Projected climate change impacts on grape growing in the Okanagan Valley, British Columbia, Canada

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Abstract

A statistical analysis was conducted on long-term climate records in the Okanagan Valley wine grape growing region of British Columbia, Canada. No observable trends for average annual temperatures were found in the region. Analyses of monthly mean and extreme temperatures show wide spatial and temporal heterogeneity, indicating that future studies using downscaling of global climate models for this region will require resolutions on the order of several kilometers. Mean winter temperatures are increasing throughout the valley, and extreme minimum temperatures are also increasing during the winter at the central and northern sites which have historically presented the most risk of winter damage to grapevines. Only the most southern and northern sub-regions are expected to see significant changes in their heat unit accumulations during the growing season. Over the coming century, the southern end of the valley will likely move from Winkler heat unit region 1 to 2. All regions of the Okanagan will continue to have latitude-temperature indices among the lowest of the world's fine table wine producing regions over the coming century. Growing season and dormant season average temperatures are expected to change by only a modest amount by 2100. Current climate maturity groupings for ripening grape varieties will likely stay constant at cool (central and southern areas) and intermediate (south-central) for all sites except Osoyoos (south). The climate trendings at Osoyoos suggest it will transition from an intermediate to a warm grouping by about 2050. The early to mid-season ripening capacity of the region may improve due to climate changes, but there is a risk of the asymmetric late season increases in minimum daily temperatures lowering the daily temperature range at some sites, possibly leading to difficulties in maintaining a balanced between sugar and sensory profiles as wine grapes approach maturity. The projected warming at the southern end of the valley should favor improved and increased Merlot production, will require Chardonnay production to shift northwards, and will allow growing of warmer climate wine grape varieties currently inaccessible because of low winter temperatures and a lack of growing season heat units. Increasing winter temperatures throughout the region are expected to result in increased risk of pests such as Pierces disease.

Keywords:
viticulture, climate change, wine production, Okanagan Valley (British Columbia, Canada)

1. Introduction

Concerns over global climate change have led to a critical examination of its potential impacts on agriculture during the past several decades. Recent evidence suggests that, in the absence of adaptation, climate change may lead to food insecurity and major disruptions in agricultural activities for both temperate and tropical regions (Battisti and Naylor, 2009). Projected impacts on wine grape production has begun to receive an increasing amount of attention due to the potentially significant impacts of anthropogenic climate forcings on the wine industry, as well as the industry's large direct global economic impact nearing one-quarter of a trillion dollars (Research and Markets, 2005).

Analysis of regional climate variability over the coming decades may allow producers to more effectively manage and adapt to expected changes. In the United States, for example, previous work has suggested that extreme heat impacts may reduce premium grape production by up to 80% in the late 21st century. These heat accumulation increases are predicted to shift production towards warmer climate varieties and/or lower-quality wines while reducing the impacts of frost damage, but the increase in extreme hot days (>35°C) may eliminate wine grape production across much of the United States (White et al., 2006). Asymmetric warming (at night and during the spring), leading to reduced frost occurrence, a longer growing season, and more rapid and advanced spring growth have been linked to increased yields and quality in California. Average springtime warming is occurring at twice the rate seen over the rest of the year in this region (Nemani et al., 2001). Another study of the impacts of climate change on the industry in California showed that, assuming ripening occurs between 1150 and 1300 growing degrees base 10°C (GDD_{10}) and using monthly average temperatures in the calculations between April and October, grape ripening is predicted to occur one to two months earlier

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and at higher temperatures by the year 2100 (Hayhoe et al., 2004). Problems with earlier harvest dates brought on by climate change, assuming that grape development has still maintained a balance between sugar, acidity, and flavour, include hot and desiccated fruit without greater irrigation inputs (Jones, 2005a). Since many of the world's grape growing regions are located in semi-arid environments where water scarcity is a major scientific and political issue, increases in irrigation demand to offset the harvesting of hot, desiccated fruit may not be possible.

Over the past century, the majority of the world's high quality wine producing regions have seen growing season average temperature increases of about 2°C (Jones, 2004). A study of climate and observed changes in European wine grape phenology (Jones et al., 2005b) showed that growing season average temperatures increased by 1.7°C, maximum temperatures increased by 1.8°C, minimum temperatures increased by 1.9°C, with more warming in the spring and summer, and an average increase in GDD_{10} of 264 across all stations. In general, grapevine phenological timing in Europe over the past 50 years is occurring earlier and with more significant changes being observed in later events than in earlier events. Strong correlations between grapevine phenology and climate parameters were observed, with maximum temperatures being more important for early season events (i.e., budbreak and bloom), and average temperatures and GDD_{10} being more important for later season events (i.e., veraison and harvest) (Jones et al., 2005b). Vintage ratings over the past 50 years in most of the world's best wine regions have increased, which has been found to be correlated to increases in growing season temperatures (Jones et al., 2005a). However, such relationships are potentially problematic as they do not explicitly incorporate improvements in wine production methods over this period.

Little work has been done regarding potential climate change effects on viticulture in Canada, and in particular, on the emerging wine grape regions in the province of British Columbia (Belliveau et al., 2006). Because of the economic importance of the Okanagan Valley wine industry to the regional and British Columbia provincial economy (several hundred million CDN dollars), as well as the regions location within the current effective northern limits of Vitis vinifera table wine grape production, we have conducted a climatic analysis of this emerging wine region with projections as to how viticulture may evolve over the coming century. Our objectives were also to examine the potential spatial heterogeneity in any climate change signatures for the Okanagan Valley over the past century, as such findings will help guide the level of downscaling required from global climate models in future studies to most adequately capture future climate change impacts for this region.

