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Climate and Terroir: Impacts of Climate Variability and Change on Wine

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SUMMARY

As part of the concept of terroir, climate is a factor that influences both the general viability of a region to ripen a specific variety of grapes and the resulting wine style. Climate variability and change affect every form of agriculture and are seldom more evident than with the production of high quality wines where narrow climate zones for optimum quality place them particularly at risk. While climates have changed dramatically during the history of the cultivation of grapes for wine, the changes in the recent past and those projected in the near future have received a great deal of attention for their potential impacts on today's wine industry. Research has shown that both recent short and long-term climate changes have resulted in generally warmer and longer growing seasons with less frost risk in many of the world's best wine regions. While these changes have been related to greater production and quality, future climate projections indicate the potential for threshold issues in which too much warming will potentially alter traditional wine styles and/or varieties planted, and likely bring about spatial shifts in viticultural viability.

SUMMAIRE

Cet élément du concept de terroir qu'est le climat détermine la viabilité d'une région à permettre le mûrissement d'une variété définie de raisin ainsi que l'élaboration du style du vin qu'on en tire. La variabilité et le changement du climat affectent toute forme d'agriculture, mais les effets sont rarement plus évidents que sur la production de grands vins où l'optimisation de la qualité nécessite une viticulture en des zones climatiques aux conditions très circonscrites, d'où les risques. Bien que les climats aient changé dramatiquement dans l'histoire de la culture des vignes vinicoles, les changements climatiques récents ainsi que les changements projetés dans un avenir rapproché ont été beaucoup étudiés en fonction de leurs impacts sur l'actuelle industrie vinicole. Les compte rendus des recherches montrent que les changements climatiques, tant à courts et qu'à longs termes, ont amené des saisons viticoles plus chaudes et plus longues comportant moins de risques de gel, et cela dans nombres des meilleures régions vinicoles du monde. Bien que ces changements aient été associés à une amélioration de la production et de la qualité, les projections climatiques montrent qu'il est possible qu'un seuil soit atteint, au-delà duquel ce réchauffement pourrait altérer le style les vins traditionnels et/ou les variétés utilisées, entraînant des changements spatiaux probables de la viabilité viticole.

INTRODUCTION

Climate is a very complex, highly variable, and pervasive factor in our natural Earth- and human-based systems. From controlling vegetation patterns and geological weathering characteristics, to influencing water resources and agricultural productivity, climate is at the heart of the delicate equilibrium that exists on Earth. Climate is a wide-ranging factor in virtually all forms of agriculture, from influencing spatial variations of crop viability to largely determining year-to-year yield variability; climate is an important issue in determining where and how crops are grown. Climate-related impacts on agriculture are generally related to climate variability over the short term (i.e., intra-annual and inter-annual) and climate change over the long term (i.e., decades to centuries or longer). Understanding such relationships is seldom more important than today, as variations and/or changes in climate can greatly impact the ability to produce a given crop.

The Climate Component of Terroir

Grapevines are some of the oldest cultivated plants and have been historically associated with Mediterranean climates (e.g., Italy). Today, however, grapevines for wine production (note that all occurrences of grapes or grapevines refer to grapes for wine production, unless stated otherwise) are grown in many types of climates throughout the mid latitudes: Mediterranean, marine west coast (e.g., Oregon), humid subtropical (e.g., eastern Australia), and semi-arid continental climates (e.g., eastern Washington state) (Fig. 1). The climates of these regions are an integral part of the notion of terroir, the French concept in which a complex interplay of physical factors (Wilson, 1998; Haynes, 1999; Meinert and Busacca, 2000) and cultural influences (Vaudour, 2000) interact to define the wine styles and quality that come from any site or region. Climate is one part of the continuum that includes the physical landscape influences of soil and terrain, which in combination largely determine the grape variety that can be grown in a given region. Once grape variety-site characteristics are considered, the remaining viticulture (the science of the cultivation of grapevines) and enology (the science of the making of wines) aspects, which include regional associations and cultural traditions, result in the defining wine style a region produces.

Of all of the site factors, climate arguably exerts the most profound effect on the ability of a region or site to produce quality grapes. Worldwide, the average climatic conditions of a wine region determine to a large degree the grape varieties that can be grown there, whereas wine production and quality are chiefly influenced by site-specific factors, husbandry decisions, and short-term climate variability (Jones and Hellman, 2003). While the average climate structure is very important for grape growth and wine quality, weather and climate factors on daily and hourly time scales are critical, and include: solar radiation, heat accumulation, temperature extremes (including high temperatures during the summer, winter freezes and spring and fall frosts), diurnal temperature ranges, precipitation (especially during flowering and ripening stages), wind, and extreme weather events such as hail. Owing to inadequate weather station locations, poor data sharing between countries, and disagreement on what weather and climate factors are most important, the climate component of terroir has been studied largely through spatial and temporal averaging, and by comparing new wine region climates to analogous climates in historical regions.

Temperature and Growing Season

Although the climate-based aspects of terroir are related to various factors that operate from the macroscale to the microscale, measures of temperature on daily, weekly, monthly, and growing season time scales have most often been employed to define the spatial differences between regions. In general, growing season length and temperatures are critical aspects because of their major influence on grape ripening and fruit quality, and therefore varietal adaptation to a specific terroir. It is in its ideal climate that a given grape variety can achieve optimum ripening profiles of sugar, acid, and flavour to maximize a given style of wine and the vintage quality.

The growing season necessary for wine grapes varies from region to region but averages approximately 170-190 days (Mullins *et al.*, 1992). The length of the frost-free season is impor-

