Climate Change in the Western United States Grape Growing Regions

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Abstract

Climate is a pervasive factor in the viability of all forms of agriculture and is never more important than with the cultivation of grapes for the production of wine. In the Western United States grapes are grown over an extensive north-south gradient of climate types. In addition, grapevines are typically grown in regions and under conditions that are considered narrow for a specific cultivar's optimum quality, ultimately putting it at a greater potential risk from climatic variations and change. Therefore, to examine the structure, variability, and trends in climate in the Western United States, this research analyzes growing season average temperatures and degree-days, annual and seasonal frost frequencies, the dates of last spring and first fall frost occurrence, and the length of the frost-free period for the principal grape growing regions in California, Oregon, and Washington from 1948-2002. Results reveal that, on average, most regions have experienced warmer growing seasons, driven mostly by changes in minimum temperatures, with greater heat accumulation, a decline in frost frequency that is most significant in the spring, earlier last spring frosts, later first fall frosts, and longer frost-free periods. While many of these trends may have been beneficial to grape growing and wine production in these regions, an examination of possible future climate change in these same regions indicates an average growing season warming of 1.7°C in the next 50 years. Depending on the seasonal structure and magnitude of climate change in the future, important issues for the wine industry include potential shifts in regional varietal viability and achieving optimum varietal ripeness and wine balance in a warmer environment.

INTRODUCTION

Climate change has the potential to greatly impact nearly all of agriculture. History has shown that the narrow climatic zones for growing grapes for high quality wines are especially prone to variations in climate and long-term climate change (Gladstones, 1992). Today's viticultural regions for quality wine production are located in narrow climatic niches that put them at particular risk from both short-term climate variability and long-term climate change. In general, the overall wine style that a region produces is a result of the baseline climate, while climate variability determines vintage yield and quality differences. Climatic changes therefore have the potential to bring about changes in wine styles. Our understanding of climate change and the potential impacts on viticulture (the science of the cultivation of grapevines) and viniculture (the science of the making of wines) has become increasingly important as changing levels of greenhouse gases and alterations in earth surface characteristics bring about changes in the Earth's radiation budget, global temperatures, atmospheric circulation, and hydrologic cycle (Houghton et al., 2001). The observed trends in temperatures have been related to agricultural production viability by impacting winter hardening potential, frost occurrence, and growing season lengths (Menzel and Fabian, 1999; Carter et al., 1991; Easterling et al., 2000; Nemani et al., 2001; Moonen et al., 2002; Jones, 2003).

Temperatures affect grape growth and wine production in many ways. During the spring, vegetative growth of the vines is initiated by prolonged temperatures above 10°C (Winkler et al., 1974). During anthesis and throughout the growth of the berries, extremes

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of heat can be detrimental to the vines. While a few days of temperatures greater than 30°C can be beneficial to ripening potential, prolonged periods can induce heat stress in the vine, premature véraison, berry abscission, enzyme inactivation, and less flavor development in the fruit (Mullins et al., 1992). During the maturation stage, a pronounced diurnal temperature range enhances the synthesis of tannins and sugars in the grapes (Gladstones, 1992). During the dormant stage, a temperature minimum or effective chilling units (hours below a certain temperature) is needed to ensure uniform budbreak. To better define spatial variations in growing season climates and varietal potential in California, Amerine and Winkler (1944) developed a heat summation index based on temperature. The heat summation index is calculated for the period of April 1 through October 31 (Northern Hemisphere) by taking the mean monthly temperature and subtracting a base of 10°C (the minimum at which vine growth occurs) and multiplying by the number of days in the month. Using the index, five climatic regions are defined that can adequately ripen different cultivars. Jones et al. (2004a,b) has also shown 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.

Frost occurrence and timing influence most forms of agriculture, including viticulture where nearly all grape growing regions can be subject to some form of cold injury. Annual crop losses in vineyards range from 5-15% due to pests (e.g., birds), disease (e.g., mildew), and frost/freeze damage. Losses due to low temperature damage are a significant problem and can be over half of all crop losses (Winkler et al., 1974). Cold injury to grapevines may result from extreme cold during the winter and moderate to severe cold in the spring (damaging developing buds) or in the fall (injuring maturing canes and berries). Research has found that the minimum winter temperature that grapevines can withstand ranges from -5 to -20°C and is chiefly controlled by micro-variations in location and topography (Winkler et al., 1974). Injury and/or death as a direct or indirect result from the formation of ice within tissues and the resulting stresses to the vine can dramatically effect yield and/or quality. Factors that affect a grapevine's ability to resist ice formation are complex and vary throughout the vine's annual cycle. The genetic properties of each cultivar, overall environmental conditions, and cultural practices (e.g., pruning timing) have all been shown to impact a vine's ability to resist freezing injury (Mullins et al., 1992). Frost timing in the spring and fall is often used to define the length of the growing season (frost free period) and has been found to average approximately 160-200 days in most viticulture regions. From a plant standpoint, the length of the frost-free season is important to the onset of budbreak, anthesis, and the time of harvest.

Analysis of the impacts climate change on viticulture in Europe has suggested that growing seasons should lengthen and that wine quality in Champagne and Bordeaux should increase (Lough et al., 1983). Spatial modeling research has also indicated potential shifts and/or expansions in the geography of viticulture regions with parts of southern Europe predicted to become too hot to produce high quality wines and northern regions becoming viable once again (Butterfield et al., 2000; Kenny and Harrison, 1992). Examining specific cultivars ('Sangiovese' and 'Cabernet Sauvignon'), Bindi et al. (1996) find that climate change in Italy will lead to shorter growth intervals but increased yield variability. A focused study for Napa and Sonoma California, found that higher yields and quality over the last 50 years were influenced by asymmetric warming (at night and in the spring) where a reduction in frost occurrence, advanced initiation of growth in the spring, and longer growing seasons were the most influential (Nemani et al., 2001). Given the importance of climate to viticultural viability and its potential to impact wine styles and quality, Jones et al. (2004a) examined climates in 27 of the world's highest quality wine regions. The research found that as growing seasons warmed during the 1950-1999 period, wine quality, as measured by vintage ratings, increased and the vintage-to-vintage variability in ratings declined. Jones et al. (2005) also found that some regions may be at their varietal optimum in terms of growing season climates and will likely suffer unbalanced wines and decreased viability with further warming. Other studies of the impacts of climate change on grape growing and wine production reveal the importance of changes in the geographical distribution of viable grape growing areas due to changes in temperature and precipitation, greater pest and disease pressure due to milder winters, changes in sea level potentially altering the coastal zone influences on viticultural climates and the effect that increases in CO_2 might have on grape quality and the texture of oak wood which is used for making wine barrels (Tate, 2001; Renner, 1989; Schultz, 2000; McInnes et al., 2003).