2. Regional Description

The Okanagan Valley is located in south-central British Columbia, Canada, approximately 300 kilometres east of the Pacific Ocean. The valley is long and narrow and runs northward for 160 kilometres from the US border at 49 to 50°N latitude (Figure 1). The region lies in a rain shadow between two

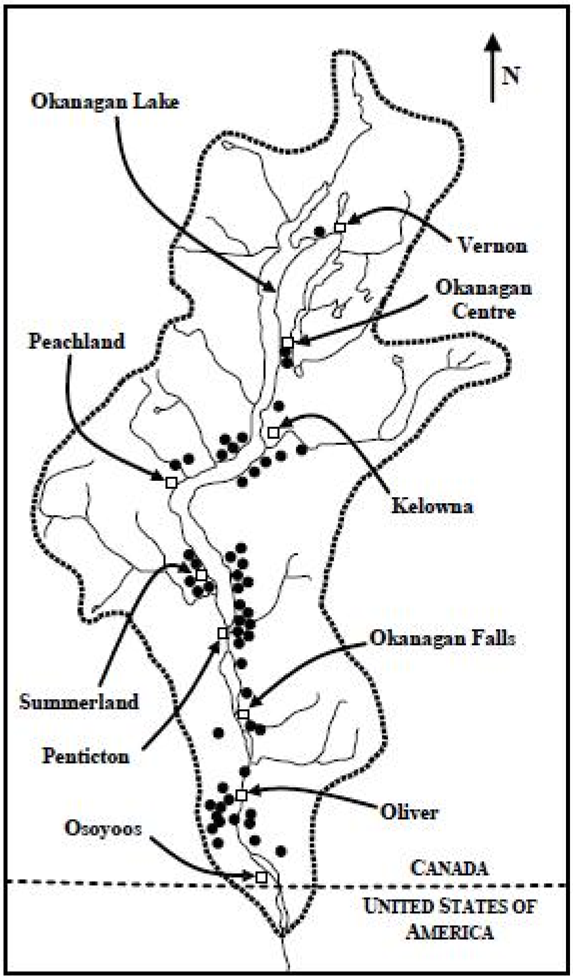

Figure 1: Map showing locations of cities (open squares), viticultural regions, and clusters of wineries (filled circles) in the study area. Note that all wineries are not shown for clarity; major groupings are indicated to demonstrate regions of concentrated viticultural activity.

north-south trending mountain ranges, resulting in low annual average precipitation (from ca. 320 mm/y at Osoyoos [southern end of the Canadian portion of the valley] to ca. 480 mm/y at Vernon [northern end of the valley]) that is distributed evenly throughout the year, and only modest winds are typical. The area between Oliver and the US border is the northern-most tip of the Sonora Desert, which begins at the Baja Peninsula in Mexico. Summers are generally hot, with average daily temperatures in July and August (ca. 22°C) that are warmer than the Napa Valley. Daytime maximum temperatures over this period can reach 40°C, and are often above 30°C for several consecutive days. In the summer, there are long daylight hours and high light intensity due to the northerly latitude, which helps with prolonged daytime photosynthesis and grape ripening.

Two primary modes of natural climatic variability affect the climate of the Okanagan Valley. Both the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) have periods of anomalous warming and cooling of the Pacific Ocean, which influence atmospheric circulation. El Nino and its warming of the tropical waters of the central Pacific, decreases the strength of the easterly trade winds. The opposite phase of ENSO, La Nina, has a cooling effect on the central Pacific that increases these trade winds. Similarly, the PDO is an alternate warming and cooling of the ocean, but is located in the northern Pacific. During the warm phases of the ENSO and PDO, winters are hotter and drier, with correspondingly colder and wetter winters during the cool phases of these patterns (Wallace and Gutzler, 1981; Trenberth and Hurrell, 1994; Mantua et al., 1997). The ENSO typically acts on an interannual timescale, with recent strong events during the winters of 1982/1983, 1986/1987, and 1997/1998. In contrast, the PDO operates on inter-decadal timescales with at least the following four phase changes since 1900: 1900 to 1925, cold; 1926 to 1946, warm; 1947 to 1976, cold; and 1977 to the late 1990s, warm (Trenberth, 1990).

During the growing season, there can be a 4°C average daily difference in temperature between the northern and southern ends of the valley. This results in a preference for red varieties in the south and white varieties in the cooler north (Bowen et al. 2005). Winters are generally cold and temperatures can drop below freezing for long periods, with rare events down to -25°C. The valley's extensive lakes are key to moderating the otherwise mountainous/continental climate extremes in summer and winter. However, the main climatic factor limiting Vitis vinifera grape production in the Okanagan Valley are the low temperatures (critical value range, <-6°C to <-23°C) occurring in late October through February (Caprio and Quamme, 2002). Within the valley, there are significant climate and soil differences from north to south, with the following five proposed broad agricultural sub-regions (Bowen et al., 2005): (1) Kelowna: ca. 1200 GDD_{10}, heavier soils with sandy loam, clay and limestone; common varietals are Vitis vinifera cv. Pinot Noir, Pinot Gris, Pinot Blanc, Riesling, and Chardonnay; (2) Penticton: ca. 1320 GDD_{10}, long frost-free autumn due to lake proximity and sloping aspect; common varietals are Vitis vinifera cv. Pinot Noir, Pinot Gris, Pinot Blanc, Chardonnay, and Merlot; (3) Okanagan Falls: ca. 1410 GDD_{10}, diverse soils and aspects with some vineyards on terraced slopes; common varietals are Vitis vinifera cv. Riesling, Gewurztraminer, and Pinot Noir; (4) Oliver: ca. 1480 GDD_{10}, well-drained gravel, clay and sandy soils; common varietals are Vitis vinifera cv. Merlot, Chardonnay, and Gewurztraminer; and (5) Osoyoos: ca. 1490 GDD_{10}, soils are deep sand; common varietals are the Vitis vinifera cv. Chardonnay, Syrah and Bordeaux varieties. We note that the GDD_{10} for these regions proposed by Bowen et al. (2005) differ substantially from both the estimates derived herein as well as the long-term calculations conducted by Environment Canada.