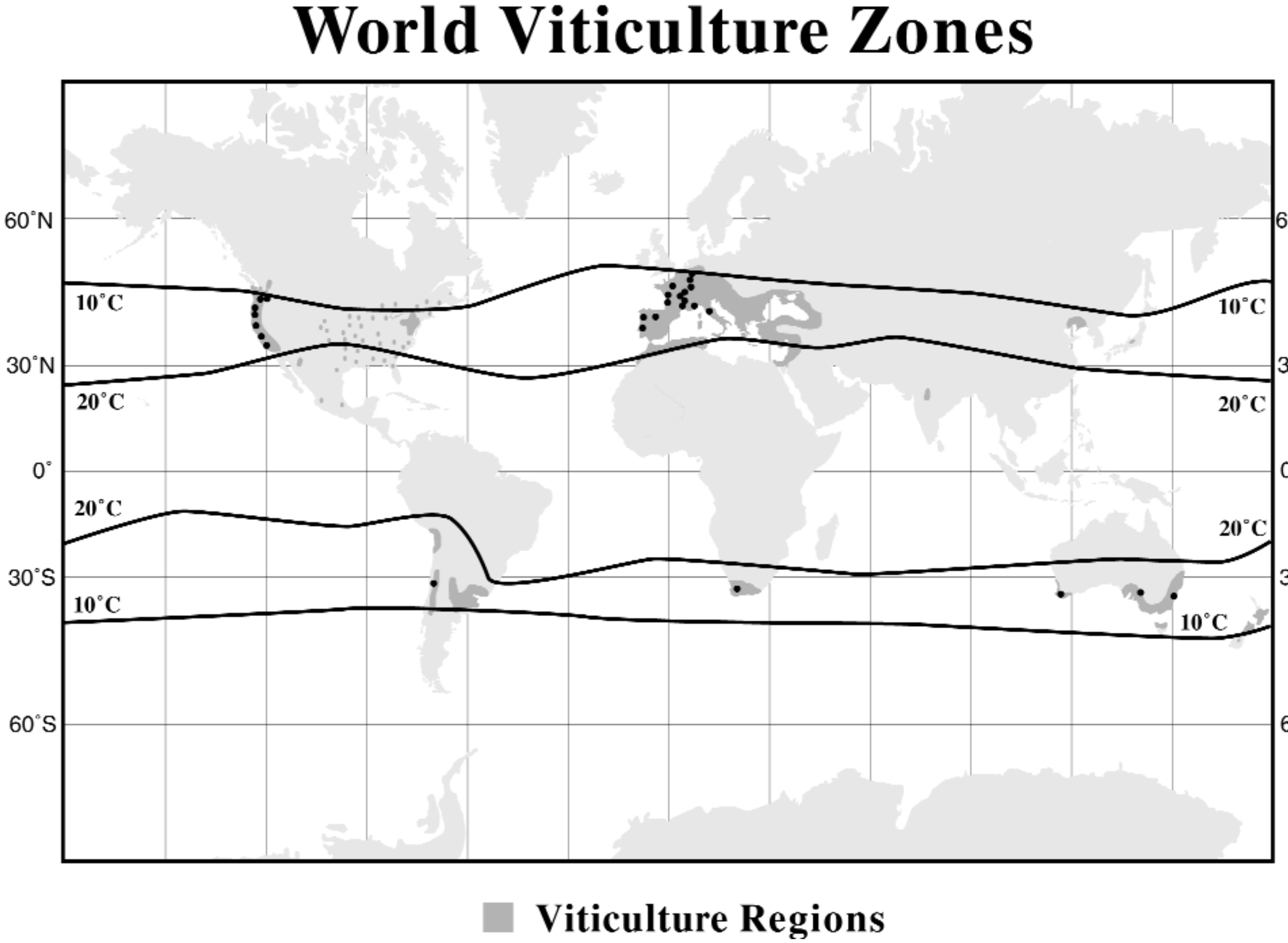

Figure 1. General geographical extent of the world's main viticulture regions (adapted from de Blij, 1983). Contours represent the mean annual 10°C and 20°C isotherms as a proxy for the latitudinal limits of the majority of the world's grape growing areas. Neither latitude nor isotherms fully accounts for the location or quality of individual vineyard regions, however. The solid dots represent the wine regions studied by Jones et al. (2005).

tant to the onset of bud break, flowering, and the timing of harvest. Prescott (1965) noted that in most areas suitable for grape production the mean temperatures of the warmest and coldest months are more than 18.9°C and -1.1°C, respectively. Winter and spring temperatures are also important in that frost and low temperatures can cause injury to grapevines. Research has also shown that there is a minimum winter temperature that the grapevines can withstand. This minimum ranges from -5°C to -20°C, and is chiefly controlled by microscale climate variations which in turn reflect location and topography (Amerine *et al.*, 1980; Winkler *et al.*, 1974). Temperatures below these thresholds will damage plant tissue by the rupturing of cells, the denaturing of enzymes by dehydration, and the disruption of membrane function (Mullins *et al.*, 1992). Another important influence on winter damage is vine health prior to winter dormancy. Diseases such as moisture-induced downy mildew that ultimately cause defoliation and reduced sugar accumulation, can affect winter hardiness (Amerine *et al.*, 1980).

Heat Summation Index

In France during the mid nineteenth century, A.P. de Candolle observed that vine growth started when the mean daily temperature reached 10°C. This led to the notion of a heat summation above a base temperature that could define vine growth and grape maturation. Amerine and Winkler (1944) followed this concept and developed a heat summation index for California that is widely used as a guide for selecting appropriate grape varieties and for determining a given area’s suitability to produce quality wine grapes. In the Northern Hemisphere the heat summation index is calculated for the period of April 1 through October 31 by summing each day’s average temperature above a base of 10°C, the minimum temperature at which vine growth occurs. Using the index, five climatic regions were defined, Winkler regions I-V, from which a minimum and maximum threshold of 950 and 2900 degree-days, based on °C respectively, was calculated for the cultivation of grapes. Although it varies by grape variety and many different terroir factors, the best quality wine typically is produced from regions that experience between 1400-2000 degree-days. However, this index has been found to be less appropriate for determining viticultural viability outside of California (Gladstones, 1992; Spellman, 1999; Jones and Davis, 2000).

Bioclimatic Indices

Other bioclimatic indices have been used to characterize a region’s potential for viticulture and are mostly developed on the basis of temperature. Various forms of a heliothermal index (Branas, 1974; Huglin, 1978) and a latitude-temperature index (Jackson and Cherry 1988; Kenny and Shao, 1992) have been used to help define the suitability of a region to the planting of certain grape varietals. Smart and Dry (1980) developed a simple classification of viticultural climates that uses five dimensions of mean temperatures, continentality (defined as the difference between the average mean temperature of the warmest and coolest months), sunlight hours, aridity (based upon the difference between rainfall and evaporation), and relative humidity. Gladstones (1992) developed a classification similar to Amerine and Winkler (1944) but refined it by imposing an upper limit on mean temperatures, a correction factor for latitude, and a correction for each month’s temperature range. In a maturity classification, Jones *et al.* (2005) related climate and ripening potential for different varieties based on average growing season

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	
N. Oregon	15.2	**Intermediate**
Loire Valley	15.3	
Burgundy-Côte	15.3	
Burgundy-Beaujolais	15.8	
Chile	16.3	
E. Washington	16.5	
Bordeaux	16.5	
C. Washington	16.6	
Rioja	16.7	
S. Oregon	16.9	
C. California	17.0	**Warm**
South Africa	17.1	
N. California	17.4	
N. Rhône Valley	17.6	
N. Portugal	17.7	
Barolo	17.8	
S. Rhône Valley	18.2	
Margaret River	18.6	
Chianti	18.8	
Hunter Valley	19.8	**Hot**
Barossa Valley	19.9	
S. Portugal	20.3	
S. 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 2 and Jones et al. (2005) for details].

temperatures — cool, intermediate, warm, and hot climates — that were derived from the benchmark climates of the world's premium quality wine producing regions (Table 1; Fig. 2).