Globally, few studies have documented the structure, variability, and trends in growing season temperatures, growing degree-days, frost occurrence, timing, and growing season length (see DeGaetano and Allen, 2002 for a good review). Of the studies done to date, even fewer analyses have documented the observed trends for grape growing regions (Jones and Davis, 2000). Those that have, in general, reveal that there are fewer frost days, earlier last spring frosts, later first fall frosts, and warmer and longer growing seasons (Jones, 1997; Moonan et al., 2002). While average growing season temperatures, growing degree-days, and frost occurrences and probabilities exist for many climate stations in California, Oregon, and Washington (CIMIS, 2004, OCS, 2004 and WRCC, 2004), no long-term analyses have been conducted for the Western United States grape growing regions. Therefore, given the importance of both frost factors and growing season temperatures and heat accumulation to viticulture viability and year to year production and quality issues, the purpose of this research is to produce a long-term climatology of annual and seasonal frost frequencies, the dates of last spring and first fall frost occurrence, the length of the frost-free period, and growing season average temperatures and degree-days for the principal grape growing regions in California, Oregon, and Washington. In addition, future projections of growing season average temperatures in these same regions are analyzed to examine potential changes in regional climatic viability for grape growing and wine production.

DATA AND METHODS

To examine the nature and trends in growing season climate parameters in California, Oregon, and Washington grape growing regions, the U.S. Historical Climatology Network (USHCN) climate database was used. The database represents a single, consistent, long-term set of over 1000 cooperative observing stations in the U.S. (Easterling et al., 1999). The data have undergone rigorous testing to ensure that bias from urbanization, station moves, and instrument changes have been minimized or corrected. Data for California, Oregon, and Washington grape growing regions were extracted resulting in 46 stations being selected (24 stations in California, 13 stations in Oregon, and 9 stations in Washington – Table 1 and Fig. 1). The stations selected are meant to represent either specific American Viticultural Areas (AVAs) such as in Oregon and Washington, or broad grape growing regions as in California (Fig. 1). The aggregation resulted in eleven areas studied and the averaging of the data depicts the climate structure, variability, and trends associated with the average climate of each area. While some missing data is evident in the USHCN, restricting the time period to 1948-2002 resulted in the chosen stations having less than five percent of their individual records missing. If missing data was encountered, only those months with less than five missing observations were used in the analysis. If less than five missing observations were encountered, the missing data points were replaced by an average of the two days both before and after the missing observations or by the region-wide average for that region when multiple days in a row where missing.

To analyze the climate structure in these regions, daily maximum and minimum temperatures from the USHCN were used to derive eleven climatically important parameters for grape growing. Five of the parameters represent temperature or heat accumulation characteristics and include: 1) growing season (April – October) average temperature, 2) growing season average maximum temperature, 3) growing season average minimum temperature, 4) ripening period (August 15–October 15) average temperature, and 5) growing degree-days using a base of 10°C with no upper cut-off. The other six parameters represent frost-related characteristics and, while the definition of what constitutes the critical minimum temperature that results in frost damage for individual crops varies, this research examines only those occurrences below 0°C and includes: 6) the number of days on an annual basis, 7) the number of days during the spring (March, April, and May), 8) the number of days during the fall (September, October, and November), 9) the last date of spring frost, 10) the first date of fall frost, and 11) the length of the frost-free period (defined as the difference between a given year's last frost in the spring and first frost in the fall).

The eleven parameters were analyzed for each of the 46 stations individually and then averaged by region (Table 1) and were subtracted from the long-term region average to create a time series of anomalies. Overall descriptive statistics were calculated for each parameter and region. In addition, each region-wide time series was then checked for first-order autocorrelation using the Durbin-Watson statistic. Finding no autocorrelation problems, the time series were then analyzed for trends using linear regression and five year moving averages.

To examine the potential future temperature changes in the regions, a 100-year run (1950-2049) of the HadCM3 coupled atmosphere-ocean general circulation model (AOGCM) developed at the Hadley Centre was used (Gordon et al., 2000; Pope et al., 2000). The model output has been used by many others in general 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), and specifically to examine future changes in grape growing regions worldwide (Jones et al., 2004a; Jones et al., 2004b). The AOGCM has a stable control climatology, does not use a flux adjustment, has 19 vertical levels, and has a 2.5° x 3.75° horizontal resolution (comparable to a spectral resolution of T42). Grids were extracted that best represent the wine regions in California, Oregon, and Washington, averaged over the growing season, and analyzed for potential changes in temperature over the time period.

RESULTS

Average growing season temperatures range from 14.3 to 22.2°C and follow a north-south transect from the coolest in the Puget Sound to the warmest in the Central Valley (Table 2). Average maximum growing season temperatures follow a similar pattern with values ranging from 20.1 to 31.1°C (Table 3). Small differences are seen in the spatial patterns in average growing season minimum temperatures with the Rogue Valley having the coolest average minimum at 7.2°C and are attributable to the higher elevations in the region (Table 4). Overall, positive trends in these three parameters are seen across each region with significant trends in 9 of 11 regions for average temperatures, 5 of 11 regions for maximum temperatures, and 10 of 11 regions for minimum temperatures (Fig. 2a and 2b). Average growing season temperatures warmed from 0.60 - 1.43°C across the regions with an overall average warming of 0.89°C. Maximum temperature changes were much less significant with an overall warming averaged across all regions of 0.99°C. Minimum temperatures changed more significantly than maximums with trends that range from 0.79 to 1.91°C with an average of 1.33°C. The ripening period average temperatures have similar north-south spatial variations and generally warmed over the time period, with seven of the regions experiencing significant trends that ranging from 0.82 to 1.40°C (Table 5 and Fig. 2c and 2d). Growing degree-days range from a low of 972 in the Puget Sound region to a high of 2618 in the Central Valley (Table 6). Variability in heat units averages roughly 125 from year-to-year with the lowest variations in the Puget Sound and North Coast regions. The greatest year-to-year variation is found in the Foothills region (Table 6). Over the time period each of the regions have experienced statistically significant changes with an average increase of 180 heat units (see Fig. 2e and 2f for examples).

Examining annual, spring, and fall frost frequencies finds that most regions have seen a decline in the overall number of days below 0°C (Tables 7, 8, and 9). The annual frequency of frost occurrence is greatest in the Columbia Valley regions of Oregon and Washington with over 100 days per year on average (Table 7). The lowest occurrence is in coastal and valley regions of California where typically only 24-27 days per year drop below 0°C. Trends in annual frost occurrence have declined across all regions with significant trends in 10 of the 11 regions (Table 7 and Fig. 3a). Averaged across all regions the trends reflect a reduction of 18 days a year with temperatures falling below 0°C. Spring frost frequency shows similar south-north ranking and has shown an overall reduction across the ten significant trends of 7 days per spring (Table 8 and Fig. 3b). Note that some regions have had trends such that spring frosts are a rare occurrence today. Fall frost frequency also follows the same spatial pattern with some regions experiencing very few frosts (Table 9 and Fig. 3c). However, the trends in fall frost frequencies are much less significant across all regions and average only 3 days.