Grape and wine production has increased steadily in this region over the past two decades, with total crop processed by wineries having grown from ca. 5000 tons in 1992 to ca. 20,000 tons in 2007 (BCWI, 2008). The value of British Columbia Vintners Quality Alliance (BC-VQA) wines sold has increased much more quickly, from about CDN$7 million in 1991/1992 (BCWI, 2005) to about CDN$160 million in 2005 (BCWI, 2008) (Figure 2). During the 1990s, the average price

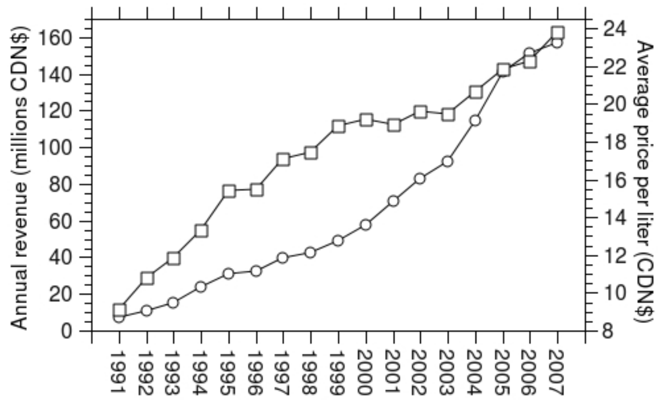

Figure 2: Total annual revenues (open circles) and average prices per liter (open squares) for British Columbia Vintner's Quality Alliance wines from the Okanagan Valley between 1991 and 2007. Information sourced from BCWI (2005, 2006, 2007, 2008).

per liter for BC-VQA wines increased more rapidly than total revenues. Between 2000 and 2003, the average price per liter stabilized at ca. $19-20 (CDN), after which average per liter wine prices have generally trended with total industry revenues. The top five varieties in British Columbia during 2007 were Vitis vinifera cv. (1) Merlot (ca. 3300 tons), (2) Chardonnay (ca. 2500 tons), (3) Pinot Gris (ca. 1700 tons), (4) Pinot Noir (ca. 1500 tons), and (5) Cabernet Sauvignon (ca. 1400 tons) (BCWI, 2008) (Figure 3). Since the mid-1990s, production of Merlot and Chardonnay has increased more rapidly that the other three varieties, establishing them as the dominant wine grape varieties in the Okanagan with continually increasing market share.

3. Effect of Climate Variability on Wine Grape Production

For the wine grape industry, climate is a dominant contributor to quantity and quality (van Leeuwen et al., 2004; Maltman, 2008; White et al., 2009). Major climatic conditions required for producing wine grapes with balanced composition and varietal typicity include low frost damage in mild winters, early and even budbreak, flowering, and development during warm springs, and optimal maturation with low summer temperature variability, adequate heat accumulation, and a lack of extreme heat (Gladstone, 1992; Jones, 1999; Nemani et al., 2001; White et al., 2006). For the northern hemisphere, the four seasonal stages of grapevine development, together with the associated general climate influences, can be summarized as follows (Jones, 1999; Nemani et al., 2001). Stage 1 includes budbreak and leaf development, begins between mid-March to the first week of April, and requires sufficient soil moisture and sunshine with temperatures >10°C. Frost or freeze occurrence during this stage can reduce bud fruitfulness, leading to poor yields and quality. In stage 2 (floraison/flowering) during

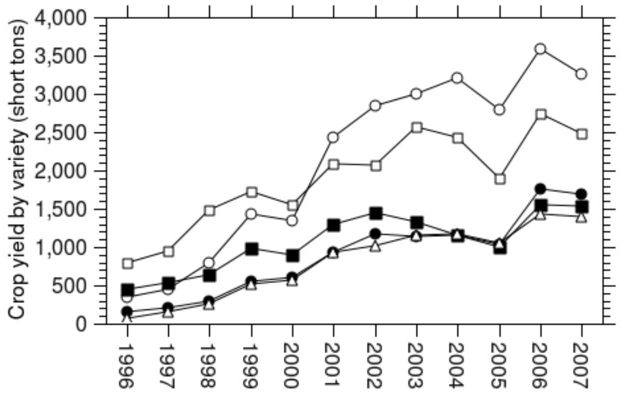

Figure 3: Annual crop yields between 1996 and 2007 for the top five wine grape varieties in the Okanagan Valley: Vitis vinifera cv. Merlot (open circles), Chardonnay (open squares), Pinot Gris (filled circles), Pinot Noir (filled squares), and Cabernet Sauvignon (open up triangles). Information sourced from BCWI (2005, 2006, 2007, 2008).

early through mid-June, dry, stable conditions are needed to avoid delaying flower growth. Stage 3 (veraison, development of the grape, and its maturation) typically begins between the end of July and the first week of August, where dry conditions with moderate temperatures are preferred to limit moisture induced grape rot. In addition, high levels of insolation and low temperature variability at this time help concentrate sugars before harvest. Finally, during stage 4 which begins between late September through mid-October (harvest through dormancy), the vine requires sufficiently cold temperatures to initiate latent bud hardening with limited freeze damage.

While these four stages describe preferred seasonal climatic conditions, daily variation within each stage also helps contribute to optimum wine grape quality. Assessing viticultural suitability with mean climatological parameters often neglects daily weather events that significantly influence the quantity and quality of harvest (Jones and Davis, 2000a). For example, maximum daily temperatures during the summer months can influence grapevine growth both positively and negatively. Short-term periods with temperatures >30°C can assist ripening potential, but extended periods can cause heat stress in the vine, premature veraison, berry abscission, enzyme inactivation, and reduced flavour development (Mullins et al., 1992). Similarly, while there is general agreement in using 10°C as the base viticultural temperature (i.e., GDD_{10}) for total growing season heat units when comparing different climatic regions, and for assessing a region's suitability for grapevine production (Oliveira, 1998; Shaw, 2001, 2005), upper limits on heat summation ranging from 19°C to 21°C have been used because of the negative effect of sustained higher average temperatures on wine quality (Winkler et al., 1974; Gladstone, 1992). We do note, however, that some have advocated caution in the use of relating GDD_{10} to vine physiology, production, and quality in some regions (Jones and Davis, 2000a,b).

In the maturation stage of late summer and early autumn, significant diurnal temperature ranges increase both sugar and tannin production in the fruit, helping preserve the balance for wine production (Gladstone, 1992). These lower autumn temperatures are important in the production of quality table wines, ideally with prolonged cool temperatures before the first frost. Cool temperatures at this time of the late growing season, just before the mean monthly temperature decreases to <10°C, slow berry development and allow for a better balance of sugar and acidity and increased flavour and aroma constituents (Gladstone, 1992; Shaw, 2001). A minimum temperature threshold also exists during the winter months, where effective chilling units are required to ensure uniform budbreak in the spring (Jones, 2005a). Grape hardiness generally increases through the winter, and daytime temperatures <-9°C in late November and early December increase grape production, likely due to the prevention of vine de-acclimation (Caprio and Quamme, 2002). However, most Vitis vinifera cultivars are injured at temperatures <-20°C, and temperatures <-12°C before mid-November can result in freeze damage, particularly to the primary buds. At <-25°C, even matured canes and young vines can be severely damaged, and at <-29°C, entire vines may be killed (Gladstone, 1992).