Importance of Climate: the Bordeaux Example

While no one study can ever capture the sum of all influences in the terroir debate, Van Leeuwen *et al.* (2004) may have come the closest to date. Studying numerous plots in the St. Émilion and Pomeral regions of Bordeaux, France, the authors examined the effect of vintage (climate), soil, and grape variety (Cabernet Sauvignon, Cabernet Franc, and Merlot) on wine quality parameters. The parameters included plant effects that influence quality (i.e., phenology, shoot growth cessation, vine water status, etc.) and yield components such as fruit weight, sugar and acid levels, and phenolics (e.g., anthocyanin). Their results showed that climate was the dominant factor, accounting for over 50% of the variation when averaged across all quality parameters. Soil type and structure was the next most important factor, accounting for a quarter of the resulting wine quality. Varietal differences, while not as important as climate or soil, still accounted for 10% of the variation in quality parameters. While the study controlled for many cultural practices (e.g., pruning type and timing, trellising, and harvest timing), it would appear in this case that the cultural component of terroir roughly accounts for only 15-20% of the variation in important wine quality parameters. If results from this study are applicable elsewhere, it would appear that climate plays the most significant role in wine quality.

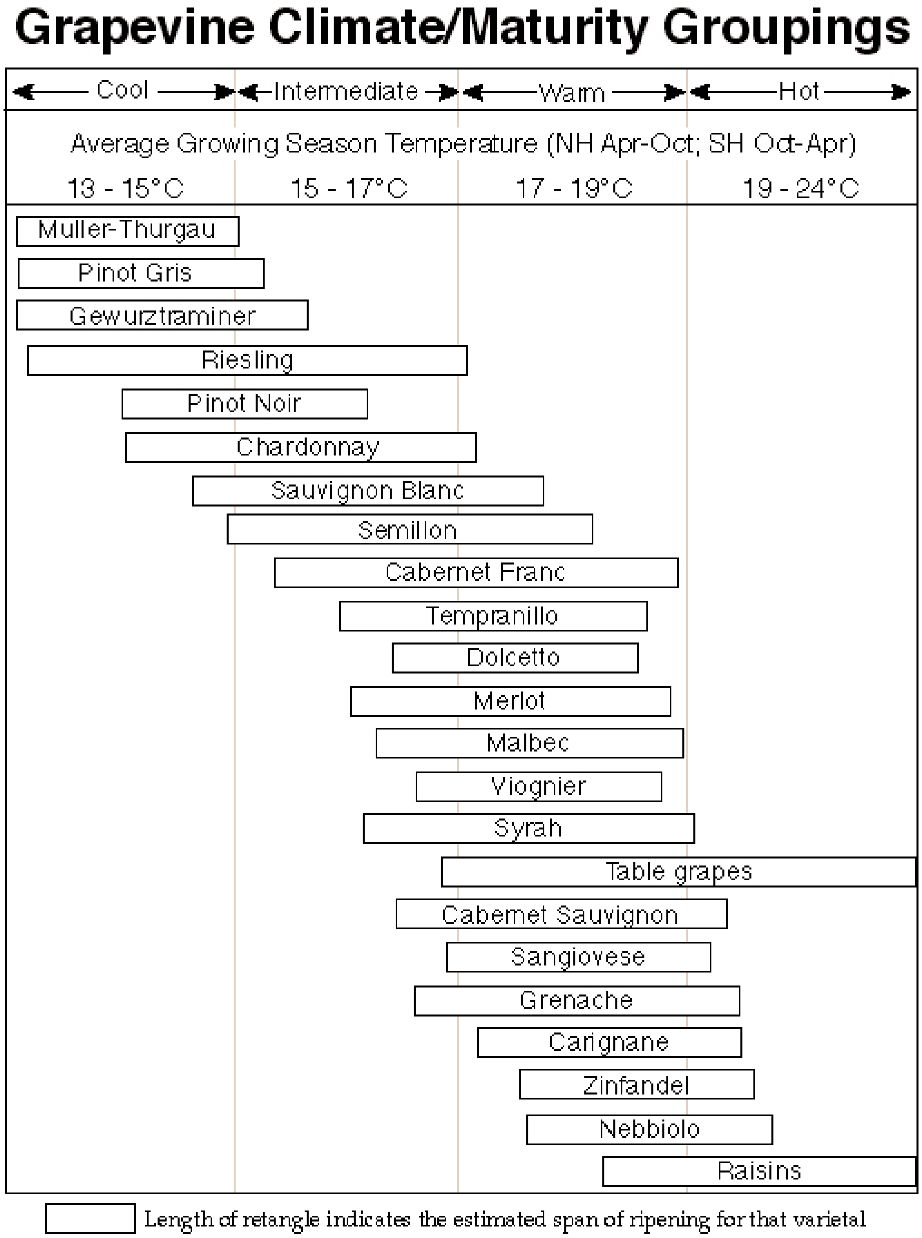

Figure 2. Climate maturity groupings based on average growing season temperatures and the estimated span of varietal ripening potential that occurs within and across the groups. While V. vinifera varieties are not typically used for table grapes and raisins, they are included for comparison of warm to hot climate wine grape production. Note that the average growing season temperatures are depicted in Table 1 and are 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).

Climate Variability, Change, and Agricultural Responses

It is clear from the observational record that global climates have changed over both short and long time scales. Global observations from the 20th century indicate that the mean surface temperature of the planet has increased by 0.6 ± 0.2°C with land areas warming more than oceans (Houghton *et al.*, 2001). In most cases observed atmospheric warming trends 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). Precipitation changes have been much more spatially variable, but show 5-10% increases over broad areas of the Northern Hemisphere while other regions have seen declines of 5-15% (IPCC, 2001). Some regions have also seen an increased frequency of heavy precipitation events, while other regions have seen moderate changes in drought frequency and severity. In addition, evidence from paleoclimatological studies has revealed large fluctuations in global and regional climate over the past million years. Furthermore, there are indications that over the last 2000-3000 years climates have shifted from cooler to warmer periods, with the most recent century potentially being the warmest in the last millennium (Mann *et al.*, 1999). Our understanding of the potential range of climate's natural variation is still somewhat limited, however.

Contemporary global climate change due to increased levels of atmospheric CO_2 has received considerable attention (Climate Research Board, 1979; CO_2/Climate Review Panel, 1982; Carbon Dioxide Assessment Committee, 1983; IPCC 2001; and others). The effects have been observed in the general climate record (e.g., Jones *et al.*, 1986) and simulated through a variety of general circulation models (GCMs; see Cess *et al.*, 1990; and Gates *et al.*, 1998 for good reviews). The observed trends in temperatures have been related to agricultural production viability through their impact on 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, 2005). On the other hand, GCM simulations – although far from perfect representations of climate reality – all indicate that climate change will continue to occur in some manner owing to anthropogenic influences. While the initial magnitude of climate change, as simulated by GCMs, has been reduced due to improved parameterization (IPCC, 2001), climate change at any magnitude or in any direction will still have an effect on agricultural productivity. The overall impacts of climate change on agriculture ultimately will depend on plant physiological requirements and the spatial variations, seasonality, and magnitude of the warming (McCarthy *et al.*, 2001; Butterfield *et al.*, 2000).