The timing of frost events in the spring and fall are typically very important factors in damage to either the young shoots or ripening fruit. Last spring frosts occur from as early as the last week in February in the Central Valley to as late as May 11 in the Columbia Valley, Oregon (Table 10 and Fig. 3d). Standard deviations in spring frost dates indicate that most regions experience a window of frost potential of 10 to 22 days of their respective mean dates. The latest dates for spring frosts during the time period were in the last two weeks of May and the earliest in the middle of January. All regions showed trends toward earlier last spring frosts (10 of 11 were statistically significant), with an average change of 24 days and a maximum change of 52 days experienced in the North Coast (Table 10). The first frosts each fall come as early as the first and second week in October in the Columbia Valley regions and the Rogue Valley (Table 11 and Fig. 3e). The latest first fall frosts occur from the third to fourth weeks in November in the California regions. The variability in the first fall date is similar to that observed for spring and, interestingly, the regions that experience early last spring frosts and late first fall frosts typically have greater variability in the timing of the events. The earliest fall frosts during the time period came in the second week of September for the Columbia, Rogue, and Umpqua Valleys. Trends in fall frost timing are less significant and of lower magnitude than spring with changes that average 10 days later (Table 11). For the time period, the frost-free season ranged from 147 to 273 days for the Columbia Valley, Oregon and the Central Valley, respectively (Table 12 and Fig. 3f). Frost-free periods typically vary from 14-30 days across the west and have been as short as 123 days (Columbia and Umpqua Valleys, Oregon) to as long as 319 days (North Coast). All regions exhibited trends to longer frost-free periods, with 9 of the 11 regions having significant trends ranging from 17 to 68 days and averaging 38 days (Table 12).

Examining the model scenario from the HadCM3 output for 1950-2049 shows that each of the six regions (based on model grid cells) are predicted to have significantly warmer growing seasons over the time period with warming trends averaging 2.5 - 3.7°C (Figure 4a-f). The model depicts a slight reduction in inter-annual variability and warming during the second half of the time period (2000-2049) that is generally higher than the 1950-1999 mean. While not directly comparable to the observations described above due to grid cell size in the HadCM3 model, the trends in the overlap period between the two analyses are of the same direction (positive) and of similar magnitude (Table 2). Comparing the two 50-year periods in the model, 1950-1999 and 2000-2049, reveals an average growing season temperature warming ranging from 0.9°C in Washington to 3.0°C in the South Coast area of California (1.7°C on average; not shown).

DISCUSSION

This research has provided an up to date look at climate parameters important for grape and wine production in the main growing regions of California, Oregon, and Washington (Table 1 and Fig. 1). Using the minimally bias USHCN climate data, the structure, variability, and trends of climate parameters important for grape growing and wine production were analyzed for 1948-2002. Overall, a consistent north-south ranking of viticultural regions is prevalent with warmer and longer growing seasons and less frost risk observed in California and cooler and shorter growing seasons and greater frost risk in Oregon and Washington. Proximity to the coast and elevation influences are also evident with those locations (i.e., North Coast, Central Coast, Puget Sound, Umpqua Valley, and Willamette Valley) experiencing lower heat accumulation and less frost risk than locations more inland and higher in elevation (i.e., Columbia Valleys of Oregon and Washington, Rogue Valley, Foothills, North Valley, and Central Valley).

Overall, the analysis shows that growing seasons have warmed over the time period with the largest contribution coming from increases in the minimum temperatures. Ripening period warming has occurred across many regions and has potentially already impacted ripening profiles of sugar, acid, and flavors (Gladstones, 1992). Declining trends in annual (averaging 18 days over all regions) and spring (averaging 7 days over all regions) frost occurrence are found in the majority of the regions. The frost-free period has increased by an average of 38 days over the time period, the last spring frost date has occurred as much as 52 days earlier (averages 24 days), and the first fall frost date is typically later (17 days on average). However, most of the change in frost occurrence and timing has come in the spring. The results are consistent with other national and international studies where frost occurrence has been declining and growing seasons have been getting warmer and longer (Cooter and LeDuc, 1995; DeGaetano, 1996; Menzel and Fabian, 1999; Schwartz and Reiter, 2000; Cayan et al., 2001; Easterling, 2002). In addition, other studies examining maximum temperatures for the Western U.S. reveals few regions with increasing trends (DeGaetano and Allen, 2002), indicating that climate change may be asymmetric with respect to days and seasons (Karl et al., 1993; Nemani et al., 2001).

It would appear from this analysis that the regional grape growing climates of the Western United States have generally become more conducive to ripening fruit and producing better wine, while experiencing less frost risk. However, while some regions are more viable to a wider range of cultivars, other locations may have become too warm for existing cultivars resulting in unbalanced fruit and greater challenges in the wine making process. In addition, a reduction in frost occurrence and longer growing seasons may impact hardening potential and change pest and/or disease severity or timing. While the exact seasonal characteristics and magnitudes of future climate change is still unknown, the model examined in this study predicts that growing seasons in the Western United States will warm by an average 1.7°C in the next 50 years (2000-2049). This amount of additional warming has numerous potential impacts including changes in grapevine phenological timing, disruption of balanced composition in grapes and wine, alterations in cultivars grown, alterations in regional wine styles, and spatial changes in viable grape growing regions (Jones et al., 2004a; Jones et al., 2005).

In addition to the general trends found in the analysis there is some indication (five-year moving averages) that swings in growing season temperatures, heat accumulation, frost occurrence, frost dates, and the length of the frost-free period occur on varying cycles over the time period (Figs. 2 and 3). This could be indicative of underlying geophysical mechanisms that influence the weather and climate of the western United States such as El Nino-Southern Oscillation and the Pacific Decadal Oscillation (Mantua et al., 1996; Taylor, 1998), which need to be examined to provide the framework by which some measure of predictability may be achieved.

Finally, this analysis is an observational study of the structure, variability, and trends in climate parameters important for grape growing and wine production. However, to provide more applied cause and effect analysis and information to the industry, long-term objective data on grapevine phenology, grape composition characteristics, yields, and quality is needed.

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Literature Cited

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

Bindi, M., Fibbi, L., Gozzini, B., Orlandini, S. and Miglietta, F. 1996. Modelling the impact of future climate scenarios on yield and variability of grapevine. Climate Res. 7:213-224.

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. p. 411. 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. Intl. J. Climatol. 11:251-269.

Cayan, D.R., Kammerdiener, S., Detinger, M., Caprio, J. and Peterson, D. 2001. Changes in the onset of spring in the western United States. Bull. Am. Meteorol. Soc. 82:399-415.

California Irrigation Management Information System (CIMIS). 2004. Office of Water Use Efficiency (OWUE), California Department of Water Resources (DWR) - http://wwwcimis.water.ca.gov/cimis

Cooter, E. and LeDuc, S. 1995. Recent frost date trends in the northeastern United States. Intl. J. Climatol. 15:65-75.

DeGeatano, A. 1996. Recent trends in maximum and minimum temperature threshold exceedences in the northeastern United States. J. Climate 9:1646-1657.

DeGeatano, A. and Allen, R.J. 2002. Trends in Twentieth-Century temperature extremes across the United States. J. Climate 15:3188-3205.