4. Methods

Monthly and annual climate data for stations in potential grape-growing regions of the Okanagan Valley were obtained from Environment Canada (2005). The absence of reliable and continuous daily climate data for older records at some stations in the region prevents an historical climatic analysis based on these values. Multi-decadal length climate series will likely average the short-term effects of ENSO events, but reliable climate records extending back to 1900 are required to evenly average PDO phases. PDO phase averaging is critical to reliable climate trending analyses on the western coast of North America to prevent spurious findings of climate trends based on asymmetric PDO phasings. For example, if a climate analysis included two warm PDO phases and only one cool phase, the analysis could reveal a spurious warming trend that does not exist where PDO phases are evenly matched. Only two stations in the Okanagan have been in operation since 1900 (Vernon and Kelowna; Table 1), but both stations have been moved (1968 at Kelowna, and 1991 at Vernon). The station relocation at Vernon was minimal, and the historical and recent climate records are synchronous. At Kelowna, a substantial lateral and vertical relocation of the station away from a large lake resulted in moving to a different climate regime. An analysis of the dataset suggests this site lost reliable synchronicity in 1968, and is thus excluded from this study.

The remaining climate station records used in the current analysis come from small towns (<10,000 to 50,000 people) which are located in rural areas that do not contain a significant urban warming component (Vincent and Gullett, 1999): Osoyoos, pop. 4,752; Oliver, pop. 4,370; Penticton, pop. 31,909; Summerland, pop. 10,828; Okanagan Centre, pop. 9,606; Vernon, pop. 35,944 (British Columbia, 2007). Significant rural land use changes have occurred in the Okanagan Valley over the past century. Areas have shifted between agricultural crops (e.g., tree fruits to grapes) and among cultivated, livestock grazed, and fallow states. These changes, even in the absence of greater urbanization, can affect the mesoclimates around nearby climate stations due to varying vegetation levels/types and irrigation systems. However, the lack of reliable historical details prevent an assessment of how these impacts may have influenced the synchronicity of long-term climate records at each station.

Each time-series was analysed for first-order autocorrelation using the Durbin-Watson statistic. No autocorrelation problems were observed. The Mann-Kendall non-parametric test was used to determine the statistical significance of a trend, and Sen's method was used to estimate the magnitude of a trend. Non-parametric testing methods were chosen as they are robust, less sensitive to non-normal distributions, and less affected by extreme values or outliers (Salmi et al., 2002). Parametric linear regression was also performed on each time series, and did not reveal any substantial differences in significance or trending compared to the non-parametric tests. Projected changes in climate at each station used significant ($p<0.05$) extrapolations of linear regressions developed over the available climate record. For the assessment of climate impacts, northern hemisphere grape growing periods were defined as follows (White et al., 2006): growing season, April 1 to October 31; dormant season, November 1 to March 31; ripening season, August 15 to October 15; winter, December 1 to February 28; spring, March 1 to May 15; summer, May 15 to August 31; and autumn, September 1 to November 30.

5. Results and Discussion

A distinct climate gradient exists in the Okanagan Valley, with average annual temperatures over the 1971-2000 period declining from 10.1°C at Osoyoos in the south to 7.4°C at Vernon in the north (Table 1). The available climate record at these major stations throughout the Okanagan Valley suggests there are no observable trends for average annual temperatures in this wine grape growing region. Analyses of monthly mean and extreme temperatures show wide spatial and temporal heterogeneity throughout the region. Isolated temporal trends at each station are offset by periods of the year with either no clear climate trend, or the opposite trend (Figure 2). Together, these influences result in non-significant annual mean temperature trends. The results complicate any general assessments for climate change impacts on viticulture throughout the Okanagan Valley, necessitating site-specific approaches that may differ substantially over relatively short macroclimatic distances (i.e., tens of km) within the region. Mean winter temperatures are increasing (2-4°C) at all sites in the Okanagan Valley with the exception of Penticton, where no change was detected. Of note, extreme minimum temperatures are also increasing during the winter at the central and northern sites (Summerland, Okanagan Centre, and Vernon) which have historically presented the most risk of winter damage to grapevines suggesting reduced vulnerability to vine damage in these regions in the coming decades.

Table 1: Summary information and observed annual climate normals (1971-2000) for mean temperatures ($T_{avg,1971-2000}$) over the available climate record, and corresponding trends at climate stations in the Okanagan Valley. Climate normals and averages are denoted by a preceding "N", with trends over the available climate record denoted by a preceding "T". Error bars are 95% confidence limits about the estimated trend (if present), with statistical significance in parentheses.

City	Region	Period of Record	Station Name(s)[a]	Latitude (°N)	Longitude (°E)	Elevation[b]	$T_{avg,1971-2000}$ (°C)
Osoyoos	South Okanagan	1954-2004	Osoyoos (1954-1990)	49.03	-119.43	297.0	N=10.1°C, T=n.s. (p=0.19)
			Osoyoos CS (1990-2004)	49.03	-119.44	282.9	
Oliver	South Okanagan	1924-2004	Oliver STP	49.18	-119.54	297.2	N=9.9°C, T=n.s. (p=0.66)
Penticton	South Okanagan	1941-2006	Penticton A	49.46	-119.6	344.1	N=9.2°C, T=n.s. (p=0.44)
Summerland	South Okanagan	1916-2004	Summerland CDA (1916-1995)	49.57	-119.65	454.2	N=9.0°C, T=n.s. (p=0.29)
			Summerland CS (1995-2004)	49.56	-119.64	454.2	
Okanagan Centre	Central Okanagan	1925-2004	Okanagan Centre	50.04	-119.41	501.0	N=9.7°C, T=n.s. (p=0.08)
Vernon	North Okanagan	1900-2004	Vernon Coldstream Ranch (1900-1991)	50.22	-119.2	482.2	N=7.4°C, T=n.s. (p=0.08)
			Vernon CS (1991-2004)	50.22	-119.19	482.0	

[a] where more than one Environment Canada climate station contributed towards the composite record at a site, the dates used from each station for the analyses are given in parentheses. [b] in meters above sea level.