Although the forecast of temperature increases for individual regions is under debate owing to the scale problem associated with GCM projections (Giorgi and Mearns, 1991; Jones *et al.*, 1995), there is one area of no debate - the atmospheric concentration of carbon dioxide will continue to rise for at least a few decades to come (Climate Research Board, 1979; CO_2/Climate Review Panel, 1982; Carbon Dioxide Assessment Committee, 1983; IPCC 2001; and others). Under optimum growing conditions, the atmospheric concentration of CO_2 is the limiting factor in photosynthesis, and increasing CO_2 concentrations will increase the water use efficiency in plants in the absence of other climate-related changes (Rosenberg, 1981a,b). Therefore, more carbon dioxide can potentially lead to greater production. However, many observational and modeling studies on the effects of increases in CO_2 on various plant systems (Reekie and Bazzaz, 1991; Hänninen, 1995; Maytin *et al.*, 1995) indicate that increased carbon uptake is partitioned, with more entering vegetative tissues and less entering reproductive organs, which could spell a reduction in grain and fruit quality. More complete research into changes in the quality of plant tissue and fruit along with better understanding of how other impacts (e.g., concomitant changes in temperature) from CO_2-induced climate change is needed.

Agricultural productivity varies with climate variations both between and within years. The observed human activities that drive changes in atmospheric composition and climate could therefore be expected to alter, perhaps significantly, the relative levels of agricultural productivity in different regions of the globe. Agriculture systems typically are chosen and developed based on the mean climatic conditions of a region and its variability, but it has been suggested that variations in the probability and duration of extreme events are more important than changes in the mean (Waggoner, 1989; Katz and Brown, 1992). Extreme events including floods, high temperatures, frost, drought, hail, rainfall, and wind all affect agriculture in some way. If extreme events increase in frequency, plant systems would tend to fail to recover over the short term and/or adjust over the long term without some form of stress and damage occurring. In addition, as an agricultural system becomes less resilient, it is more susceptible to increased outbreaks in disease and pests. Therefore, climatic variability and its relation to climate change will play an important role in the long and short-term structure and yields of agriculture systems, including the growing of wine grapes.

Past Climate Variability, Change, and Viticulture: the European Example

Viticulture and enology combine to produce a very geographically defined and therefore climatically distinct agricultural pursuit. Experience over thousands of years has resulted in grapes being grown and wine being produced in mostly mid-latitude regions that are roughly defined by their ability to ripen fruit to produce certain wine styles (Fig. 1). Although many new world wine regions are relatively young, long-term historical records of European viticulture have been maintained for nearly a thousand years. Records of harvest dates and yield were initially maintained by monks during the Middle Ages and later by merchants and the prominent châteaux. These records indicate that the region has experienced wide fluctuations of climate and viticultural productivity in the past (e.g. Penning-Roswell, 1989). Gladstones (1992) depicted climatic variability in Europe from historical records and details that, during the medieval "Little Optimum," temperatures were about 1°C above the present day and the warmth lasted from about the eighth century to the early fourteenth century. During this time, vineyards were planted over most of southern England and along the coasts of the North and Baltic Seas. Subsequently the "Little Ice Age" brought an abrupt fall in temperatures and a prolonged cold period that lasted from the early fourteenth century through the early 1800s. While there were some large fluctuations in weather during this period, the overall climate regime was extremely rough on all aspects of agriculture in Europe with failed crops and famine for many consecutive years. Vineyards throughout the British Isles and northern Europe died out and harvests did not occur for many years in southern Europe and the Mediterranean. Temperatures during the coldest decades of the Little Ice Age were about 2°C lower than the warm periods of the Middle Ages, and at least 1°C lower than today (Le Roy Ladurie, 1971).

Pfister (1988) used the recorded dates of harvests and other vine developmental stages to study the direct effects of climate variability on viticulture in Europe from the Middle Ages to 1860. He inferred that temperatures during the growing season in the High Middle Ages must have averaged 1.7°C warmer than today, and that harvest dates began around the first of September compared to early to mid October today. These grape harvest records correlated well with other long-term records of climate change as evidenced in glacial advances and retreats, ice core analyses, palynological studies, varve chronologies, and dendrochronologies. Carrying the viticulture record even further into the twentieth century, Ray (1985) compiled the dates of the start of vintage harvest for a single château in Bordeaux (Lafite). While he noted that some of the variation is due to biotic influences (mildew, fungus, pests, diseases, etc.), the dates correspond very well with land-based climatologies of temperature (Jones *et al.*, 1986). In addition, recent research by Chuine *et al.* (2004) and colleagues used contemporary grape harvest dates from Burgundy to reconstruct spring-summer temperatures from 1370 to 2003 and, while the results indicate that temperatures as high as those reached in the warm 1990s have occurred several times in the region since 1370, the extremely warm summer of 2003 appears to have been higher than in any other year since 1370.

Climate Variability and Climate Change Impacts on Wine

Recent research on the impacts of climate on wine factors has followed two lines of analysis: 1) how short-term climate variability and trends have impacted grapevine phenology, production, and quality (e.g., Braslavska, 2000; Jones and Davis, 2000; Esteves and Orgaz, 2001), and 2) how future climate change may potentially impact the spatial viability of wine growing regions, vine and grape growth potential, and overall wine quality and styles (Kenny and Harrison, 1992; Bindi *et al.*, 1996; Jones *et al.*, 2005). Owing to the fact that many viticulture climates are dry during the growing season, most of the research conducted to date has focused on temperature-related impacts.

Climate Variability Impact: Small Scale

Climate variability impacts agriculture and, in particular, grape and wine production are typically related to site-specific extreme events such as frost, hail, and heavy rain, or to broader scale interannual cycles of warmer, colder, wetter, or drier conditions brought about by recurring modes of atmospheric circulation and/or sea surface temperatures. Analyzing a nearly 50-year record of grape and wine data for Bordeaux (1949-1997), Jones and Davis (2000) found trends towards earlier phenological events (bud break, flowering, véraison, and harvest), shorter intervals between events, and a lengthening of the growing season. This study also found that the two main varieties grown in Bordeaux, Merlot and Cabernet Sauvignon, exhibited larger berry weights and higher sugar to total acid ratios, which resulted in higher vintage ratings and less year-to-year variability in quality. Warmer temperatures during the growing season and a reduction of ripening period rainfall were found to be the most significant climate factors in Bordeaux phenology, composition, and wine quality. Wine production trends in Bordeaux were found to be more variable than phenology, composition, and quality; however, the study revealed that rainfall during the physiologically important stages of flowering and maturation tended to decrease production (Jones and Davis, 2000). Similar results were found for California’s Napa and Sonoma Valleys where, since the 1950s, grape growers have seen dramatic increases in premium wine quality (along with decreased year to year variability in quality), grape yield, and crop value (Nemani *et al.*, 2001). This research found that the climate of the region has experienced greater warming at night and during spring. As a consequence of the asymmetric warming, the diurnal temperature range — the difference between daily maximum and minimum temperatures — declined by 1.9°C over 47 years. Although the average annual warming trend was a modest 1.1°C over the 47 years, there was a 71% decline in frost frequency (20-day reduction) and a 25% increase in the length of the frost-free growing season (65-day increase). The decline in frost frequency was significantly correlated with the increase in vintage ratings. A possible explanation for such a relation could be that frosts may damage the primary buds on the vine, leaving secondary or tertiary buds that are less fruitful, along with delaying subsequent plant physiology and ultimately leading to uneven maturity and poor wine quality. Additionally, for the same time period, grape yields grew 34% and were significantly influenced by minimum temperatures in spring and decreases in summer vapor pressure deficits. If the current trends in frost frequency continue, Napa/Sonoma could become a frost-free climate in another decade or two. In a larger study covering the entire west coast of the United States, Jones (2005) documented climate variability during 1948-2002 for the principal grape growing regions in the states of California, Oregon, and Washington. This research showed that on average, most regions have experienced a decline in frost frequency, earlier last spring frosts, later first fall frosts, longer frost-free periods, and warmer growing seasons with greater heat accumulation.

