data for each wine region are difficult to obtain, we used a 0.5° × 0.5° gridded climatology of monthly mean air temperature to examine the effects on vintage ratings (Willmott and Matsuura, 2002). The gridded temperature data archive was produced from the Global Historical Climatology Network (GHCN version 2) and station records of monthly and annual mean air temperature (Legates and Willmott, 1990). Data from 1950–1999 for the respective wine regions (Table I and Figure 1) were extracted and averaged over the growing season (Apr–Oct in the Northern Hemisphere and Oct–Apr in the Southern Hemisphere) and dormant season (Nov–Mar in the Northern Hemisphere and May–Sep in the Southern Hemisphere) to create 27 time series for each season.

The structure, variability, and trends of growing season average temperatures and vintage ratings were then examined using descriptive statistics and regression. Since ratings are likely to suffer from heteroscedasticity (i.e., a reduction in the year-to-year rating variability), equations were estimated with White's heteroscedasticity-consistent standard errors. To account for potential non-climate trends in the vintage ratings (i.e., increased knowledge of grape growing and better production technology), the following econometric regression model approach, similar to Jones and Storchmann (2001), was applied in the climate/vintage ratings analysis:

$$R_{i,t} = \alpha_{0_i} + \alpha_{1_i} \mathrm{temp}_{i,t} + \beta_{1_i} \mathrm{trend}_i + \varepsilon_{i,t} \quad (1)$$

where $R_{i,t}$ and $\mathrm{temp}_{i,t}$ represent the vintage rating in points and the average growing season temperature in °C for vintage *t* in region *i*. 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 50 in 1999). The equation constant and marginal effects of each variable are given by α and β where a positive value for β_1 indicates better ratings over time (independent of climate), which could potentially be explained by improvements in production technologies or 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. (1995) and Jones and Storchmann (2001) used the same linear relationship and found a positive correlation between temperature and prices for

TABLE I
Gridded climatology locations and results for the 27 wine producing regions used in the analysis

Region	Grid cell latitude[a]	Grid cell longitude[a]	Growing season[b] tavg (°C)	Climate maturity grouping	Trend[c] (°C)	R^2	Dormant season[d] tavg (°C)	Trend[c] (°C)	R^2
Mosel Valley	49.75°	6.75°	13.0	Cool	0.12	NS	2.5	0.20	NS
Alsace	48.25°	7.25°	13.1	Cool	0.88	0.15***	1.8	1.20	0.08**
Champagne	49.25°	3.75°	14.5	Cool	0.54	0.07*	4.2	0.48	NS
Rhine Valley	49.25°	8.25°	14.9	Cool	0.69	0.10**	3.3	1.24	0.09**
Northern Oregon	45.25°	−122.75°	15.2	Intermediate	0.88	0.18***	6.1	0.59	NS
Loire Valley	47.25°	−1.25°	15.3	Intermediate	0.93	0.14***	6.5	1.06	0.11**
Burgundy-Côte	47.25°	5.25°	15.3	Intermediate	0.10	NS	4.1	0.49	NS
Burgundy-Beaujolais	45.75°	4.25°	15.8	Intermediate	1.08	0.19***	4.8	1.43	0.17***
Chile	−35.25°	−71.25°	16.3	Intermediate	0.35	NS	8.5	0.65	NS
Eastern Washington	46.25°	−118.25°	16.5	Intermediate	0.24	NS	3.4	0.10	NS
Bordeaux	44.75°	−0.25°	16.5	Intermediate	1.76	0.38***	7.1	1.72	0.24***
Central Washington	46.25°	−120.25°	16.6	Intermediate	0.53	NS	2.8	0.16	NS
Rioja	42.25°	−2.25°	16.7	Intermediate	1.32	0.25***	6.9	1.62	0.31***
Southern Oregon	42.25°	−122.75°	16.9	Intermediate	0.83	0.15***	4.9	1.24	0.17***
Coastal California	35.25°	−120.25°	17.0	Warm	0.93	0.24***	8.8	0.63	0.06*
South Africa	−33.25°	19.25°	17.1	Warm	0.42	NS	8.5	0.23	NS
Northern California	38.25°	−122.25°	17.4	Warm	1.23	0.41***	10.1	0.50	NS
N. Rhône Valley	44.75°	4.75°	17.6	Warm	4.07	0.75***	6.4	3.85	0.60***
Northern Portugal	41.25°	−7.25°	17.7	Warm	0.88	0.16***	7.5	1.52	0.34***
Barolo	44.75°	7.75°	17.8	Warm	1.57	0.33***	4.6	0.28	NS

(*Continued on next page*)

TABLE I
(*Continued*)

Region	Grid cell latitude[a]	Grid cell longitude[a]	Growing season[b] tavg (°C)	Climate maturity grouping	Trend[c] (°C)	R^2	Dormant season[d] tavg (°C)	Trend[c] (°C)	R^2
S. Rhône Valley	44.25°	4.25°	18.2	Warm	1.91	0.50***	6.9	1.87	0.32***
Margaret River	−33.75°	115.75°	18.6	Warm	0.17	NS	12.3	0.49	0.08**
Chianti	43.25°	11.25°	18.8	Warm	0.16	NS	7.7	0.59	NS
Hunter Valley	−32.25°	151.25°	19.8	Hot	0.77	0.12**	11.4	0.62	0.13***
Barossa Valley	−34.25°	138.25°	19.9	Hot	0.20	NS	12.3	0.24	NS
Southern Portugal	39.25°	−7.75°	20.3	Hot	0.12	NS	11.2	0.92	0.13**
Southern California	33.25°	−117.25°	20.4	Hot	1.23	0.28***	14.0	1.23	0.22***

Average growing season and dormant period temperatures along with their respective trends over the 1950–1999 time period are given. The regions are ordered by growing season average temperatures and the climate-maturity grouping as detailed by Jones (2005a).
[a]Grid values are defined as the center of the 0.5° × 0.5° grid.
[b]The growing season is Apr–Oct in the Northern Hemisphere and Oct–Apr in the Southern Hemisphere.
[c]The trend is over the 1950–1999 time period and only those that are statistically significant are shown.
[d]The dormant season is Nov–Mar in the Northern Hemisphere and May–Sep in the Southern Hemisphere.
NS indicates trends that are not significant and *, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