Several climate based indices have been developed for wine grape production. One of the earliest indices developed for agriculture is the heat units concept using GDD_{10} (Amerine and Winkler, 1944). Correlating the GDD_{10} with quality wine grape production has led to Winkler heat unit regions, whereby increasing Winkler region numbering (e.g., 1, 2, 3, 4) denotes increased heat units accumulating during the growing season (Winkler et al., 1974). However, the GDD_{10} based heat unit approach for discriminating among wine grape growing regions has been found to be most accurate for intermediate through hot regions (e.g., southern Europe, California, Australia, and South America), and less successful for analyzing cool through intermediate zones (e.g., northern Europe, northeastern and northwestern North America, and New Zealand). For this reason, the latitude-temperature index (LTI; Jackson and Cherry, 1988) was developed and is generally thought to better discriminate between cool climate viticulture areas (i.e., those in Winkler regions 1 and 2) than the GDD_{10}. Cool climate regions are generally defined as those where the GDD_{10} is <1390 (Amerine and Winkler, 1944) and/or where the LTI is <270 (Jackson and Cherry, 1988). Based on these assessment frameworks, the Okanagan Valley would be generally considered a region of cool climate viticulture (Figures 4 and 5).

During the growing season, only Osoyoos and Vernon are expected to see increases in GDD_{10} by 22% and 14%, respectively, over the next century, driven by increasing mean temperatures in spring and late summer. By the year 2100, Osoyoos is expected to exceed 1640 GDD_{10}, moving its growing season heat units from the current Winkler region 1 similar to the Niagara Peninsula (Canada) and Geneva (New York, USA) to values in Winkler region 2 greater than the current climates in Sienna (Italy), Napa Valley (California, USA), and the Margaret River region of Australia. The varietal suitability would likely transition from the interface between the upper limit for the cooler red and white Vitis vinifera cultivars (e.g., Pinot Noir, Pinot Gris, Chardonnay) and the lower limit for the classic Bordeaux reds (e.g., Merlot, Cabernet Sauvignon) and Burgundian whites (e.g., Aligote), to a heat unit range at the interface between the upper limit for the Bordeaux reds and Burgundian whites and the lower limits for the warmer whites (e.g., Sauvignon Blanc) and reds (Malbec, Barbera) of southern France, California, and South America.

In contrast, the trends at Oliver and Penticton suggest a decline in heat units by 2100 (4% and 13%, respectively) due to decreasing mean temperatures in mid-summer at both locations, and also late summer/early autumn declines at Penticton. Both stations will still remain in Winkler region 1 over the next century. The slight decline in GDD_{10} at Oliver will likely have little impact on suitable varieties for this region, but the larger decline near Penticton will move this locale into a similar heat unit regime as Geisenheim (Germany). The central Okanagan regions of Summerland and Okanagan Centre are expected to maintain their current GDD_{10} of 1125 and 1085, respectively, in Winkler region 1 with similar heat units to Freiburg (Germany). The expected warming at Vernon, while GDD_{10} remains constant at Summerland and Okanagan Centre, suggests that the central through northern parts of the Okanagan Valley will become approximately equal in heat units by 2100, thereby increasing the homogeneity in wine grape ripening capacity over this region.

Osoyoos and Vernon are expected to see increases in their LTIs (by 17% and 6%, respectively) by 2100, whereas Oliver, Summerland, and Okanagan Centre will have no significant changes. All regions of the Okanagan, by virtue of their high latitude (49.0 to 50.2°N), will continue to have LTIs among the lowest of the world's fine table wine producing regions. At Osoyoos, the LTI increase from 238 to 278 by 2100 will move the region from an LTI similar to Freiburg (Germany) to a value closer to Nova Scotia. Vernon will continue, despite the slight increase, to have a LTI similar to Geisenheim (Germany). The other stations in the Okanagan are expected to maintain their LTIs between about 230-235 (Oliver), 212-215 (Penticton and Summerland), and 199 (Okanagan Centre). Growing season and dormant season average temperatures in the Okanagan Valley are expected to only change modestly by 2100 (Figure 6), and will maintain the existing climate maturity groupings for ripening grape varieties at cool (Vernon, Okanagan Centre, Summerland, and Penticton) and intermediate (Oliver) for all sites except Osoyoos. The observed climate trendings at Osoyoos suggest it will transition from its existing intermediate climate maturity grouping to a warm grouping by about 2050.

In terms of other climate descriptors such as the mean temperature of the warmest (MTWM) and coldest (MTCM) months, the greatest change is expected to occur for the MTWM at Osoyoos (1971 to 2000 average of 21.7°C increasing to 25.3°C by 2100). Throughout the remainder of the Okanagan, MTWM and MTCM are not expected to change by more than 1°C. The MTWM/MTCM profiles at Oliver through Okanagan Centre (MTWM ca. 20 to 22°C; MTCM ca. -1 to -3°C) over the next century will be similar to that currently found in the Yakima Valley (Washington State, USA; MTWM 22°C, MTCM -2°C). Vernon will maintain a MTWM/MTCM signature similar to Geneva (New York, USA), while Osoyoos will develop a larger MTWM/MTCM gap indicative of increasing continentality - having an increased risk of excessive vine heating in the summer months, while still maintaining a winter cold damage risk. Extreme minimum temperatures are decreasing in early autumn when the vine is particularly susceptible to damage prior to dormancy. Extreme maximum temperatures are increasing year-round, leading to both a higher risk of heat damage during the summer and unpredictable day-to-day variations in temperatures during the autumn and early winter.