Easterling, D.R., Karl, T.R., Lawrimore, J. and DelGreco, S. 1999. United States Historical Climatology Network daily temperature, precipitation, and snow data for 1871-1997. Carbon Dioxide Information and Analysis Center, Publ. 4887, NDP-070, Oak Ridge National Laboratory, Oak Ridge, TN, 83 pp. plus appendixes.

Easterling, D.R., Evans, J.L., Groisman, P. Ya., Karl, T.R., Kunkel, K.E. and Ambenje, P. 2000. Observed variability and trends in extreme climate events: A brief review. Bull. Amer. Meteorol. Soc. 81:417-425.

Easterling, D.R. 2002. Recent changes in frost days and the frost-free season in the United States. Bull. Amer. Meteorol. Soc. 83:1327-1332.

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, Australia. 310 p.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B. and Wood, R.A. 2002. The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim. Dy. 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, 944 p.

Jones, G.V. 1997. A Synoptic Climatological Assessment of Viticultural Phenology, Dissertation, University of Virginia, Department of Environmental Sciences, 394 pp.

Jones, G.V. and Davis, R.E. 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Amer. J. Vitic. Enol. 51:249-261.

Jones, G.V. 2003. Trends in frost occurrence and the frost-free growing season length in Oregon grape-growing regions. Proceedings of the 117th Annual Meeting of the Oregon Horticultural Society. Portland, Oregon, January 2003.

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 XI Œonometrics Conference, Vineyard Data Quantification Society, Dijon, France. May 21-22, 2004.

Jones, G.V., Nelson, P. and Snead, N. 2004. Modeling viticultural landscapes: A GIS analysis of the terroir potential in the Umpqua Valley of Oregon. In: Geology and Wine 8. GeoScience Canada, 31:167-178.

Jones, G.V., White, M.A. and Cooper, O.R. 2005. Climate change and global wine quality. Climatic Change (In Press).

Karl, T.R., Jones, P.D., Knight, R.W., Kukla, G., Plummer, N., Razuvayev, V., Gallo, K.P., Lindseay, J., Charlson, R.J. and Peterson, T.C. 1993. A new perspective on global warming: asymmetric trends of daily maximum and minimum temperature. Bull. Amer. Meteorol. Soc. 74:1007-1023.

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.

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.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M. and Francis, R.C. 1996. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteorol. Soc. 78:1069-1079.

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

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

Moonen, A.C., Ercoli, L., Mariotti, M. and Masoni, A. 2002. Climate change in Italy indicated by agrometeorological indices over 122 years. Agric. For. Meteorol. 111:13-27.

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

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.

Oregon Climate Service (OCS). 2004. Office of the State Climatologist, Oregon State University, Corvallis, OR. http://www.ocs.orst.edu/

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.

Pope, V.D., Gallani, M.L., Rowntree, P.R. and Stratton, R.A. 2000. The impact of new physical parametrizations in the Hadley Centre climate model -- HadAM3. Clim. Dyn. 16:123-147.

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

Schwartz, M.D. and Reiter, B.E. 2000. Changes in North American Spring. Intl. J. Climatol. 20:929-932.

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

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

Taylor, G.H. 1998. Impacts of the El Niño/Southern Oscillation on the Pacific Northwest. Oregon Climate Service Online Report, March 1998. http://www.ocs.orst.edu/reports/enso_pnw.html

Western Regional Climate Center (WRCC). 2003. National Oceanic and Atmospheric

Administration (NOAA), Reno, NV - http://www.wrcc.sage.dri.edu/

Winkler, A.J., Cook, J.A., Kliewer, W.M. and Lider, L.A. 1974. General Viticulture, (4th ed.), University of California Press, Berkeley. 740 pp.

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.

Tables

Table 1. Climate station locations used to develop the climatology for the eleven grape growing regions in California, Oregon, and Washington (see the text for details and Figure 1 for their spatial locations).

City	State	WBAN Station#	Lat	Lon	Region
LIVERMORE	CA	044997	37.67	-121.77	CENTRAL COAST
OJAI	CA	046399	34.46	-119.24	CENTRAL COAST
PASO ROBLES	CA	046730	35.64	-120.69	CENTRAL COAST
SAN LUIS OBISPO POLY	CA	047851	35.30	-120.67	CENTRAL COAST
SANTA BARBARA	CA	047902	34.42	-119.69	CENTRAL COAST
SANTA CRUZ	CA	047916	36.99	-122.02	CENTRAL COAST
CHICO UNIV FARM	CA	041715	39.71	-121.82	NORTH VALLEY
DAVIS EXP FARM 2WSW	CA	042294	38.54	-121.77	NORTH VALLEY
LODI	CA	045032	38.12	-121.29	NORTH VALLEY
MARYSVILLE	CA	045385	39.16	-121.60	NORTH VALLEY
VACAVILLE	CA	049200	38.41	-121.95	NORTH VALLEY
FRESNO WSO AP	CA	043257	36.79	-119.72	CENTRAL VALLEY
HANFORD 1S	CA	043747	36.30	-119.66	CENTRAL VALLEY
LEMON COVE	CA	044890	36.39	-119.04	CENTRAL VALLEY
MERCED MUNICIPAL AP	CA	045532	37.29	-120.52	CENTRAL VALLEY
TEJON RANCHO	CA	048839	35.04	-118.75	CENTRAL VALLEY
WASCO	CA	049452	35.61	-119.34	CENTRAL VALLEY
COLFAX	CA	041912	39.11	-120.95	FOOTHILLS
ELECTRA PH	CA	042728	38.34	-120.67	FOOTHILLS
HEALDSBURG	CA	043875	38.62	-122.87	NORTH COAST
NAPA STATE HOSPITAL	CA	046074	38.29	-122.27	NORTH COAST
PETALUMA FIRE STN #2	CA	046826	38.27	-122.66	NORTH COAST
SANTA ROSA	CA	047965	38.46	-122.70	NORTH COAST
UKIAH	CA	049122	39.16	-123.20	NORTH COAST
HEPPNER	OR	353827	45.37	-119.55	COLUMBIA VALLEY
HERMISTON 1SE	OR	353847	45.82	-119.27	COLUMBIA VALLEY
HOOD RIVER EXPERIMENT STN	OR	354003	45.69	-121.52	COLUMBIA VALLEY
MILTON-FREEWATER	OR	355593	45.96	-118.42	COLUMBIA VALLEY
ASHLAND	OR	350304	42.22	-122.72	ROGUE VALLEY
GRANTS PASS	OR	353445	42.44	-123.35	ROGUE VALLEY
DRAIN	OR	352406	43.67	-123.32	UMPQUA VALLEY
RIDDLE	OR	357169	42.96	-123.35	UMPQUA VALLEY
CORVALLIS – OSU	OR	351862	44.64	-123.20	WILLAMETTE VALLEY
COTTAGE GROVE 1S	OR	351897	43.79	-123.07	WILLAMETTE VALLEY
FOREST GROVE	OR	352997	45.54	-123.10	WILLAMETTE VALLEY
HEADWORKS PORTLAND WTRB	OR	353770	45.46	-122.16	WILLAMETTE VALLEY
MCMINNVILLE	OR	355384	45.22	-123.17	WILLAMETTE VALLEY
DAYTON 1WSW	WA	452030	46.32	-118.00	COLUMBIA VALLEY
KENNEWICK	WA	454154	46.22	-119.10	COLUMBIA VALLEY
POMEROY	WA	456610	46.49	-117.59	COLUMBIA VALLEY
SUNNYSIDE	WA	458207	46.32	-120.00	COLUMBIA VALLEY
CENTRALIA	WA	451276	46.72	-122.95	PUGET SOUND
GRAPEVIEW 3SW	WA	453284	47.30	-122.87	PUGET SOUND
PORT TOWNSEND	WA	456678	48.12	-122.75	PUGET SOUND
PUYALLUP EXPERIMENT STN 2W	WA	456803	47.21	-122.34	PUGET SOUND
SEDRO WOOLLEY	WA	457507	48.51	-122.24	PUGET SOUND