Bordeaux wines. However, many wines are produced in much warmer areas where a further increase in temperature might produce unbalanced wines with high alcohol content (resulting from high sugar levels and over-ripe fruit), lower acidity, and compromised flavor profiles. The hypothesis "warmer is better" may not be correct for these wine regions. In fact, the correlation of vintage rating and temperature may be negative or non-linear. To account for this possibility, a quadratic relationship between vintage rating and growing season temperatures was used. Equation (2) below assumes that increasing growing season temperatures improve the ripeness of the grapes and therefore the quality of the wines, but at a decreasing rate and that ultimately, if temperature is higher than a certain optimum, grape quality declines:

$$R_{i,t} = \alpha_{0_i} + \alpha_{1_i}\text{temp}_{i,t} + \alpha_{2_i}\text{temp}^2_{i,t} + \beta_{1_i}\text{trend}_i + \varepsilon_{i,t} \quad (2)$$

Taking the partial derivative of Equation (2) and setting it equal to zero allowed for the calculation of an estimated growing season temperature optimum for each category of wine or region:

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

To examine the potential future temperature changes in the wine regions, we used a 100-yr 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, 2002; and others). The AOGCM has a stable control climatology, does not use a flux adjustment, has 19 vertical levels, and has a $2.5^\circ \times 3.75^\circ$ horizontal resolution (comparable to the $2.8^\circ \times 2.8^\circ$ transform grid for a T42 spectral resolution). The model output used in this analysis comes from the SRES A2 scenario and represents mid-range predictions compared to the other climate models (Houghton et al., 2001). Similar to the 1950–1999 gridded climatology, grids were extracted and averaged over the growing and dormant 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).

3. Results and Discussion

The analysis of the 1950–1999 gridded climatology revealed that all regions experienced growing season warming with 17 of the 27 wine regions having statistically significant trends (Table I and Figure 2). Temperature trends were significant in the majority of the U.S. and European wine regions while the majority of the Southern Hemisphere trends were insignificant. Averaged across regions with significant trends, 1950–1999 warming was 1.26 °C. Similar trends were found during the dormant period (winter) with all regions warming and 15 of the 27 locations having

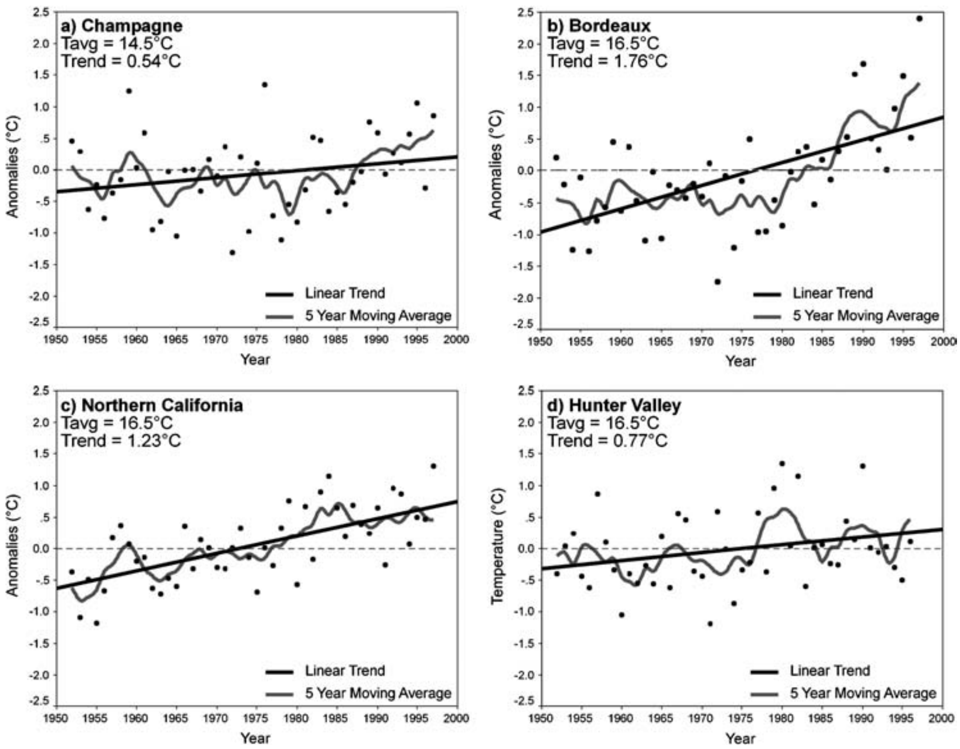

Figure 2. Observed (1950–1999) growing season average temperature anomalies for a) the Champagne region, b) Bordeaux, c) Northern California, and d) the Hunter Valley. Tavg is the average growing season temperature (Apr–Oct in the Northern Hemisphere and Oct–Apr in the Southern Hemisphere) and the Trend is over the 50-yr period.

statistically significant changes that averaged 1.38 °C over the time period. The most dramatic of these changes, confirmed by another observation-based study (Moisselin et al., 2002), occurred in the Rhône Valley of France where the growing season warmed by 4.07 °C and the dormant period by 3.85 °C (Table I).

On average, vintages tend to rate near 80 on a 100 scale with a standard deviation of 15 points (Table II). This indicates the peaked nature of vintage rating systems: the majority of scores were between 65–95 and the best vintages with ratings of 95–100 were typically more than one standard deviation from the mean. In addition, vintage ratings showed trends of increasing quality in 25 of the 30 wine regions (Table II) and decreasing vintage-to-vintage variation (not shown). Champagne was the only region to have a negative trend in ratings (−3.4 ratings points over the time period), but the trend was insignificant and could be due to the unranked years when vintage wines are not typically released. The reduction in quality variability over time was likely due in large part to changes in vineyard and winery production technologies.

TABLE II
Vintage rating statistics and trends for the 30 categories of wine or regions