In addition, regions within a vineyard that have a higher T_{min} and lower daily temperature range (DTR) over the early to mid growing season periods are generally associated with higher quality wines (Johnson, 1985). As the harvest approaches, though, larger DTRs are often preferred to allow the development of color, flavour, and aroma compounds to keep pace with sugar development and maintained a balanced grape composition. The Okanagan sites at Oliver, Okanagan Centre, and Vernon are expected to have future increases in their current T_{min} values during the early to mid-growing season periods, whereas no change is expected at Penticton and a decrease is anticipated at Osoyoos.

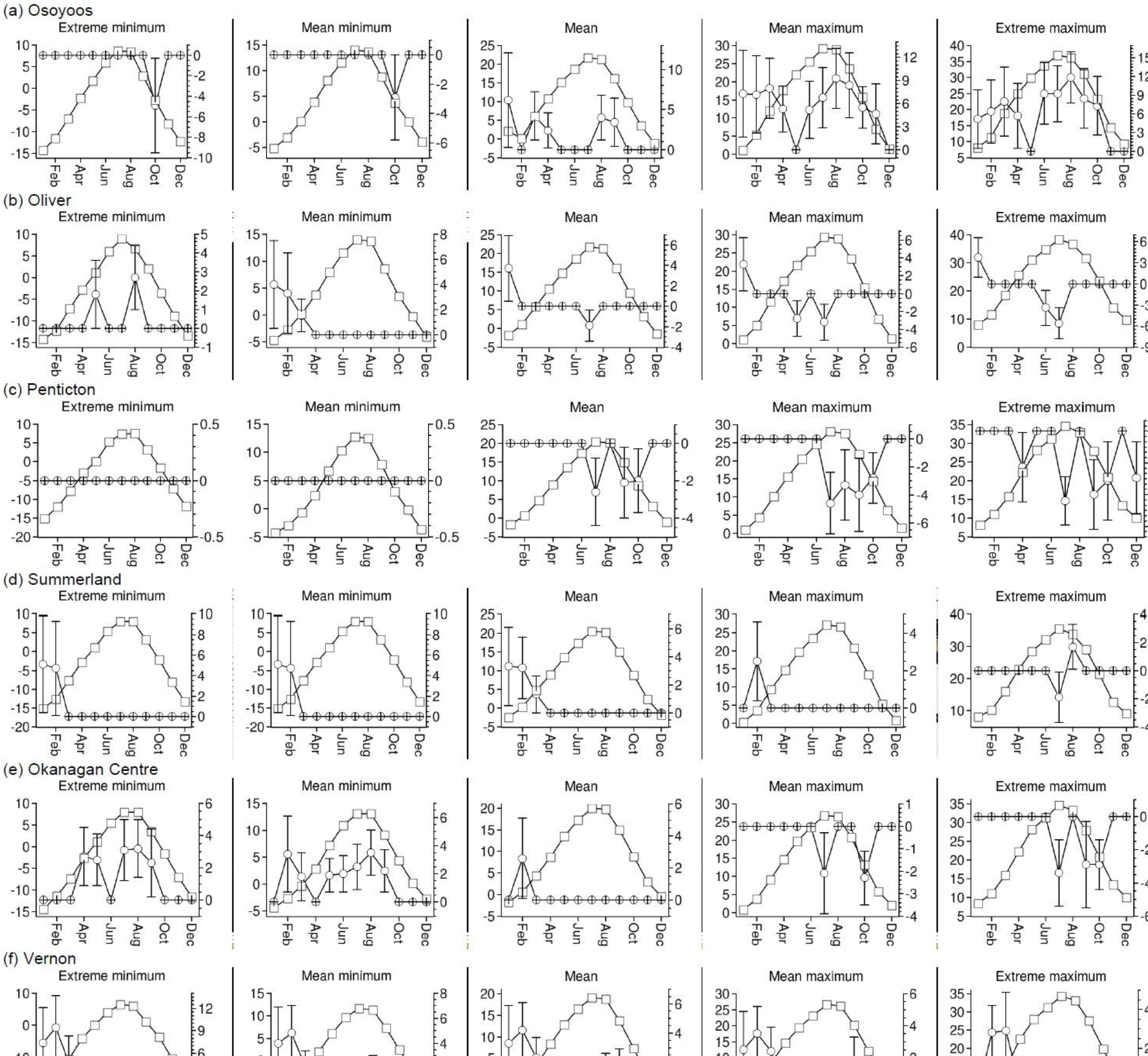

Figure 4: 1971-2000 climate averages (open squares; left y-axis) and projected per century changes (open circles; right y-axis) in extreme minimum, mean minimum, mean, mean maximum, and extreme maximum monthly temperatures at the cities of (a) Osoyoos, (b) Oliver, (c) Penticton, (d) Summerland, (e) Okanagan Centre, and (f) Vernon in the Okanagan Valley. Values are in °C. Error bars represent 95% confidence intervals about the temperature projections.