Climate Variability Impact: Large Scale

Examining larger scale influences of climate variability, Rod—and Com’n (2000) detailed how the North Atlantic Oscillation (NAO; a north-south seesaw in the pressure fields of the North Atlantic) and the El Ni–o-Southern Oscillation (ENSO; a combined east-west seesaw in sea surface temperatures and pressure fields in the tropical Pacific) impacted grape production and wine quality in Spain. Acting as a climate “teleconnection”, where the impact of an atmospheric variation in one region is conveyed to other regions; El Ni–o events (warmer than average sea surface temperatures in the eastern tropical Pacific) were found to have significant impact on wine quality, providing more rain during the growing season in Spain over the last thirty years. The NAO, on the other hand, did not impact wine quality even though the condition is closer to the wine producing regions of Spain. Esteves and Orgaz (2001) found similar results for the Viseu wine region of Portugal. The authors conducted a spectral analysis between wine quality and teleconnection indices (ENSO and NAO) and determined that wine quality in Portugal follows a 3 to 7 year cycle that is similar to that of the ENSO cycle. Whereas the NAO had some impact on Portuguese wine quality, its effect was much less than that of ENSO. Jones (1997) also found that the NAO was insignificant for Bordeaux phenology, grape composition, yields, and wine quality. The authors of each of the papers noted above speculate that the best explanation for these observations is due to the fact that the NAO is a dominant winter mode of circulation variability, whereas ENSO can influence moisture levels throughout the year depending on its strength and length of activity. For the wine regions of the west coast of the United States, Jones (2005) analyzed short-term climate variability in relation to the Pacific Decadal Oscillation (PDO, a measure of the dominant variability in sea surface temperatures in the North Pacific) and ENSO, finding that the PDO was the most dominant influence on important viticulture climate parameters. However, neither the PDO nor ENSO was significantly related to vintage ratings for Napa (Jones, 2005). The geographical location of Australian and Chilean wine producing regions places each near one of the main centers of action of ENSO. For Australia, ENSO is the main contributor of rainfall variability and El Niño years often result in moderate to severe drought. A similar but opposite situation is experienced in Chile where greater than average rainfall occurs during El Niño years. Although direct studies of the impacts of ENSO on wine production and quality in Chile and Australia are incomplete, climate modeling indicates that ENSO conditions are expected to increase in frequency and severity with climate change. Finally, the authors in the studies noted above state that since many of the circulation modes can be assessed months ahead of a given growing season, there may be some potential for seasonal prediction that would allow a greater latitude of planning for the impacts noted above. Clearly, more research needs to be done in the area of climate variability modes and their impact on viticulture and wine quality for other areas of the world.

Climate Change Impacts

Lough *et al.* (1983) examined scenarios of a warmer world in Europe using the noted 20th century warming as an analog. They compared thermal, moisture, and pressure changes over the two coolest and warmest twenty year periods during the 1900s, and used the results to construct scenarios of the impacts of future climate change on agriculture and energy usage. While noting the difficulty in assessing the consequences of technological advances and the "fertilizer effect" of increasing CO_2 concentration, these authors showed that the length of the growing season should expand over all of Europe with precipitation increasing in the north and decreasing in the south. Using mean climate values and Broadbent's (1981) compilation of vintage ratings for Bordeaux and Champagne, the authors noted that the climate variables explained 58 percent and 63 percent of the vintage ratings, respectively. Their warmer world scenarios suggested that conditions would lead to improvements in wine quality, particularly in Bordeaux. From recent analyses by Jones *et al.* (2005), where vintage ratings for Bordeaux and Champagne have trended higher with less year-to-year variability, the work of Lough *et al.* (1983) appears to have been generally correct for these regions.

Tate (2001) discussed the general impact of future climate change on grape production and wine quality. Although no data were analyzed, this author described the potential consequences of climate change as affecting where grapes can be grown ("ideal" locations today ceasing to be so in the future and more poleward locations becoming viable), changing the distribution and intensity of pests and diseases, causing sea level changes that could alter coastal climates, and increasing CO_2 such that it might impact grape components or the texture of oak wood used in barrels. In another overview of potential climate change impacts, Schultz (2000) discussed how shifts in precipitation would greatly affect the dry summer regimes of most high quality wine regions. In regions where irrigation practices are controlled or completely forbidden (i.e., many parts of France) the tendency to drier summers could be detrimental to yields and flavor profiles. Schultz (2000) also detailed how changes in CO_2, temperature, and solar radiation likely would have direct impacts on yields, grape composition, and flavor development.

Addressing the climate change effects for a specific area and grape varieties, Bindi *et al.* (1996) studied the effects of increased CO_2 levels and the associated changes in climate on Cabernet Sauvignon and Sangiovese grapes in Northern Italy. Using field data from 1992-1994 and a model of grapevine growth and yield, they found that projected temperature increases resulted in a composite 23 day reduction in the interval from bud break to harvest, and that doubled concentrations of CO_2 in the atmosphere resulted in a 36% increase in yield. However, the combined effects of increases in temperature and CO_2 resulted in an increase in yield variability with the potential to create greater economic risk. Pincus (2003) provided insight into the connections between wine, place, and identity – the heart of terroir – by examining how climate change may make the "associations between wine and place difficult or impossible to maintain." Examining climate projections to 2025 and discussing the results with grape growers and wine makers in various regions, Pincus (2003) found that some form of adaptation – including changing varieties, vineyard management, and regional identities – must occur for the industry to survive. Examining projected climate change scenarios for 2030 and 2070 for Australian viticulture, McInnes *et al.* (2003) found that temperatures are predicted to warm by 1.0-6.0°C by 2070, thus increasing the number of hot days and decreasing frost risk, while precipitation changes are predicted to be more variable, potentially resulting in greater growing season stress on irrigation. These authors indicate that the challenges facing the Australian wine industry include more rapid phenological development, changes in suitable locations for some varieties, a reduction in the optimum harvest window for high quality wines, excessive vegetative growth due to increased CO_2 levels, and greater management of already scarce water resources.