Region/categories of wine	Climate maturity grouping	N	Mean	Standard deviation	Trend[b] R^2
Germany – Mosel-Saar-Ruwer Valleys	Cool	38	79.4	19.5	0.12**
Alsace	Cool	38	74.0	22.5	0.21***
Champagne	Cool	30	86.1	8.7	NS
Germany – Rhine Valley	Cool	38	79.0	19.3	0.11**
US – Pacific Northwest (red)	Intermediate	27	86.4	8.4	0.10*
US – Pacific Northwest (white)	Intermediate	27	84.7	6.5	NS
Loire Valley – red	Intermediate	38	70.1	25.8	0.08*
Loire Valley – sweet white	Intermediate	36	70.8	23.7	NS
Burgundy – Côte D'Or (red)	Intermediate	38	75.0	24.0	0.22***
Burgundy – Côte D'Or (white)	Intermediate	38	79.1	20.2	0.27***
Burgundy – Beaujolais (red)	Intermediate	38	77.2	13.9	0.33***
Chile[a]	Intermediate	14	87.4	3.0	0.42**
Bordeaux – Médoc and Graves	Intermediate	38	76.2	20.8	0.33***
Bordeaux – St. Émilion and Pomeral	Intermediate	38	75.7	20.8	0.30***
Bordeaux – Sauternes and Barsac	Intermediate	38	73.8	19.7	0.24***
Spain – Rioja	Intermediate	38	77.3	17.5	0.08*
US – California (red)	Warm	38	86.7	6.4	0.17**
US – California (white)	Warm	38	85.9	5.9	0.12**
South Africa[a]	Warm	10	87.8	3.7	0.32**
Northern Rhône Valley	Warm	38	82.1	14.9	0.11**
Portugal – Vintage Port	Warm	18	88.3	8.3	NS
Italy – Barolo	Warm	38	80.8	16.5	0.10*
Southern Rhône Valley	Warm	38	81.7	13.6	0.09*
Australia – Margaret River (red)	Warm	27	81.3	15.9	0.44***
Australia – Margaret River (white)	Warm	27	79.4	16.2	0.38***
Italy – Chianti	Warm	38	76.3	17.4	0.31***
Australia – Hunter Valley (red)	Hot	38	78.0	16.8	0.13**
Australia – Hunter Valley (white)	Hot	34	81.8	13.9	NS
Australia – Barossa Valley (red)	Hot	28	81.0	18.6	0.25***
Australia – Barossa Valley (white)	Hot	28	80.7	17.6	0.24***

[a]Rating data for South Africa and Chile are from a different source than the other locations (see text for details).
[b]The trends are over varying time periods and are for the total change in vintage ratings over the given time period.
NS indicates trends that are not significant and *, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

Tables III and IV give the results of the multiple regressions that account for trend interactions (Equation 1) and trend interactions and potential optimum growing season temperatures (Equation 2), respectively. The linear specification revealed that variation in growing season temperatures significantly influenced vintage ratings in 16 of the 30 regions with as much as 60–62% in German ratings explained and an unweighted average explained variance of 30% (Table III). While the effect of growing season average temperatures varies from region to region, the average response is a 13-point rating increase for each 1 °C increase. For example, a temperature increase of 1 °C was associated with the following ratings increases: white Rhine Valley wines by 21.5 points; white Mosel Valley wines by 20.8; red Burgundy wines by 12.7; and red St. Émilion and Pomerol wines by 10.4 points.

In other regions, the connection between growing season average temperature and wine quality was weaker. Many wine regions of the New World (e.g., the U.S.) had no relationship or even a slight insignificant negative relationship between temperature and wine ratings while emerging wine regions, such as Australia, Chile, and South Africa experienced higher wine ratings seemingly unrelated to climate change. Given the comparatively long estimation period for the climate/rating analysis, it is assumed that a combination of technological advances, accumulating experience, and increasing reviewer recognition influenced increased ratings in these regions. It can also be speculated that other ratings-dependent issues may have confounded the results for many of the less significant regions. For example, non-vintage designations for Port and Champagne, typically due to poor quality, result in discontinuous time series for those regions and potentially less significance in the analysis. In addition, broad vintage rating categories (i.e., Pacific Northwest, California, Chile, South Africa, etc.) reflecting numerous varieties and/or wine styles, may have masked the variability contained in the more defined wine categories. Finally, for some regions, growing season average temperatures may not be the ideal metric of climatic influences on wine quality.

The addition of a quadratic term, to account for potential optimum growing season temperatures, significantly refined the results of the linear specification and indicated that many regions may be at or near their ideal climates (Table IV). First, for most wine regions the quadratic estimates of (Equation 2) increased R^2 values by a mean of 35% over the linear specification (median increase of 13%). For instance, the explained variance for the Rhine Valley improved from 0.60 to 0.72; and for Saint-Émilion and Pomerol the increase was from 0.39 to 0.54. Figure 3 shows examples of predicted optimum growing season average temperatures for the Alsace region, the Loire Valley (sweet white wines), Bordeaux, and Barolo. For the four regions depicted, the predicted optimum growing season temperatures for the best wine quality (Equation 3), ranged from 13.7 °C for the Alsace region, 16.7 °C for the Loire Valley, 17.3 °C for Bordeaux, to 18.6 °C for Barolo (explained variances range from 0.48–0.72). Therefore, it appears that the general rule of thumb "the warmer the better" does not necessarily apply for even cool climate wine regions. The variation about the prediction lines indicates that, even when

TABLE III
Linear specification: Regression coefficients and test statistics for the 30 categories of wine or regions

Region/categories of Wine	Constant	Growing season tavg	Trend variable	R^2	Adj. R^2
Germany – Mosel-Saar-Ruwer Valleys	−191.11*** (−5.33)	20.75*** (7.38)	0.11 (0.55)	0.62	0.60
Alsace	−126.79* (−1.80)	14.04** (2.30)	0.50 (1.38)	0.35	0.31
Champagne	5.83 (0.12)	6.02* (1.87)	−0.22 (−1.47)	0.17	0.10
Germany – Rhine Valley	−240.92*** (−5.55)	21.51*** (7.37)	−0.02 (−0.12)	0.60	0.57
US – Pacific Northwest (red)[b]	38.69 (0.43)	2.63 (0.48)	0.14 (1.19)	0.06	0.03
US – Pacific Northwest (white)[b]	100.41*** (2.98)	−0.87 (−0.42)	−0.03 (−0.24)	0.01	0.07
Loire Valley – red	−216.31*** (−3.08)	18.68*** (4.11)	−0.02 (−0.04)	0.32	0.28
Loire Valley – sweet white	−249.07*** (−3.62)	21.36*** (4.82)	−0.27 (−0.79)	0.41	0.37
Burgundy – Côte D'Or (red)	−147.70 + (−1.78)	12.68** (2.43)	0.89** (2.61)	0.32	0.28
Burgundy – Côte D'Or (white)	−99.21 (−1.28)	9.83** (2.06)	0.87*** (2.76)	0.36	0.32
Burgundy – Beaujolais (red)	−78.09* (−1.70)	9.09*** (2.96)	0.33* (1.86)	0.47	0.44
Chile	40.37* (1.82)	1.38 (1.09)	0.57*** (3.97)	0.47	0.38
Bordeaux – Médoc and Graves	−78.70 (−1.30)	8.11** (2.07)	0.62* (1.71)	0.39	0.35
Bordeaux – St. Émilion and Pomerol	−111.20* (−1.82)	10.44** (2.58)	0.42 (1.08)	0.39	0.35
Bordeaux – Sauternes and Barsac	−149.52*** (−3.60)	13.29*** (4.67)	0.07 (0.21)	0.40	0.37
Spain – Rioja	−56.11 (−0.80)	8.98* (1.72)	0.02 (0.05)	0.19	0.14
US – California (red)[b]	96.76*** (3.24)	−1.11 (−0.64)	0.28*** (3.02)	0.17	0.13
US – California (white)[b]	100.27*** (3.62)	−1.26 (−0.76)	0.22** (2.32)	0.12	0.07
South Africa	12.59 (0.37)	2.23 (1.08)	0.84*** (4.23)	0.39	0.22
Northern Rhône Valley	−74.63* (−1.72)	9.19*** (3.83)	−0.33* (−1.72)	0.28	0.24
Portugal – Vintage Port	26.65 (0.33)	3.28 (0.71)	0.09 (0.40)	0.07	0.06
Italy – Barolo	−175.22** (−2.11)	15.09*** (3.04)	−0.42 (−1.57)	0.40	0.36
Southern Rhône Valley	−75.84 (−1.24)	8.51** (2.68)	−0.00 (−0.02)	0.19	0.15
Australia – Margaret River (red)	22.83 (0.22)	0.32 (0.07)	1.43** (2.38)	0.45	0.40
Australia – Margaret River (white)	162.53 (1.30)	−6.46 (−1.13)	1.00 (1.62)	0.43	0.40
Italy – Chianti	8.62 (0.17)	2.18 (0.61)	0.83*** (2.88)	0.32	0.28
Australia – Hunter Valley (red)	30.44 (0.42)	1.58 (0.43)	0.52* (2.01)	0.13	0.08
Australia – Hunter Valley (white)	−0.32 (−0.01)	3.66 (1.60)	0.27 (0.96)	0.09	0.03
Australia – Barossa Valley (red)	53.89 (0.83)	−0.85 (−0.29)	1.22** (2.08)	0.28	0.22
Australia – Barossa Valley (white)	58.21 (1.08)	−0.89 (−0.36)	1.12** (2.10)	0.26	0.20