Table 2. Descriptive statistics and trend parameters for the average temperature (in °C) over the growing season (April through October) for the eleven grape growing regions in California, Oregon, and Washington (see Table 1 and Fig. 1 for climate stations). Decadal trend represents the change per decade while the overall trend represents the total change over the 1948-2002 time period.

Region	Descriptive Statistics (°C)				Trend Parameters (°C)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Puget Sound	14.3	0.6	15.8	12.9	0.14	***	0.13	0.72
Willamette Valley	15.0	0.6	16.9	13.5	0.27	***	0.21	1.12
Umpqua Valley	15.8	0.6	17.4	14.5	+			
Rogue Valley	16.2	0.6	17.5	14.9	+			
Columbia Val., WA	16.7	0.7	17.9	15.2	0.12	***	0.14	0.76
Columbia Val., OR	16.7	0.7	18.2	15.3	0.07	**	0.11	0.60
Central Coast	18.0	0.6	19.4	16.9	0.15	***	0.14	0.73
North Coast	18.2	0.5	19.2	17.0	0.22	***	0.15	0.79
Foothills	19.8	0.9	21.3	16.7	0.24	***	0.27	1.43
North Valley	20.6	0.6	22.0	18.9	0.22	***	0.19	1.02
Central Valley	22.2	0.6	23.6	20.9	0.20	***	0.16	0.86

[a] *P*-value represents the trend's statistical significance.

***, **, * the model is significant at the 0.01, 0.05, 0.1 levels, respectively

+/- indicates the trend direction if not significant

Table 3. Descriptive statistics and trend parameters for the average maximum temperature (in °C) over the growing season. Other information is as given in Table 2.

Region	Descriptive Statistics (°C)				Trend Parameters (°C)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Puget Sound	20.1	0.7	22.4	18.6	+			
Willamette Valley	22.4	0.9	24.7	20.5	0.09	**	0.16	0.87
Umpqua Valley	23.8	0.9	25.7	22.1	+			
Columbia Val., OR	24.4	0.8	26.3	22.7	+			
Columbia Val., WA	24.7	0.8	26.6	22.9	+			
Rogue Valley	25.3	0.9	27.6	23.1	0.08	**	0.17	0.91
Central Coast	26.0	0.7	27.5	24.7	+			
North Coast	26.7	0.7	28.0	25.3	+			
Foothills	28.6	1.3	30.7	23.6	0.16	***	0.32	1.74
North Valley	29.6	0.8	31.2	27.6	0.07	*	0.13	0.68
Central Valley	31.1	0.7	32.7	29.4	0.09	**	0.13	0.73

Table 4. Descriptive statistics and trend parameters for the average minimum temperature (in °C) over the growing season. Other information is as given in Table 2.

Region	Descriptive Statistics (°C)				Trend Parameters (°C)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Rogue Valley	7.2	0.7	8.6	5.7	+			
Willamette Valley	7.7	0.6	9.2	6.4	0.43	***	0.25	1.36
Umpqua Valley	7.9	0.6	9.3	6.2	0.16	***	0.15	0.79
Puget Sound	8.4	0.7	10.1	7.1	0.48	***	0.30	1.64
Columbia Val., WA	8.6	0.6	10.0	6.9	0.27	***	0.20	1.10
Columbia Val., OR	9.0	0.7	10.6	7.4	0.28	***	0.22	1.21
North Coast	9.7	0.7	11.2	8.0	0.62	***	0.35	1.91
Central Coast	10.1	0.7	11.8	8.8	0.51	***	0.33	1.79
Foothills	11.0	0.7	12.6	9.4	0.24	***	0.21	1.13
North Valley	11.5	0.6	13.0	10.1	0.39	***	0.25	1.37
Central Valley	13.4	0.6	14.6	12.1	0.28	***	0.19	1.04

Table 5. Descriptive statistics and trend parameters for the average temperature (in °C) during the ripening period of August 15th through October 15. Other information is as given in Table 2.

Region	Descriptive Statistics (°C)				Trend Parameters (°C)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Puget Sound	15.1	0.7	16.9	13.7	0.11	**	0.15	0.82
Willamette Valley	16.2	0.9	18.4	14.7	0.16	***	0.22	1.19
Umpqua Valley	16.9	0.8	18.7	15.4	+			
Columbia Val., WA	17.1	1.0	20.0	15.2	0.07	**	0.17	0.92
Columbia Val., OR	17.2	1.1	20.1	14.8	0.06	*	0.17	0.91
Rogue Valley	17.2	0.9	19.6	15.3	+			
Central Coast	19.5	0.7	21.6	18.1	+			
North Coast	19.6	0.7	21.3	18.2	+			
Foothills	21.1	1.2	24.0	18.6	0.12	***	0.25	1.40
North Valley	21.6	0.9	23.8	20.0	0.09	**	0.17	0.91
Central Valley	23.1	0.9	25.4	21.3	0.10	**	0.17	0.93

Table 6. Descriptive statistics and trend parameters for the summation of growing degree-days above a base of 10°C from April through October. Other information is as given in Table 2.

Region	Descriptive Statistics (GDD)				Trend Parameters (GDD)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Puget Sound	972	102	1267	730	0.13	***	23	123
Willamette Valley	1142	122	1503	858	0.27	***	39	211
Umpqua Valley	1319	120	1660	1036	0.14	***	25	136
Rogue Valley	1460	116	1723	1208	0.09	**	21	113
Columbia Val., OR	1489	125	1830	1215	0.11	**	50	252
Columbia Val.,WA	1504	124	1762	1216	0.13	***	27	147
Central Coast	1724	117	2001	1495	0.15	***	29	154
North Coast	1761	105	1962	1513	0.22	***	31	164
Foothills	2080	237	2433	1168	0.11	**	50	270
North Valley	2267	137	2569	1910	0.22	***	40	216
Central Valley	2618	127	2922	2299	0.21	***	36	193

Table 7. Descriptive statistics and trend parameters for the total annual number of days with temperatures below 0°C. Other information is as given in Table 2.