In a multi-region analysis of the impacts of climate change on wine quality, Jones *et al.* (2005) analyzed growing season temperatures in 27 of arguably the best wine producing regions in the world, in terms of being highly recognized for quality (Fig. 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 (Fig. 2; Table 1). For example, Cabernet Sauvignon is grown in regions that span intermediate to hot climates with growing season averages that range from roughly 16.5-19.5°C (e.g., Bordeaux or Napa). Results from the analysis of 1950-1999 revealed that 17 of the 27 wine regions experienced statistically significant warming during their respective growing seasons. Figure 3 provides an example of the warming where both the Bordeaux and Napa regions warmed by 1.8°C and 1.2°C from 1950-1999, respectively. Also note that Napa has a warmer average growing season and that Bordeaux has greater growing season temperature variability. In the study, a large majority of the U.S. and European wine regions saw significant temperature increases whereas the majority of the Southern Hemisphere locations changes were not significant. Averaged across all wine regions with significant trends, the warming was 1.3°C. 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 4.1°C.

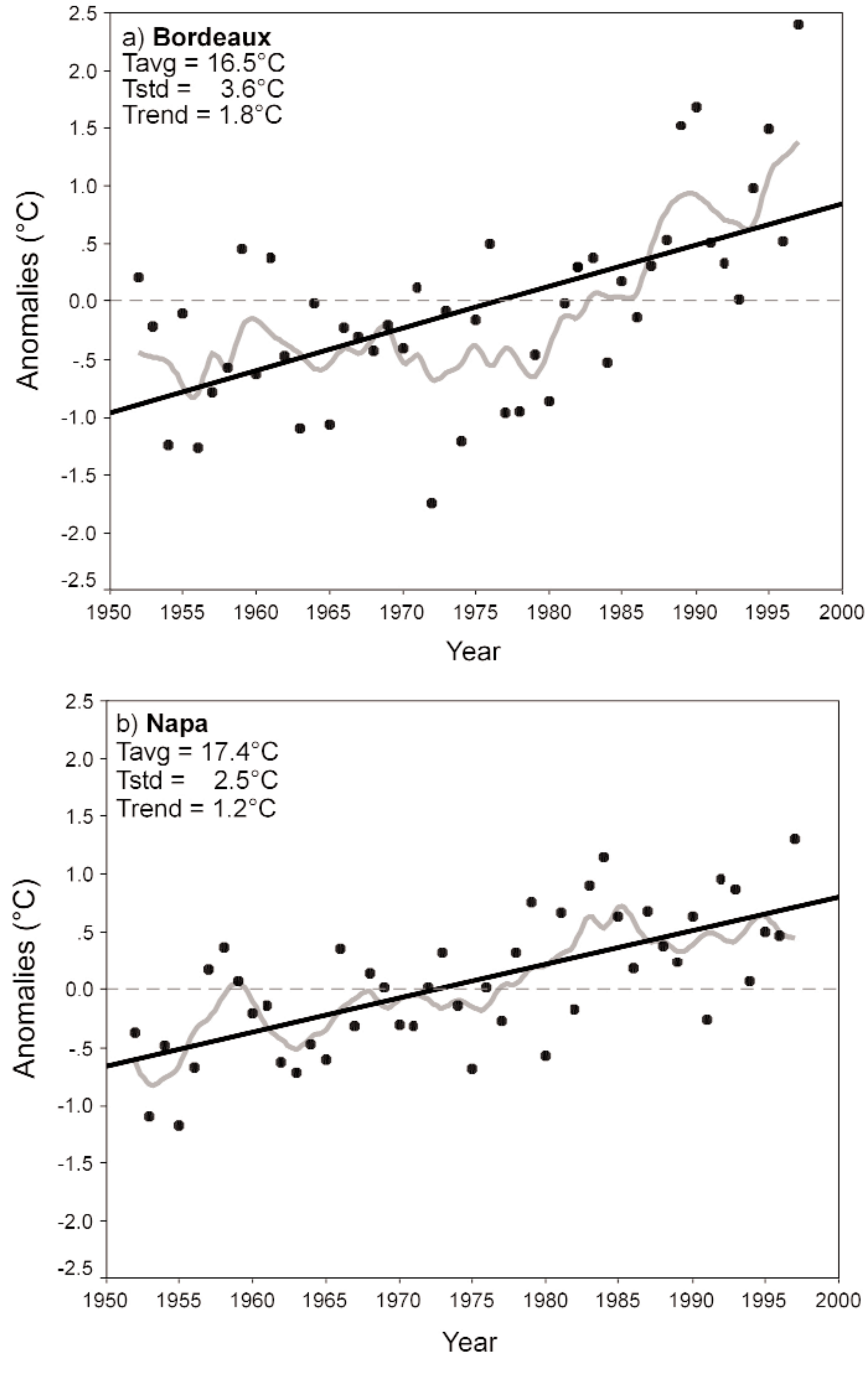

Figure 3. Observed growing season average temperature anomalies for a) Bordeaux, France, and b) Napa, California, as analyzed by Jones et al. (2005). The temperature data are monthly values extracted from a 0.5° x 0.5° grid centered over the wine producing regions for 1950-1999. Tavg is the average growing season temperature (April-October in the Northern Hemisphere and October-April 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.

Jones *et al.* (2005) also examined the relationships between average growing season temperatures and vintage ratings as given by Sotheby's and the Wine Enthusiast (Stevenson, 2002; Mazur, 2002). Ratings are commonly used to compare vintages and have a have strong influence on the economic success of a wine producing region (de Blij, 1983). Although vintage ratings are inherently subjective, the correlations between different rating systems typically are very high (*r* > 0.9; Jones, 1997) indicating their usefulness as a wine quality metric. Furthermore, in the absence of a worldwide systematic, consistent, and readily available set of compositional data, vintage ratings currently provide the best metric for global scale analyses of wine quality. Vintage ratings do have limitations, however, as they are often averaged over large regions, effectively masking inter-region variations, and not all ratings systems cover all regions, nor have all regions received the publicity necessary to be more thoroughly rated. The Sotheby's vintage ratings data analyzed by Jones *et al.* (2005) represent one of the most complete rating systems and, when combined with the Wine Enthusiast ratings for South Africa and Chile (Mazur, 220), cover 27 regions and 30 categories of wine over varying time periods during 1967-2000 (Table 2; Fig. 1). Some regions are divided into subregions or wine styles with separate ratings, whereas others are simply divided into ratings for red and white wines. 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. As an example, Figure 4 depicts the vintage ratings for 1963-2000 for red wines from the Médoc and Graves region of Bordeaux, and red wines from

California: a general trend over time to better quality, with less variability, can be seen. Also note the greater relative variability in Bordeaux vintages as compared to California, indicating the impact of greater growing season climate variability as seen in Figure 3. Examining the relationships between climate and wine quality found that the majority of the trends in vintage ratings were significantly related to average growing season temperatures. Whereas the effect varied by region, vintage ratings on average rose by 13.3 points (on a 100 point scale) for every 1°C warmer the growing season. From 10-62% of the variation in vintage ratings (32% average) was related to growing season temperature variations, with the most significant results being found in the cooler climate regions (e.g., the Mosel and Rhine Valley of Germany).