The regressions are run with heteroscedasticity consistent *t*-statistics as shown in parentheses below each coefficient.
[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.
*, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

TABLE IV
Quadratic specification: Regression coefficients and test statistics for the 30 categories of wine or regions

Region	Constant	Trend variable	Growing season tavg	(Growing season tavg)^2	R^2	Adj. R^2	% R^2 over linear model	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	15	13.92
Alsace	−2868.08*** (−4.34)	0.76* (2.01)	437.57*** (4.18)	−16.36*** (−3.93)	0.48	0.43	37	13.72
Champagne	−1625.32** (−2.17)	−0.19 (−1.36)	229.75** (2.28)	−7.66** (−2.26)	0.33	0.25	94	14.99
Germany – Rhine Valley	−3009.67*** (−5.58)	0.14 (0.82)	397.27*** (5.45)	−12.74*** (−5.20)	0.72	0.69	20	15.59
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	67	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	500	NS
Loire Valley – red	−2052.92* (−1.98)	−0.04 (−0.11)	256.52* (1.96)	−7.68* (−1.85)	0.37	0.31	16	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	22	16.63
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	0	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	3	NS
Burgundy – Beaujolais (red)	−641.21 (−0.39)	0.37** (2.27)	80.83 (0.87)	−2.29 (−0.78)	0.48	0.44	2	NS
Chile	−493.95 (−0.76)	0.57*** (3.65)	65.58 (0.84)	−1.93 (−0.83)	0.51	0.36	9	NS
Bordeaux – Médoc and Graves	−2091.10*** (−4.10)	0.66* (1.99)	248.71*** (4.19)	−7.18*** (−4.16)	0.53	0.49	36	17.33
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	38	17.47
Bordeaux – Sauternes and Barsac	980.15 (1.63)	0.09 (0.26)	112.6 (1.60)	−2.96 (−1.44)	0.43	0.38	7	NS
Spain – Rioja	−1304.23** (−2.10)	0.20 (0.58)	178.33** (2.20)	−5.75** (−2.17)	0.27	0.21	42	17.50
US – California (red)[b]	70.35 (0.07)	0.26*** (2.75)	1.45 (0.01)	−0.06 (−0.02)	0.17	0.09	0	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	42	NS
South Africa	848.57 (0.95)	0.92*** (4.08)	−100.86 (−0.91)	3.16 (0.92)	0.46	0.18	18	NS
Northern Rhône Valley	197.26 (0.41)	−0.36* (−1.72)	−22.00 (−0.40)	0.89 (0.56)	0.28	0.22	0	NS
Portugal – Vintage Port	−11.15 (−0.01)	0.09 (0.39)	7.54 (0.04)	−0.12 (−0.02)	0.06	−0.16	−14	NS

(*Continued on next page*)

TABLE IV
(*Continued*)

Region	Constant	Trend variable	Growing season tavg	(Growing season tavg)^2	R^2	Adj. R^2	% R^2 over linear model	Estimated optimum growing season tavg (°C)
Italy – Barolo	−2504.87** (−2.31)	−0.02 (−0.07)	279.60** (2.31)	−7.53** (−2.24)	0.48	0.43	20	18.57
Southern Rhône Valley	−2754.94* (−1.78)	−0.08 (−0.47)	300.55* (1.80)	−7.94* (−1.76)	0.27	0.20	42	18.93
Australia – Margaret River (red)	−204.29 (−0.26)	1.44** (2.39)	24.41 (0.29)	−0.64 (−0.28)	0.45	0.37	7	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	7	NS
Italy – Chianti	0.76*** (2.81)	8.62 (0.17)	−88.19 (−0.92)	2.47 (0.95)	0.33	0.27	3	NS
Australia – Hunter Valley (red)	−93.38 (−0.05)	0.52* (1.97)	13.86 (0.07)	−0.3 (−0.07)	0.13	0.05	0	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	0	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	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	12	19.89

The regressions are run with heteroscedasticity consistent *t*-statistics as shown in parentheses below each coefficient. The estimated optimum growing season average temperature is calculated from the fitted multiple regression (see Figure 3 for examples).
[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.
*, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