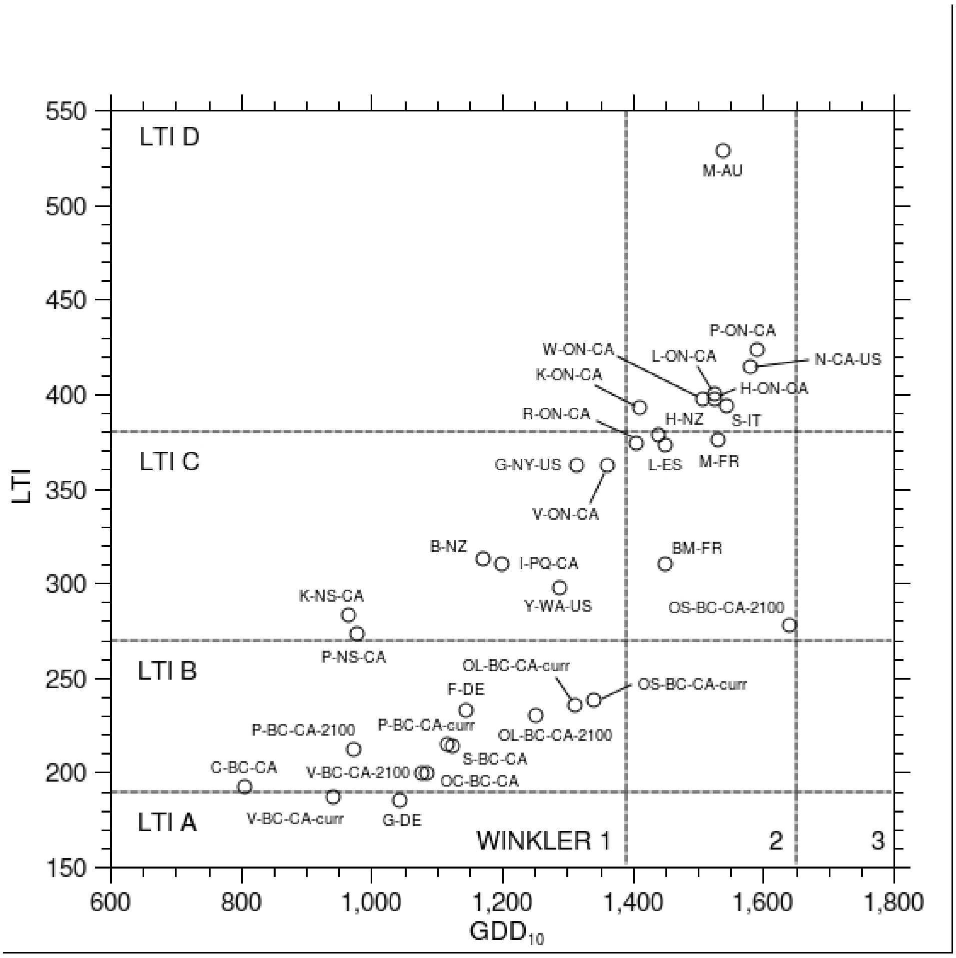

Figure 5: Comparison of current and projected year 2100 growing season conditions for the Okanagan Valley cities and sub-regions with current conditions at established wine regions elsewhere in Canada and worldwide. Adapted from Shaw (2001) to include the current dataset. GDD_{10} use the April through October growing season in the Northern Hemisphere and the October through April growing season in the Southern Hemisphere. Latitude-temperature index (LTI) classes based on those of Jackson and Cherry (1988). Winkler heat unit groupings based on those of Winkler et al. (1974). Site codings are as follows: K-NS-CA (Kentville, NS, Canada); P-NS-CA (Pugwash, NS, Canada); I-PQ-CA (Iberville, PQ, Canada); V-ON-CA (Vineland, ON, Canada); H-ON-CA (Harrow, ON, Canada); K-ON-CA (Kingsville, ON, Canada); P-ON-CA (Pelee Island, ON, Canada); L-ON-CA (Leamington, ON, Canada); R-ON-CA (Ridgetown, ON, Canada); W-ON-CA (Windsor, ON, Canada); OS-BC-CA-curr (Osoyoos, BC, Canada - current climate); OS-BC-CA-2100 (Osoyoos, BC, Canada - year 2100 climate); OL-BC-CA-curr (Oliver, BC, Canada - current climate); OL-BC-CA-2100 (Oliver, BC, Canada - year 2100 climate); P-BC-CA-curr (Penticton, BC, Canada - current climate); P-BC-CA-2100 (Penticton, BC, Canada - year 2100 climate); S-BC-CA (Summerland, BC, Canada - current through year 2100 climate); OC-BC-CA (Okanagan Centre, BC, Canada - current through year 2100 climate); V-BC-CA-curr Vernon, BC, Canada - current climate); V-BC-CA-2100 (Vernon, BC, Canada - year 2100 climate); C-BC-CA (Cowichan Bay, BC, Canada); M-FR (Montpellier, France); BM-FR (Bordeaux/Medoc, France); S-IT (Sienna, Italy); L-ES (Logrono, Spain); F-DE (Freiburg, Germany); G-DE (Geisenheim, Germany); N-CA-US (Napa Valley, CA, USA); G-NY-US (Geneva, NY, USA); Y-WA-US (Yakima Valley, WA, USA); M-AU (Margaret River, Australia); H-NZ (Hawkes Bay, New Zealand); and B-NZ (Blenheim, New Zealand).