Region	Descriptive Statistics (days)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Central Coast	24	9.0	52	5	0.35	***	-3.4	-18
North Coast	25	12.0	57	4	0.36	***	-4.6	-25
North Valley	26	10.6	50	6	0.10	**	-2.2	-12
Central Valley	27	10.9	53	4	0.07	**	-1.8	-10
Foothills	42	14.7	76	14	–			
Puget Sound	46	14.1	89	20	0.22	***	-4.0	-22
Umpqua Valley	46	15.5	87	14	0.19	***	-4.3	-23
Willamette Valley	57	15.2	108	29	0.21	***	-4.2	-23
Rogue Valley	84	17.0	126	41	0.09	**	-3.3	-18
Columbia Val., WA	102	16.2	141	67	0.08	**	-2.6	-14
Columbia Val., OR	113	13.1	146	84	0.10	**	-2.5	-13

Table 8. Descriptive statistics and trend parameters for the total spring number of days with temperatures below 0°C (March, April, and May). Other information is as given Table 2.

Region	Descriptive Statistics (days)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Central Valley	2	1.3	5	0	0.20	***	-0.4	-2
North Valley	2	1.7	8	0	0.15	***	-0.4	-2
Central Coast	3	2.3	9	0	0.29	***	-0.8	-4
North Coast	3	2.7	12	0	0.37	***	-1.1	-5
Foothills	7	4.4	19	0	–			
Puget Sound	10	5.1	24	2	0.28	***	-1.7	-9
Umpqua Valley	11	6.2	24	1	0.23	***	-1.9	-10
Willamette Valley	13	5.6	29	3	0.24	***	-1.7	-9
Columbia Val.,WA	20	6.1	34	9	0.19	***	-1.7	-9
Rogue Valley	21	6.7	37	6	0.08	**	-1.8	-10
Columbia Valley, OR	26	6.1	40	14	0.22	***	-1.8	-10

Table 9. Descriptive statistics and trend parameters for the total fall number of days with temperatures below 0°C (September, October, and November). Other information is as given in Table 2.

Region	Descriptive Statistics (days)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Central Coast	3	1.8	7	1	0.16	***	-0.4	-2
Central Valley	3	2.7	9	0	–			
North Coast	3	2.3	10	0	0.11	**	-0.5	-3
North Valley	3	2.4	9	0	0.06	*	-0.4	-2
Foothills	5	3.6	16	0	0.08	**	-0.6	-4
Umpqua Valley	6	5.0	19	0	–			
Puget Sound	7	4.1	20	1	0.08	**	-0.4	-4
Willamette Valley	9	4.8	22	1	0.07	*	-0.8	-4
Rogue Valley	15	7.0	36	4	–			
Columbia Val., WA	22	6.4	35	9	–			
Columbia Val., OR	24	5.7	36	12	–			

Table 10. Descriptive statistics and trend parameters for the date of the last spring frost (below 0°C). Other information is as given in Table 2.

Region	Descriptive Statistics (date)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Central Valley	2/25	16.7	3/30	1/14	0.13	***	-3.8	-20
North Valley	3/5	16.9	4/8	1/17	0.09	**	-3.3	-18
Central Coast	3/8	18.7	4/15	1/18	0.26	***	-6.3	-34
North Coast	3/9	22.4	4/22	1/13	0.46	***	-9.6	-52
Foothills	4/6	17.9	5/12	2/18	–			
Puget Sound	4/9	15.2	5/7	3/4	0.31	***	-5.0	-27
Umpqua Valley	4/20	17.7	5/17	2/28	0.23	***	-5.4	-29
Willamette Valley	4/25	13.6	5/21	3/21	0.17	***	-3.5	-19
Columbia Val.,WA	4/26	11.4	5/16	3/28	0.20	***	-3.1	-17
Rogue Valley	5/5	10.6	5/24	4/9	0.06	*	-1.8	-8
Columbia Val.,OR	5/11	9.6	5/28	4/14	0.18	***	-2.5	-14

Table 11. Descriptive statistics and trend parameters for the date of the first fall frost (below 0°C). Other information is as given in Table 2.

Region	Descriptive Statistics (date)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Columbia Val.,OR	10/5	8.9	10/28	9/12	+			
Columbia Val.,WA	10/10	9.4	11/3	9/17	0.14	***	2.2	12
Rogue Valley	10/12	14.5	11/14	9/14	0.08	**	-2.5	-13
Willamette Valley	10/25	12.2	11/27	9/30	0.12	**	2.5	14
Umpqua Valley	10/28	20.0	12/8	9/13	+			
Puget Sound	11/2	13.0	12/9	10/2	0.17	***	3.2	17
Foothills	11/18	13.7	12/18	10/14	+			
Central Coast	11/21	10.2	12/14	11/28	0.12	***	2.4	13
North Valley	11/23	10.9	12/31	11/2	0.07	**	1.9	10
North Coast	11/25	12.4	12/23	10/29	0.15	***	3.2	17
Central Valley	11/26	10.5	12/21	11/4	+			

Table 12. Descriptive statistics and trend parameters for the length of the frost free period (from the date of the last spring frost to the date of first fall frost). Other information is as given in Table 2.

Region	Descriptive Statistics (days)				Trend Parameters (days)			
	Mean	Std. Dev.	Max.	Min.	R^2	P-value[a]	Decadal Trend	Overall Trend
Columbia Val.,OR	147	13.6	178	123	0.14	***	3.2	17
Rogue Valley	160	18.8	209	125	+			
Columbia Val.,WA	168	17.5	208	140	0.24	***	5.3	29
Willamette Valley	183	20.4	234	140	0.23	***	5.9	32
Umpqua Valley	192	29.1	261	123	0.13	***	6.5	35
Puget Sound	206	24.4	269	154	0.31	***	7.9	43
Foothills	227	21.2	273	183	+			
Central Coast	251	21.9	301	215	0.38	***	9.4	51
North Coast	259	27.6	319	203	0.49	***	12.5	68
North Valley	263	19.7	309	212	0.13	***	4.7	35
Central Valley	273	21.0	308	229	0.15	***	5.0	27