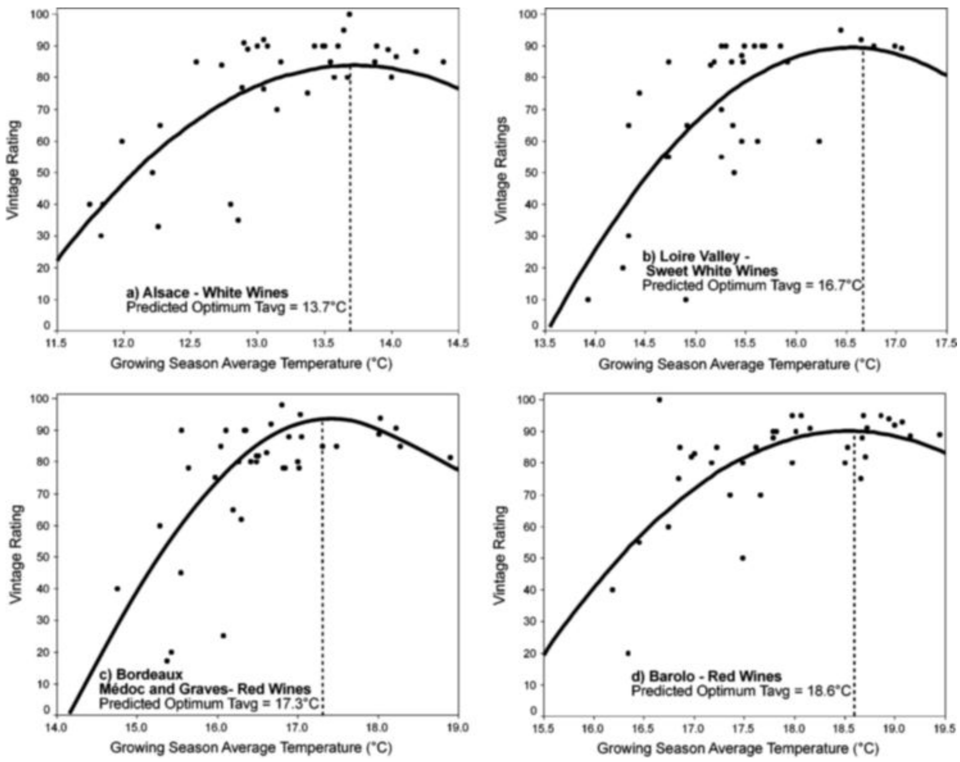

Figure 3. Predicted optimum growing season temperatures for a) Alsace white wines, b) the Loire Valley sweet white wines, c) the red wines from the Médoc and Graves of Bordeaux, and d) the red wines of Barolo. The dashed lines represent the quadratic model predicted optimum for each region shown.

a growing season had near optimum temperatures, weather events such as frost, hail, or untimely rain likely reduced vintage quality. Conversely, high ratings were achieved during cooler than average growing seasons (e.g., for Barolo a score of 100 was achieved during a growing season 1.1 °C below average) and were likely due to less variability in the day-to-day temperatures during the season.

The importance of these predictions becomes obvious when compared to the long-term (1950–1999) mean growing season temperatures for the regions (Table V). The regions range from being at their optimum (Barossa Valley white wines) to being 1.4 °C below their optimum (Loire Valley red wines) with an average across all twelve regions of 0.8 °C below the predicted optimum. However, Table V also shows that the average from 1950–1999 was well below the 1990–1999 average, when growing season temperatures in almost all wine regions increased dramatically: during this time period, many wine regions were extremely close to their optimum temperature. For a few regions the 1990s were even too warm for the predicted optimum (e.g., Alsace, Médoc and Graves).

TABLE V

Actual, estimated optimal, and predicted growing season average temperatures for those wine regions and categories of wine with significant models from Table IV

Region/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	13.7	−0.1	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

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.

A comparison of the 1950–1999 and 2000–2049 time periods from the HadCM3 climate model for grid cells encompassing the wine regions suggests that the mean growing season temperatures will increase by an average of 1.24 °C for the regions (Table VI). Figure 4 shows four examples for the Rhine Valley, Bordeaux, Northern California, and the Barossa Valley indicating mean changes of 0.9–1.7 °C between the two time periods. Changes are also predicted to be greater in the Northern Hemisphere (1.31 °C) than in the Southern Hemisphere (0.93 °C) with areas in the western United States predicted to have the greatest change and South Africa the least change.

An examination of the temporal changes from a 50-yr run (2000–2049) of the model revealed significant average growing season temperature trends across all regions, ranging 0.18–0.58 °C per decade (Table VI). Overall changes average 2.04 °C/50 yr, ranging from 0.88 °C/50 yr in South Africa to 2.85 °C/50 yr for southern Portugal. Figure 4 depicts example trends for the Rhine Valley, Bordeaux, Northern California, and Barolo regions that are modeled at 0.3–0.5 °C

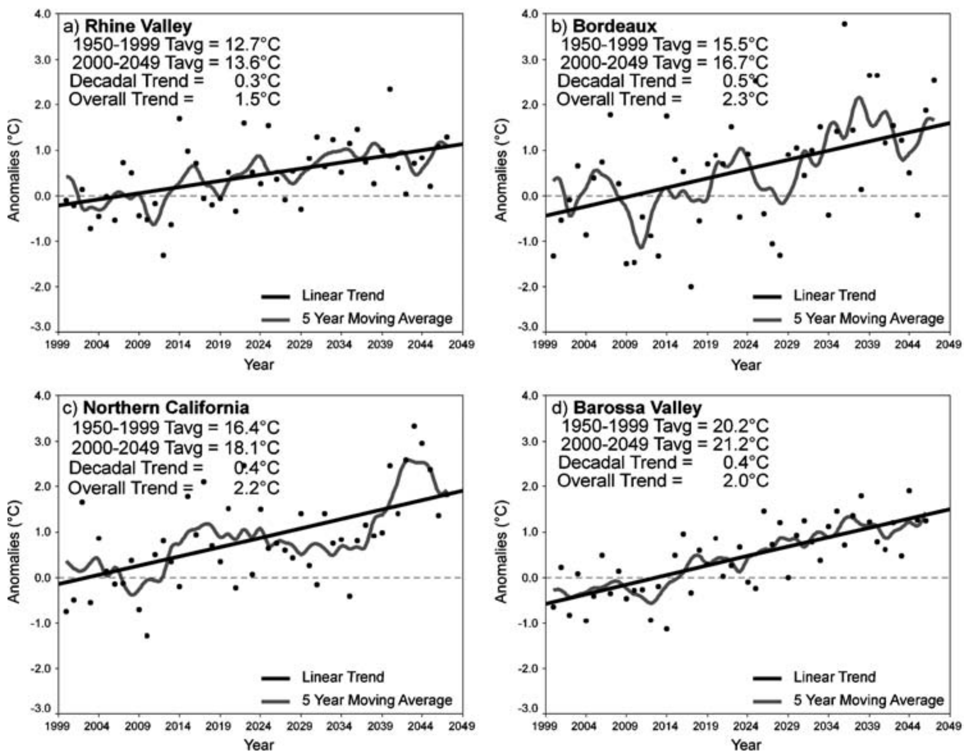

Figure 4. HadCM3 modeled growing season average temperature anomalies for a) the Rhine Valley, b) Bordeaux, c) Northern California, and d) the Barossa Valley. The anomalies are referenced to the 1950–1999 base period from the HadCM3 model. Trend values are given as an average decadal change and the total change over the 2000–2049 50-yr period.