To examine future climate change, Jones *et al.* (2005) used output from the HadCM3 general circulation model (GCM; Gordon *et al.*, 2000; Pope *et al.*, 2000) from 1950-2049 for 25 grid cells encompassing the same wine regions as described above. A comparison of the two periods, 1950-1999 and 2000-2049, suggested that mean growing season temperatures would warm by an average 1.2°C over the 27 wine regions studied with the differences for Bordeaux and Napa 1.2°C and 1.7°C, respectively (Fig. 5). The projected changes are greater for the Northern Hemisphere (1.3°C) than the Southern Hemisphere (0.9°C). Examining the rate of change projected for 2000-2049 revealed significant changes in each wine region with trends ranging from 0.2°C to 0.6°C per decade. Overall changes during the 2000-2049 period averaged 2.0°C across all regions with the smallest warming in South Africa (0.9°C/50 years) and greatest warming in Portugal (2.9°C/50 years). For the Napa and Bordeaux regions, decadal trends are 0.4 and 0.5°C while the overall change is 2.2 and 2.3°C, respectively (Fig. 5). In addition, the HadCM3 model predicted significant increases in growing season temperature variability and warming during the dormant season across most regions.

While the observed warming of the last fifty years appears to have mostly benefited the quality of wine grown worldwide, the predicted regional warming rates and magnitudes detailed by Jones *et al.* (2005) for the next ~half century have numerous potential impacts on grapevine growth, grape production, and wine production in the future. The impacts 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 similar varieties. 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 (Fig. 2). For example, if a region has an average growing season temperature of 15°C and the climate warms by 1°C, that region is climatically more conducive to ripening some varieties, while potentially

Table 2: Wine regions and categories of wine analyzed by Jones et al. (2005). The wine regions correspond to the locations shown 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 Pomeral 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]	**Overall Vintage**
Chile[a]	**Overall Vintage**

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

less conducive to ripening for others. If the magnitude of the warming is 2°C or larger, a region may potentially shift into another climate maturity type (e.g., from intermediate to warm, using the climate scale of Jones *et al.* 2005 – cool, intermediate, warm, and hot – as noted above). 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, grape growing becomes challenging and may even be 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, 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 “flabbly” wines (high alcohol with little acidity for freshness). In addition, harvests that occur earlier in the summer, in a warmer part of the growing season (e.g., September instead of October in the Northern Hemisphere), will result in hot and potentially desiccated fruit without greater irrigation inputs.

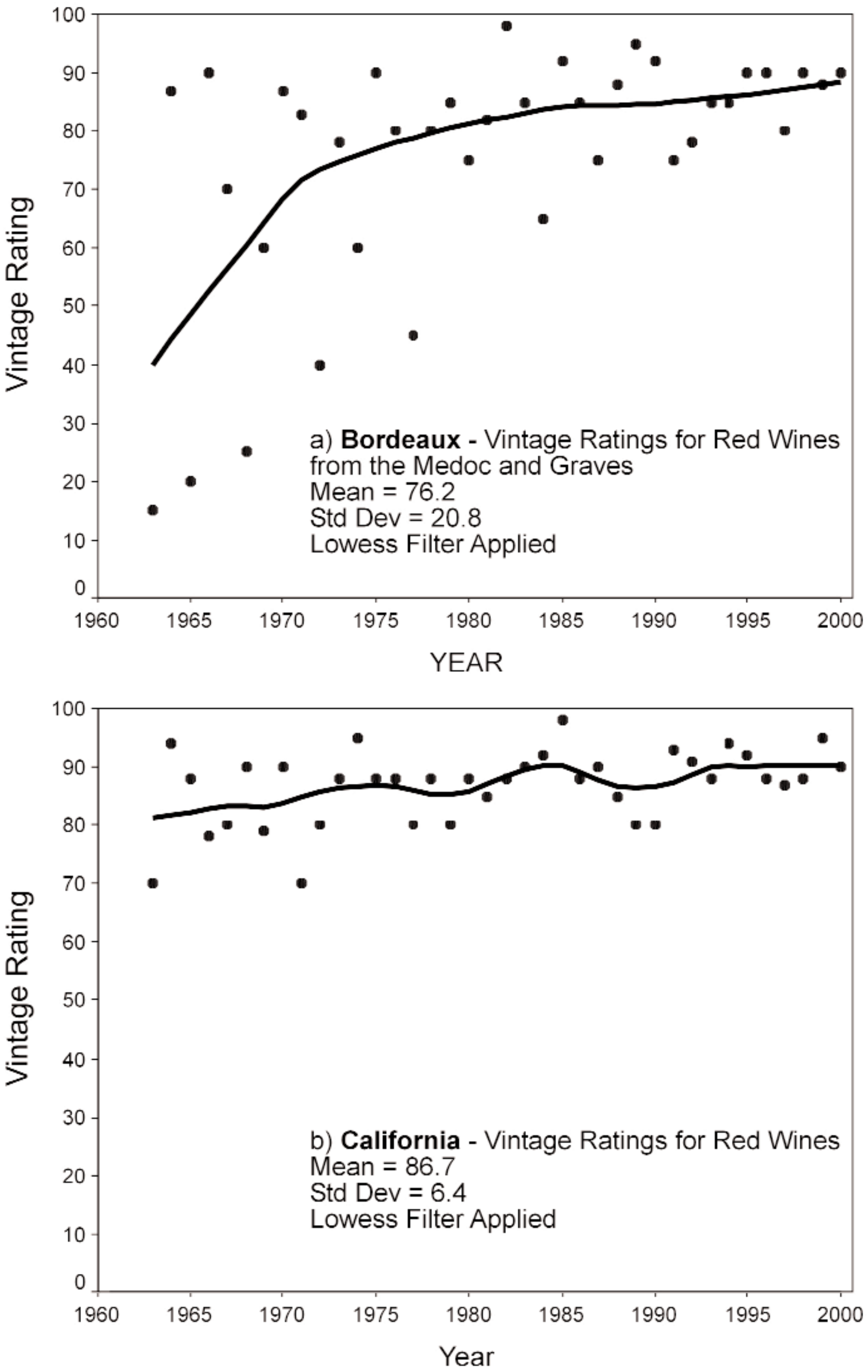

Figure 4. Vintage ratings for (a) red wines from the Médoc and Graves regions of Bordeaux and (b) red wines from California as analyzed by Jones et al. (2005). The ratings are from Sotheby's (Stevenson, 2001) and are based on a 0-100 scale. A LOWESS filter is applied to indicate the underlying pattern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

CONCLUSIONS

Cultivation of grapevines for wine production has a rich geographical and cultural history of development. This history has helped shape the notion of terroir, which describes the interrelationships among climate, soil, landscape, and the people who cultivate the grapevine for the production of wine. While there is much debate as to what is the most important aspect of terroir (e.g., Seguin, 1986; and others), environmental change has the potential to impact the balance that exists in any region. Today's viticultural regions for premium quality wine production are located in narrow climatic zones that put them at particular risk from both short term climate variability and long term climate change. This was clearly evident during the Little Ice Age when viticultural viability was threatened throughout much of Europe. The warming of the last century or more appears to have largely benefited grape growing and wine production through the expansion of viable growing regions, providing longer growing seasons, earlier phenological development, and more optimum ripening leading to better overall quality. It is clear that advances in viticultural practices such as irrigation, nutrition, trellising, and pest/disease control, and more knowledge and experience in winemaking techniques, certainly have contributed to larger yields and better quality. In spite of such advances, however, grape growers and winemakers generally believe climate plays the most significant role in determining the overall quality and style of wine from a given region, and that year-to-year variations in the quantity and quality of vintages are controlled by climate variability.