Figures

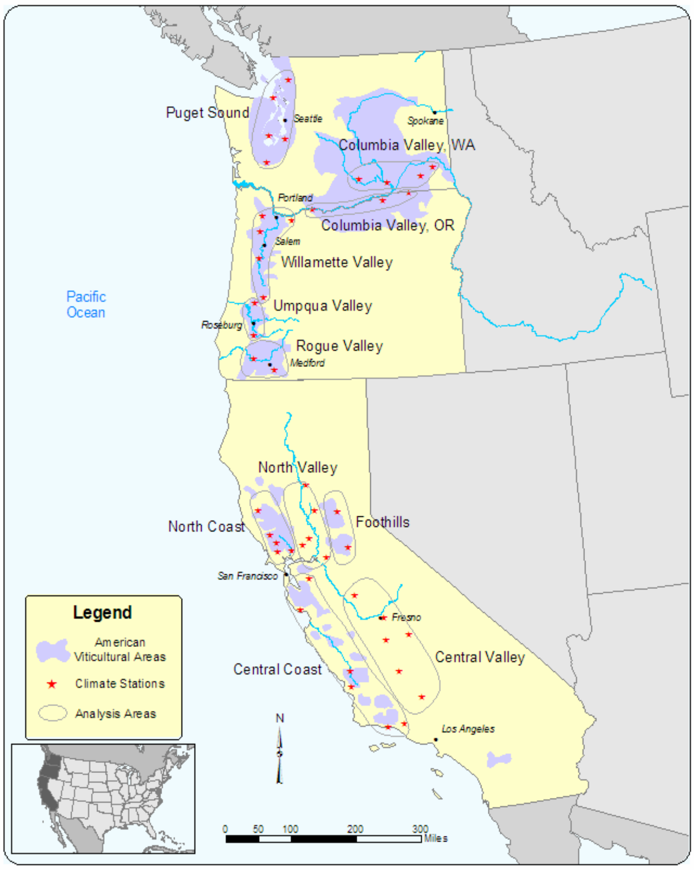

Fig. 1. The spatial depiction of the western United State's American Viticultural Areas (AVAs), the general grape growing areas studied, and the U.S. Historical Climatology Network cooperative stations used in the analysis.

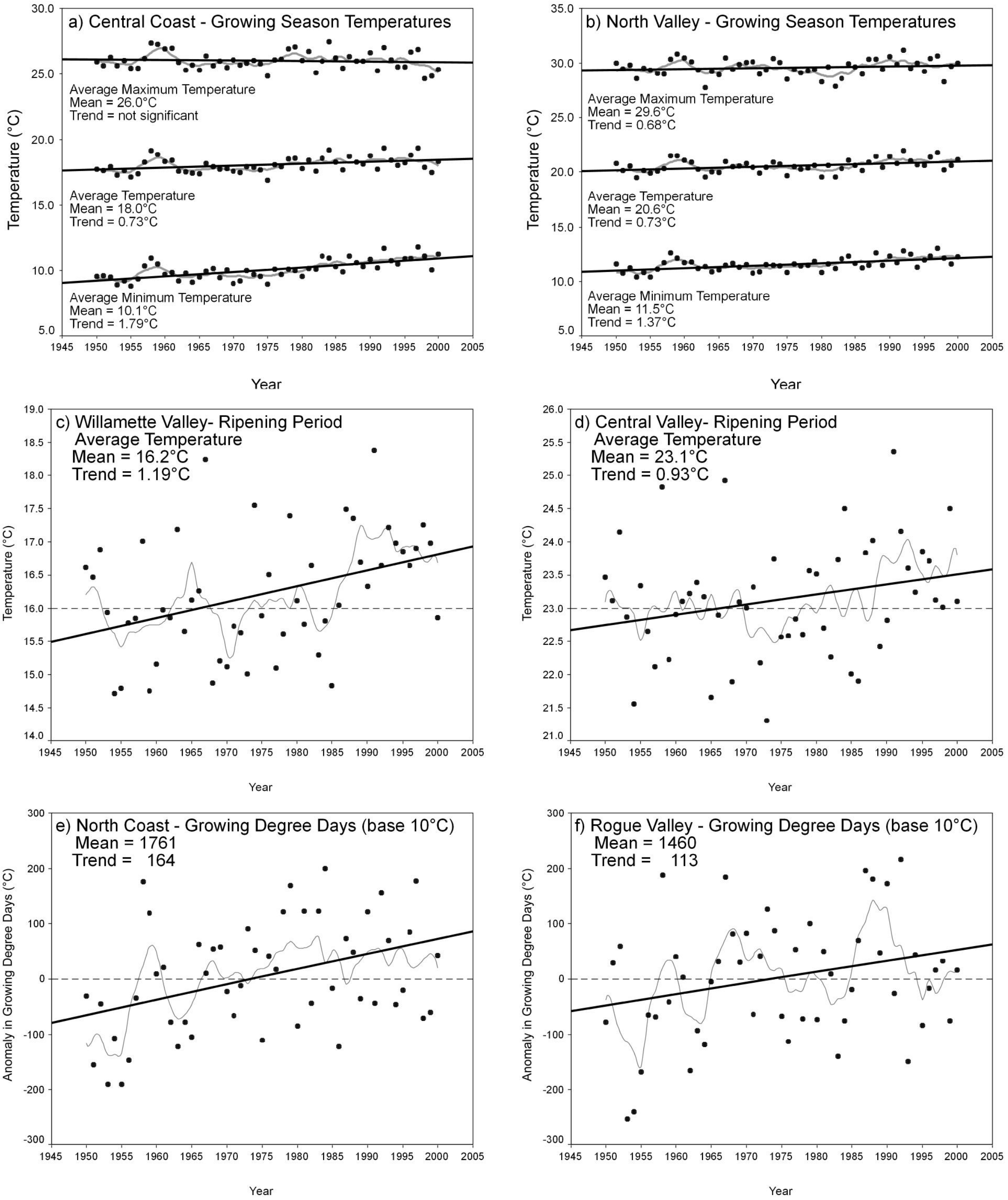

Fig. 2. Examples of trends and five-year moving averages for; a) the Central Coast growing season average, average maximum, and average minimum temperatures, b) the North Valley growing season average, average maximum, and average minimum temperatures, c) the Willamette Valley ripening period average temperatures, d) the Central Valley ripening period average temperatures, e) the North Coast growing degree-days, and f) the Rogue Valley growing degree days. Values depicted are either region-wide absolute values or anomalies in GDD units with means and trends over the entire time period inset in each chart (the full descriptive and trend statistics are given in Tables 1-5).