TABLE VI
Results from the analysis of the HadCM3 GCM output for the 27 wine producing regions used in the analysis

Region[a]	Climate maturity grouping	Change in growing season[b] tavg	Growing season trend by decade[c]	Growing season trend overall[c]	Trend R^2
Mosel Valley[d]	Cool	0.93	0.31	1.51	0.32***
Alsace	Cool	0.94	0.34	1.65	0.37***
Champagne	Cool	0.87	0.31	1.51	0.32***
Rhine Valley[d]	Cool	0.93	0.31	1.51	0.32***
Northern Oregon	Intermediate	1.27	0.32	1.56	0.32***
Loire Valley	Intermediate	1.01	0.44	2.14	0.31***
Burgundy-Côte	Intermediate	1.06	0.43	2.09	0.31***
Burgundy-Beaujolais	Intermediate	1.24	0.46	2.26	0.37***
Chile	Intermediate	1.11	0.38	1.84	0.38***
Eastern Washington	Intermediate	1.81	0.57	2.81	0.37***
Bordeaux	Intermediate	1.20	0.48	2.33	0.27***
Central Washington	Intermediate	1.86	0.46	2.27	0.22***
Rioja	Intermediate	1.33	0.52	2.52	0.40***
Southern Oregon	Intermediate	1.27	0.48	2.35	0.21***
Coastal California	Warm	1.59	0.38	1.85	0.25***
South Africa	Warm	0.52	0.18	0.88	0.12**
Northern California	Warm	1.71	0.44	2.16	0.37***
N. Rhône Valley[d]	Warm	1.24	0.46	2.26	0.37***
Northern Portugal	Warm	1.29	0.50	2.42	0.29***
Barolo	Warm	1.41	0.49	2.41	0.40***
S. Rhône Valley[d]	Warm	1.24	0.46	2.26	0.37***
Margaret River	Warm	1.00	0.42	2.04	0.55***
Chianti	Warm	1.59	0.47	2.30	0.37***
Hunter Valley	Hot	1.09	0.37	1.78	0.20***
Barossa Valley	Hot	0.95	0.42	2.01	0.58***
Southern Portugal	Hot	1.62	0.58	2.85	0.25***
Southern California	Hot	1.43	0.28	1.38	0.23***

[a]Grid temperature values are defined as the average over a grid of 2.50° latitude × 3.75° longitude.
[b]The growing season is Apr–Oct in the Northern Hemisphere and Oct–Apr in the Southern Hemisphere and the change is calculated from the 1950–1999 to the 2000–2049 time periods.
[c]The trend is over the 2000–2049 time period.
[d]These regions fall within one grid cell and therefore have the same values.
*, **, and *** indicate significance at the 0.10, 0.05, and 0.01 levels, respectively.

per decade with overall trends predicted to be 1.5–2.3 °C. Similar to the average growing season changes given above, the 2000–2049 trends are greater in the Northern Hemisphere (2.11 °C/50 yr) than those modeled for the Southern Hemisphere (1.71 °C/50 yr).

The magnitudes of these predicted 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 I). For example, if a wine region with a mean growing season average temperature of 14 °C (cool climate) warms by 1.5 °C, then that region is climatically more conducive to ripening some varieties (intermediate maturity group), while potentially less so for those that are currently being grown. 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 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. In addition, Table V shows that many of the wine regions/categories of wine are at or near their optimum growing season temperature and further increases, as predicted during for 2000–2049, will place some regions outside their theoretical optimum growing season climate.

HadCM3 predicted growing season temperature variability, as measured by the annual seven-month growing season standard deviation, increases in 20 of the regions and declines in seven (not shown). Changes in winter temperature variability (annual five-month dormant season standard deviations) increases in 13 regions and declines in 14. Dormant period trends during 2000–2049 are significant for 20 of the 27 regions (western Europe stands out as not exhibiting changes in dormant period average temperatures). Average winter warming is 1.31 °C/50 yr or 0.26 °C per decade with Chianti and Barolo warming the most during the dormant period and Northern Oregon the least (not shown). Differences between the hemispheres are less during the dormant period (0.79 °C versus 0.89 °C for the Southern and Northern Hemispheres, respectively) with Barolo warming the most (1.12 °C) and South Africa the least (0.52 °C). Smaller increases are predicted for mean winter temperatures (0.87 °C on average, not shown) than for mean growing season temperatures.

Overall, the climate change scenarios given for the wine regions suggest potential for changes in varieties planted and wine styles and/or regional changes in viticultural viability. The wine quality issues related to climate change and shifts in climate maturity potential are seen mostly through a more rapid plant growth and out of balance ripening profiles. For example, if a region has a maturation period (véraison to harvest) that produces optimum sugar, acid, and flavor profiles for that variety, then balanced and superior wines can be produced. If the climate is warmer than ideal, grapevines have more rapid phenological development that results in earlier sugar ripeness and loss of acidity through respiration while flavors develop. The result is unbalanced or “flabby” wines (high alcohol with little acidity retained for freshness). In addition, harvests occurring earlier in the summer (e.g., August or September instead of October in the Northern Hemisphere) would likely produce desiccated fruit (raisoning and lower yields) unless irrigation is increased.

Climate change impacts are likely to be region-specific. Changes in cool climate regions (Table I – i.e., the Mosel Valley, Alsace, Champagne, and the Rhine Valley) could lead to more consistent vintage quality and possibly even ripening of warmer climate varieties. However, the quadratic models indicated each of these cool climate regions may be at or near their optimum climate for producing the best quality wine with current varieties. Other regions, currently with warmer growing seasons (Table I – i.e., southern California, southern Portugal, the Barossa Valley, and the Hunter Valley) may become too warm for the existing varieties grown there and hot climate maturity regions (Table I) may become too warm to produce high-quality wines of any type. Winter temperature changes would also affect viticulture by making regions that experience hard winter freezes (e.g., the Mosel Valley, Alsace, and Washington) less prone to vine damage, while other regions (e.g., California and Australia) would have such mild winters that latent bud hardening may not be achieved and cold-limited pests may increase in number or severity.