Future climate change issues for the wine industry are mostly related to changes in temperature, precipitation, and CO_2 concentrations and their interactive effects on the spatial viability of wine producing regions, plant growth timing, production, and quality. The climate change scenarios predicted for grape growing regions point to the potential for regional changes in viticultural viability owing to changes in growing season temperatures and precipitation seasonality and distribution (Pincus, 2003; McInnes *et al*., 2003; Jones *et al*., 2005). Regions with cool growing season temperatures today (e.g., the Mosel and Rhine Valleys of Germany □ more poleward locations) theoretically would have reduced year-to-year vintage quality variations and potentially could ripen warmer climate varieties (Schultz, 2000). Other regions, currently with warmer growing seasons (e.g., the Iberian Peninsula and Chianti □ more subtropical regions) may become too warm for the existing varieties grown there, while the hottest regions may lose production viability altogether. While growing season changes clearly are important, projected dormant period temperature changes would also affect viticulture by reducing winter freeze damage in some regions (e.g., eastern Washington state), while other regions (e.g., parts of California and Australia) would have very mild winters where the hardening of latent buds may not occur and pests limited by winter minimum temperatures may increase in number or severity. Although grape growing typically requires less water demand than many other crop systems, changes in seasonally dependent snowmelt or rainfall could also place added stress on vines in water-limited regions. 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 is predicted for several growing regions and varieties. However, thresholds may be reached by which grape quality could be jeopardized when varieties come to maturity too early in the season and the typical balance between sugar and acids cannot be achieved. This suggests increasing potential economic risks for grape growers and winemakers (Bindi and Fibbi, 2000). Changes in growth and quality due to increases in CO_2 are more complex owing to the interactive effects with changes in temperature and moisture availability. Observations and modeling indicate that photosynthesis and water-use efficiency (ratio of photosynthesis to water consumption) is stimulated by increased CO_2 and that grapevine production should increase without causing

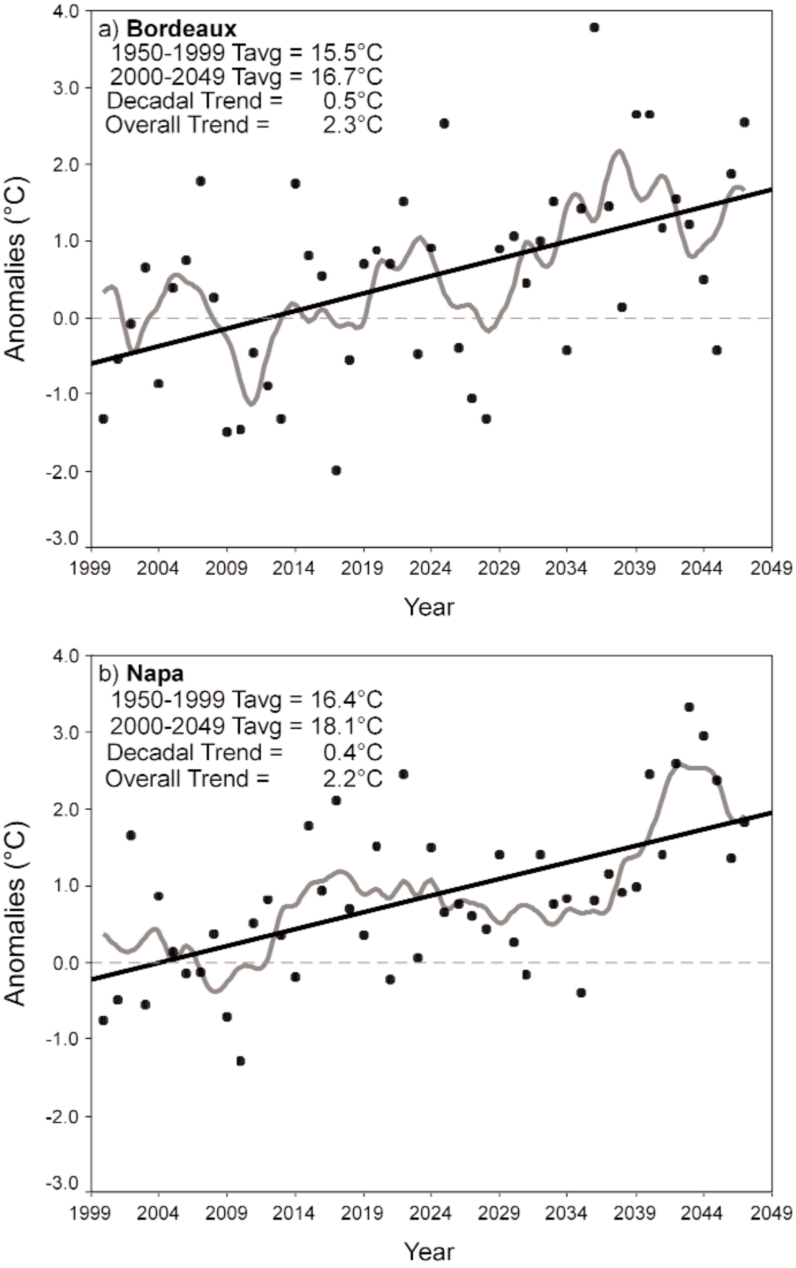

Figure 5. Modeled growing season average temperature anomalies for a) Bordeaux and b) Napa as analyzed by Jones et al. (2005). The modeled temperature data are from the HadCM3 climate model on a monthly time scale extracted from a 2.5□ x 3.75□ grid centered over the wine producing regions for 2000-2049. The anomalies are referenced to the 1950-1999 base period from the HadCM3 model. Note that the difference between the 1950-1999 growing season average temperature in Figure 3 and the 1950-1999 growing season average temperature shown here are due to the larger size of the grid square used in the HadCM3 model. Trend values are given as an average decadal change and the total change over the 50-year period.

negative influences on the quality of grapes and wine (Bindi *et al*., 2001).

In most of the wine producing regions of the world, especially those with the longest history, both physical and cultural landscapes and local economies are shaped by wine production. In these regions the wine industry drives regional development and dominates many economic sectors from production to trade to tourism. While much uncertainty still exists in the magnitude and rate of climate change, any change is likely to bring about cultural change where regional identities may shift with the varieties and wine styles that can be produced there. To prepare for the future, the industry will most certainly need to integrate planning and adaptation strategies to adjust accordingly to the predicted changes in climate.

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