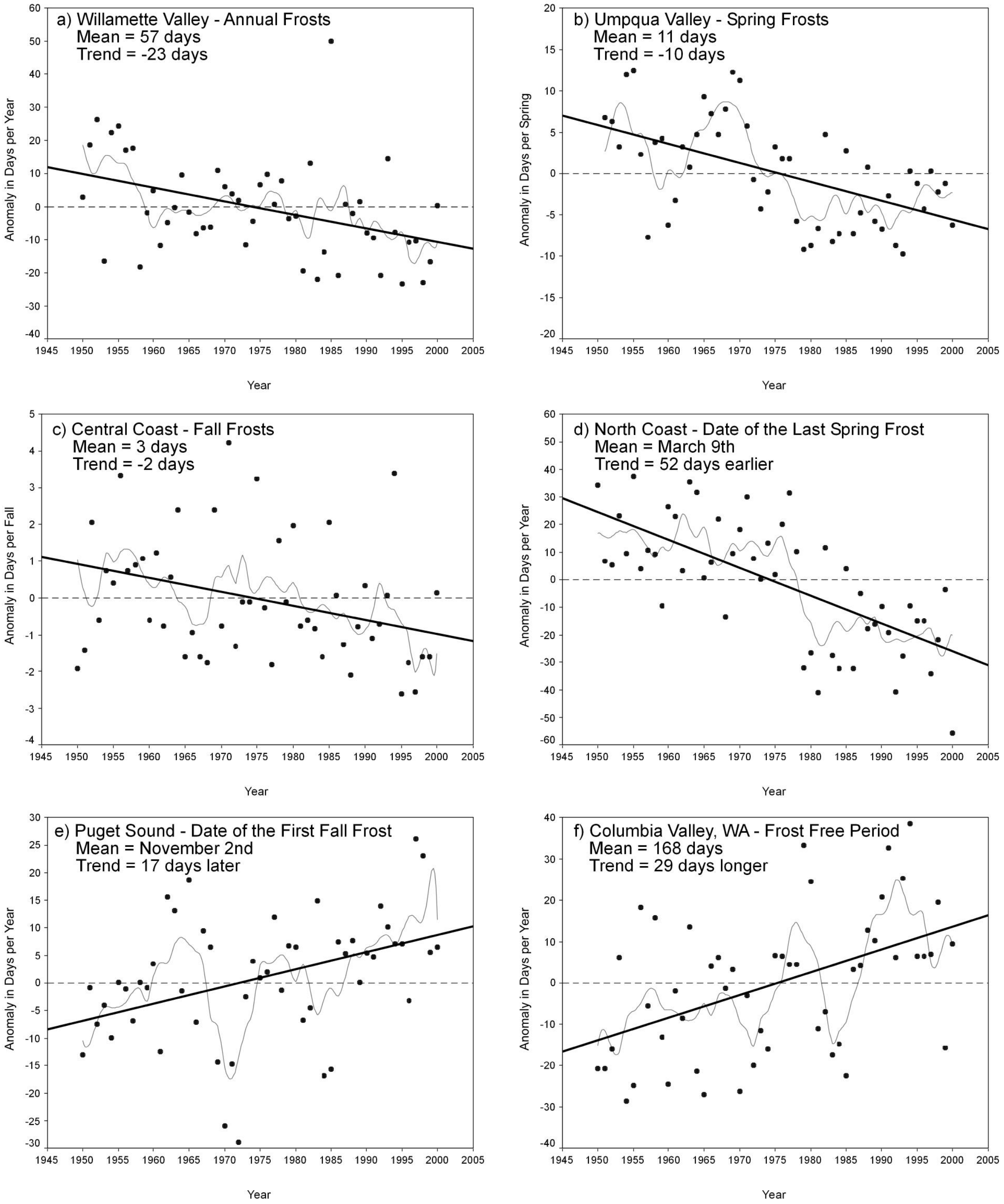

Fig. 3. Examples of trends and five-year moving averages for; a) the Willamette Valley annual number of frost days, b) the Umpqua Valley spring frost days, c) the Central Coast fall frost days, d) the North Coast dates of the last spring frost, e) the Puget Sound dates of the first fall frost, and f) the Columbia Valley, Washington frost free period. Values are depicted as region-wide anomalies in days with means and trends over the entire time period inset in each chart (the full descriptive and trend statistics are given in Tables 6-12).

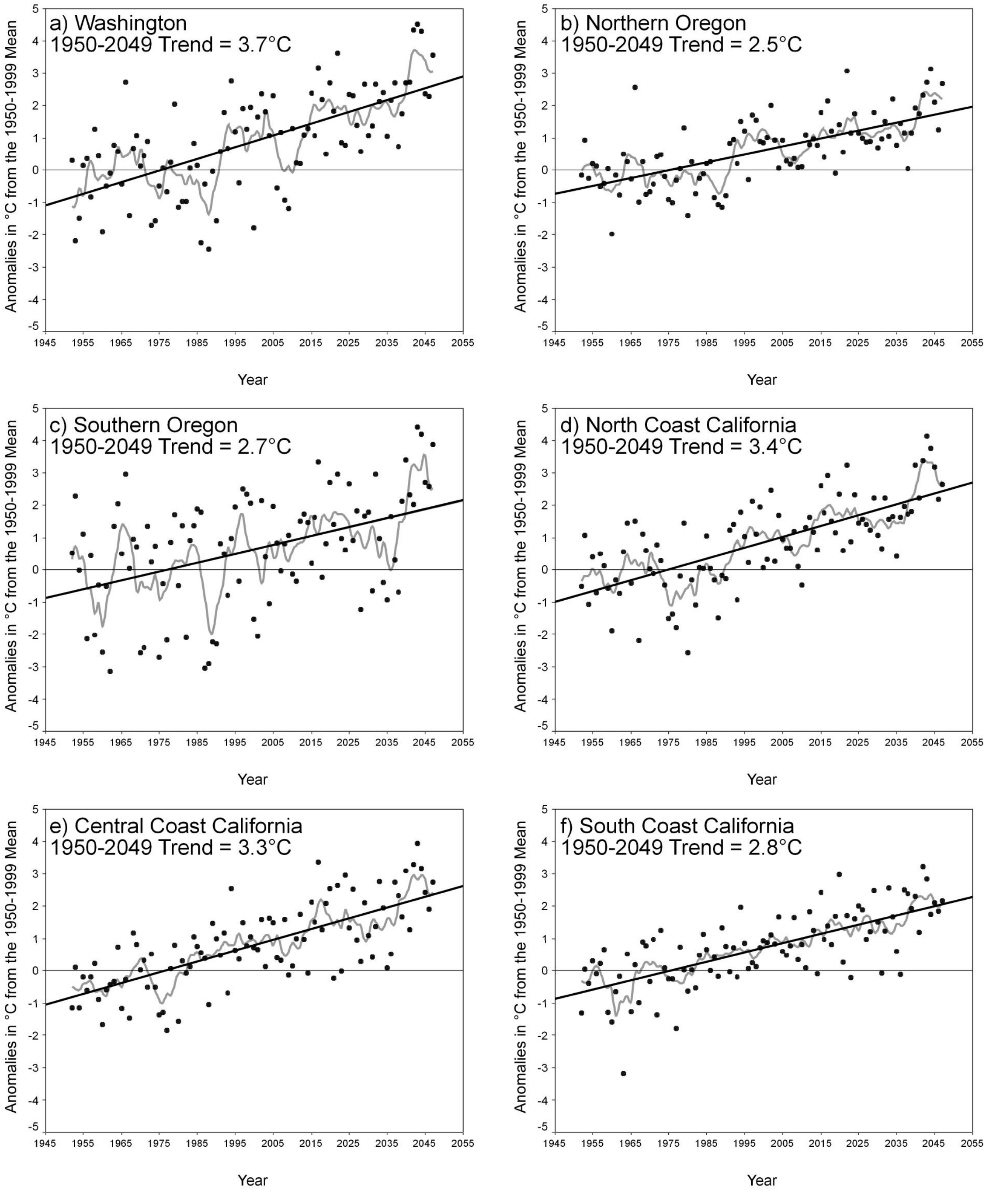

Fig. 4. Examples of trends and five-year moving averages for the HadCM3 model output for 2.75°x3.5° grid cells that best represent; a) central Washington, b) northern Oregon, c) southern Oregon, d) the North Coast of California, e) the Central Coast of California, and f) the South Coast of California. Values depicted are grid cell growing season average temperature anomalies with overall trend from 1950-2049 given.