While this analysis examines only those effects to vintage quality brought about by temperature changes, grape growers and wine makers could potentially be faced with many compounded issues in a warmer world. Given the observed and modeled acceleration of vegetative and reproductive growth of grapevines in a warmer climate, a general trend of increased yields and higher sugar contents has been found for several growing regions and varieties (Bindi et al., 1996; Jones and Davis, 2000). However, based on these trends and the grape ripening/quality thresholds that may be reached in a warmer climate, increasing potential economic risks for grape growers and winemakers have been predicted (Bindi et al., 1996; Bindi and Fibbi, 2000). In addition, while many crop models show greater growth and plant water use efficiency due to increases in CO_2 (Houghton et al., 2001; Butterfield et al., 2000), changes in crop quality are more complex due to the interactive effects with changes in temperature and moisture availability (Schultz, 2000). Recent grapevine modeling indicated that photosynthesis and water-use efficiency (ratio of photosynthesis to water consumption) in grapevines was stimulated by increased CO_2 and that production should increase without causing negative influences on the quality of grapes and wine (Bindi et al., 2001). Although grape growing requires less water per value of the crop than many other crop systems, changes in seasonally dependent snowmelt or rainfall could also place added stress on vines in water-limited regions. Finally, climate change will alter the presence and/or intensity of certain diseases and pests resulting in a more challenging growing environment from both a soil and vegetative standpoint.

4. Conclusions

Using historical climate data, model simulations of future climates, and vintage ratings, four central conclusions were reached regarding climate change implications for quality global wine production. First, from 1950–1999, growing season average temperatures have increased in the world's high-quality wine producing regions by 1.26 °C. Second, while some of the trend in better quality can undoubtedly be attributed to better viticultural and enological (the science of the making of wines) practices, in the majority of regions, climate variations and trends were found to influence year-to-year variations and trends in vintage quality ratings: from 10–60% of vintage ratings were explained by growing season temperature variations with the greatest effects in the cool climate regions of the Mosel and Rhine Valleys of Germany. Third, based on a quadratic econometric modeling approach, 12 of the wine regions were found to have an optimum growing season temperature above which vintage ratings tended to decline, suggesting that the rule of thumb "the warmer the better" is not globally applicable. In addition, many of the wine regions for which the quadratic specification is significant have trended to their optimum, while some are already beyond the predicted optimums.

Fourth, based on the HadCM3 climate model, between the 1950–1999 to 2000–2049 periods, temperatures regimes for the high-quality wine producing regions are predicted to warm by an average of 1.24 °C. Average predicted temperatures increases within the 2000–2049 period alone, are 0.42 °C per decade and 2.04 °C overall, with warming rates for the Northern Hemisphere that are typically greater than the Southern Hemisphere wine regions. While the observed warming of the late 20th century appears to have been mostly beneficial for high-quality wine production worldwide, this analysis suggests that the impacts of future climate change will be highly heterogeneous across varieties and regions. Critically, in some regions, warming may exceed the varietally specific optimum temperature threshold such that the ability to ripen balanced fruit from the existing varieties grown and the production of current wine styles will be challenging if not impracticable. Furthermore, the projected wine region warming found in this analysis comes from a single model and scenario of future warming, with the results falling in the mid-range of potential changes predicted from the many climate models currently employed (Houghton et al., 2001).

High-quality wine regions create unique physical and cultural landscapes that, through production, processing, trade, and tourism industries, are a vibrant component of local economies. While the exact magnitude and rate of future climate change is uncertain, any change can greatly impact the narrow geographical limits of high-quality production viability and will likely bring about related changes in suitable grape varieties, regional wine styles, and regional cultures. To prepare for the future, the wine industry should integrate planning and adaptation strategies to adjust accordingly. To facilitate planning for and adaptation to climate change, focused research is needed in two main fields: production of finer resolution climate simulations more appropriate for assessing microclimates critical for grape growing; and improved viticulture modeling incorporating treatment of varietal potential, phenological development, and vine management.

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References

Amerine, M. A. and Winkler, A. J.: 1944, 'Composition and quality of musts and wines of California grapes', *Hilgardia* **15**, 493–675.

Ashenfelter, O., Ashmore, D., and Lalonde, R.: 1995, 'Bordeaux wine quality and the weather', *Chance* **8**(4), 7–19.

Ashenfelter, O. and Byron, R. P.: 1995, 'Predicting the quality of an unborn Grange', *Econ. Rec.* **7**(212), 40–53.

Ashenfelter, O. and Jones, G. V.: 2000, The demand for expert opinion: Bordeaux Wine. VDQS Annual Meeting, d'Ajaccio, Corsica, France. October, 1998. Published in *Cahiers Scientifique* from the Observatoire des Conjonctures Vinicoles Europeenes, Faculte des Sciences Economiques, Espace Richter, Ave. de La Mer, BP 9606, 34054 Montpellier Cedex 1, France.

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S., and Miglietta, F.: 1996, 'Modeling the impact of future climate scenarios on yield and variability of grapevine', *Clim. Res.* **7**, 213–224.

Bindi, M. and Fibbi, L.: 2000, 'Modeling climate change impacts at the site scale on grapevine', in Downing, T. E., and Harrison, P. A. (eds.), *Climate Change, Climatic variability and Agriculture in Europe: An Integrated Assessment*, pp. 117–134.

Bindi, M., Fibbi, L., and Miglietta, F.: 2001, 'Free Air CO_2 Enrichment (FACE) of grapevine (Vitis vinifera L.): II. Growth and quality of grape and wine in response to elevated CO_2 concentrations', *Eur. J. Agron.* **14**(2), 145–155.

Broadbent, M.: 1980, *The Great Vintage Wine Book*. Alfred A. Knopf, New York.

Butterfield, R. E., Gawith, M. J., Harrison, P. A., Lonsdale, K. J., and Orr, J.: 2000, 'Modelling climate change impacts on wheat, potato and grapevine in Great Britain', in Downing, T. E., Harrison, P. A., Butterfield, R. E. and Lonsdale, K. G. (eds.), *Climate Change, Climatic Variability and Agriculture in Europe: An Integrated Assessment*. Final Report. Environmental Change Institute, University of Oxford.

Carter, T. R., Parry, M. L., and Porter, J. H.: 1991, 'Climatic change and future agroclimatic potential in Europe', *Int. J. Climatol.* **11**, 251–269.

Chahine, M. T.: 1992, 'The hydrologic cycle and its influence on climate' *Nature* **359**, 373.

Dai, A., Del Genio, A. D., and Fung, I. V.: 1997, 'Clouds, precipitation and temperature range', *Nature* **386**, 665.

de Blij, H. J.: 1983, 'Geography of viticulture: Rationale and resource', *J. Geog.* **82**, 112–121.

Easterling, D. R. et al.: 2000, 'Observed variability and trends in extreme climate events: A brief review', *Bull. Am. Meteorol. Soc.* **81**, 417–425.

Fischer, G., Shah, M., and van Velthuizen, H.: 2002, 'Global Agro-ecological Assessment in the 21st Century', *Climate Change and Agricultural Vulnerability*. (IIASA, Austria).

Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R., and Webster, M. D.: 2002, 'Quantifying uncertainties in climate system properties with the use of recent climate observations', *Science* **295**, 113–117.

Gladstones, J.: 1992, *Viticulture and Environment*. Winetitles, Adelaide.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: 2000, 'The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments', *Clim. Dyn.* **16**, 147–168.

Houghton, J. T. et al.: 2001, *Climate Change 2001: The Scientific Basis. Contribution of the Working Group 1 to the Third Assessment of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Johnson, H.: 1985, *The World Atlas of Wine*. Simon and Schuster, New York, 3rd Edition.

Jones, G. V.: 1997, *A Synoptic Climatological Assessment of Viticultural Phenology*, Dissertation, University of Virginia, 410 pp.

Jones, G. V. and Davis, R. E.: 2000, 'Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France', *Am. J. Viti. Enol.* **51**, 249–261.

Jones, G. V. and Storchmann, K.: 2001, 'Wine market prices and investment under uncertainty: An econometric model for Bordeaux Crus Classés', *Agr. Econ.* **26**, 115–133.

Jones, G. V. and Hellman, E.: 2003, Site Assessment: in "*Oregon Viticulture*" Hellman, E. (ed.), 5th Edition, Oregon State University Press, Corvallis, Oregon, pp. 44–50.

Jones, G. V.: 2005a, Climate and terroir: Impacts of climate variability and change on wine. *GeoScience Canada*, Terroir Series (in press).

Jones, G. V.: 2005b, Climate change in the western United States grape growing regions. *Proceedings of the 7th International Symposium on Grapevine Physiology and Biotechnology*. Davis, California, June 2004. In press: *Acta Horticulturae*.

Jones, G. V., White, M. A., Cooper, O. R., and Storchmann, K.-H.: 2004, Climate and wine: Quality issues in a warmer world. *Proceedings of the Vineyard Data Quantification Society's 10th Œonometrics Meeting* (in press). Dijon, France, May 2004.

Karl, T. R. et al.: 1993, 'A new perspective on global warming: Asymmetric trends of daily maximum and minimum temperature', *Bull. Am. Meteor. Soc.* **74**, 1007.

Kenny, G. J. and Harrison, P. A.: 1992, 'The effects of climate variability and change on grape suitability in Europe', *J. Wine Res.* **3**, 163–183.

Le Roy Ladurie, E.: 1971, *Times of Feast, Times of Famine: A History of Climate Since the Year 1000*. Doubleday, Garden City, New York.

Legates, D. R. and Willmott, C. J.: 1990, 'Mean seasonal and spatial variability global surface air temperature', *J. Theor. Appl. Climatol.* **41**, 11–21.

Lough, J. M., Wigley, T. M. L., and Palutikof, J. P.: 1983, 'Climate and climate impact scenarios for Europe in a warmer world', *J. Clim. Appl. Meteorol.* **22**, 1673–1684.

Mazur, M.: 2002, 'Wine Enthusiast's 2002 Vintage Chart,' *The Wine Enthusiast Magazine* (http://www.winemag.com/vintage.cfm).

McCarthy, J. J. et al.: 2001, *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Contribution of the Working Group 1 to the Third Assessment of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

McInnes, K. L., Whetton, P. H., Webb, L., and Hennessy, K. J.: 2003, 'Climate change projections for Australian viticultural regions', *The Aust. NZ. Grapegrower and Winemaker*. February 2003, 40–47.

Menzel, A. and Fabian, P.: 1999, 'Growing season extended in Europe', *Nature* **397**, 659.

Moisselin, J.-M., Schneider, M., Canellas, C., and Mestre, O.: 2002, 'Climate change over France during the 20th century: A study of long-term homogenized data of temperature and rainfall', *La Météorlogie* **38**, 45–56.

Moonen, A. C., Ercoli, L., Mariotti, M., and Masoni, A.: 2002, 'Climate change in Italy indicated by agrometeorological indices over 122 years', *Agri. Forest Meteorol.* **111**, 13–27.

Mullins, M. G., Bouquet, A., and Williams, L. E.: 1992, *Biology of the Grapevine*, Cambridge University Press, Great Britain, 239 pp.

Nemani, R. R., White, M. A., Cayan, D. R., Jones, G. V., Running, S. W., and Coughlan, J. C.: 2001, 'Asymmetric climatic warming improves California vintages', *Clim. Res.* **19**, 25–34.

Palutikof, J. P., Goodess, C. M., Watkins, S. J., and Holt, T.: 2002, 'Generating rainfall and temperature scenarios at multiple sites examples from the Mediterranean', *J. Clim.* **15**, 3529–3548.

Parker, R. M.: 1985, *Bordeaux: The Definitive Guide for the Wines Produced Since 1961*. Simon and Schuster, New York.

Penning-Rowsell, E.: 1989, *Wines of Bordeaux*, Penguin Books, London/New York, 6th Edition.

Pfister, C.: 1988, Variations in the spring-summer climate of central Europe from the High Middle Ages to 1850, in *Long and Short Term Variability of Climate*, H. Wanner, U. Siegenthaler (eds.) Springer-Verlag, Berlin, pp. 57–82.

Pope, V. D., Gallani, M. L., Rowntree, P. R., and Stratton, R. A.: 2000, 'The impact of new physical parameterizations in the Hadley Centre climate model – HadAM3', *Clim. Dynam.* **16**, 123.

Raval, A. and Ramanathan, A.: 1989, 'Observational determination of the greenhouse effect', *Nature* **342**, 758.

Renner, B.: 1989, 'The shape of things to come', *Wine and Spirit*, December 1989, 55–57.

Schultz, H. R.: 2000, 'Climate change and viticulture: An European perspective on climatology, carbon dioxide, and UV-B effects', *Aust. J. Grape and Wine Res.* **6**, 2–12.

Stevenson, T.: 2001, *New Sothebys Wine Encyclopedia: A Comprehensive Reference Guide to the Wines of the World*, Dorling Kindersley, London, 3rd Edition.

Tate, A. B.: 2001, 'Global warming's impact on wine', *J. Wine Res.* **12**, 95–109.

Unwin, T.: 1991, *Wine and the Vine: An Historical Geography of Viticulture and the Wine Trade*, Routledge, London and New York.

Willmott, C. and Matsuura, K.: 2002, Terrestrial Air Temperature and Precipitation: Monthly and Annual Time Series 1950–1999. (http://climate.geog.udel.edu/~climate/html_pages/README.ghcn_ts2.html).

Winkler, J. A., Andresen, J. A., Guentchev, G., and Kriegel, R. D.: 2002, 'Possible impacts of projected climate change on specialized agriculture in the Great Lakes Region', *J. Great Lakes Res.* **28**, 608–625.

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