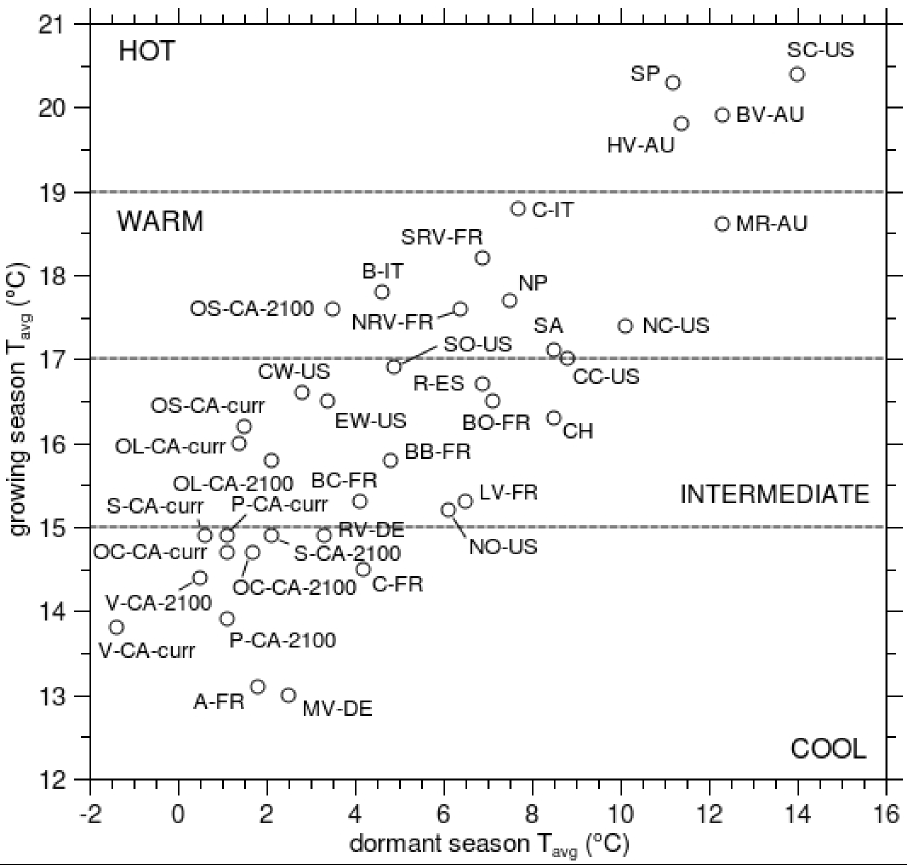

Figure 6: Comparison of current and projected year 2100 average growing and dormant season temperatures for the Okanagan Valley cities and sub-regions with current conditions at established wine regions worldwide. Adapted from Jones et al. (2005a) to include the current dataset. Growing season is April through October in the Northern Hemisphere and October through April in the Southern Hemisphere. Dormant season is November through March in the Northern Hemisphere and May through September in the Southern Hemisphere. Climate maturity groupings are based upon the average growing season temperatures and ability to ripen a variety. Site codings are as follows: MV-DE (Mosel Valley, Germany); A-FR (Alsace, France); V-CA-curr (Vernon, BC, Canada - current climate); P-CA-2100 (Penticton, BC, Canada - year 2100 climate); V-CA-2100 (Vernon, BC, Canada - year 2100 climate); C-FR (Champagne, France); OC-CA-curr (Okanagan Centre, BC, Canada - current climate); OC-CA-2100 (Okanagan Centre, BC, Canada - year 2100 climate); S-CA-curr (Summerland, BC, Canada - current climate); P-CA-curr (Penticton, BC, Canada - current climate); S-CA-2100 (Summerland, BC, Canada - year 2100 climate); RV-DE (Rhine Valley, Germany); NO-US (Northern Oregon, USA); LV-FR (Loire Valley, France); BC-FR (Burgundy-Cote, France); OL-CA-2100 (Oliver, BC, Canada - year 2100 climate); BB-FR (Burgundy-Beaujolais, France); OL-CA-curr (Oliver, BC, Canada - current climate); OS-CA-curr (Osoyoos, BC, Canada - current climate); CH (Chile); EW-US (Eastern Washington, USA); BO-FR (Bordeaux, France); CW-US (Central Washington, USA); R-ES (Rioja, Spain); SO-US (Southern Oregon, USA); CC-US (Coastal California, USA); SA (South Africa); NC-US (Northern California, USA); OS-CA-2100 (Osoyoos, BC, Canada - year 2100 climate); NRV-FR (Northern Rhone Valley, France); NP (Northern Portugal); B-IT (Barolo, Italy); SRV-FR (Southern Rhone Valley, France); MR-AU (Margaret River, Australia); C-IT (Chianti, Italy); HV-AU (Hunter Valley, Australia); BV-AU (Barossa Valley, Australia); SP (Southern Portugal); and SC-US (Southern California, USA).

For the late-season harvest times, DTRs are expected to decrease at Oliver, Penticton, and Okanagan Centre and not change significantly at Summerland or Vernon. Thus, while the early to mid-season ripening capacity of the region may improve due to climate changes, there appears to be a risk of the asymmetric late season increases in minimum daily temperatures lowering the DTR at some sites, possibly leading to difficulties in maintaining a balanced between sugar and sensory profiles.

For the central regions of the valley (Summerland and Okanagan Centre), there is expected to be little change in the growing season average temperatures and corresponding suitable wine grape varieties based on these climate maturity groupings (Figure 7). Representative suitable varieties at these sites between the present time and 2100 include Muller-Thurgau, Pinot Gris, Gewurztraminer, Pinot Noir, Chardonnay, Sauvignon Blanc, and Riesling. Summerland will also maintain its suitability for Semillon over this period. Warming expected during the growing season in the north (Vernon) will make this region suitable for Pinot Noir and Chardonnay by 2050, and maintain suitability for Muller-Thurgau, Pinot Gris, and Gewurztraminer over the next century. The growing season cooling expected at Penticton between the present and 2100 suggests this site will become too cool for Semillon by 2020, Sauvignon Blanc by 2050, and Chardonnay by 2100, but will remain suitable for Muller-Thurgau, Pinot Gris, and Gewurztraminer.

The intermediate climate maturity grouping at Oliver will stay approximately constant over the next century, making this locale suitable for varieties such as Pinot Noir, Chardonnay, Sauvignon Blanc, Riesling, Semillon, Cabernet Franc and Tempranillo. Because of the growing season warming expected at Osoyoos (from 16.2°C at present to 17.6°C by 2100), this site will likely become too warm for Pinot Noir by 2020, Chardonnay and Riesling after 2050, but will remain suitable for Sauvignon Blanc, Semillon, Cabernet Franc, Tempranillo, Merlot, and Syrah/Shiraz over all periods. Other varieties will become more suitable as the Osoyoos climate warms, including Dolcetto, Malbec, and Viognier after 2020, Cabernet Sauvignon, Sangiovese, and Grenache after 2050, and Carignane, Zinfandel, and Nebbiolo after 2100.

At present, most of the Okanagan Valley's wine grape production occurs near Osoyoos and Oliver, with a focus on Merlot and Chardonnay. Our findings suggest that should the industry want to continue increasing the production of Chardonnay, this variety will likely need to shift northwards in the valley over the next few decades. The projected warming at Osoyoos will likely make this area too warm for quality Chardonnay production. In contrast, the projected warming at the southern end of the valley will likely favor improved quality in Merlot production, consistent with the recent trends towards increased planting of this variety near Osoyoos and Oliver.

In addition to direct impacts on the vine, climate changes also alter the distribution of pests in a region. For example, Pierce's disease (from the bacterium Xylella fastidiosa) has been well established in California for over a century, but its range is highly temperature dependent. Where moisture and vegetation are abundant and average January temperatures are >4.5°C, the pest is a major problem. In the average January temperature range between 1.1°C and 4.5°C, Pierce's disease is common but controllable, and at <1.1°C, the disease is rare (Tate, 2001). Although there have been no previously reported occurrences of Pierces disease in the Okanagan, based on the expected rapid warming in average monthly temperatures during the winter months at all Okanagan sites except Penticton, the pest may become problematic in the region by the mid-21st century.

6. Conclusions

Despite a general absence of statistically significant trends in annual average temperatures at stations throughout the Okanagan Valley, historical changes in monthly mean and extreme temperatures show wide spatial and temporal heterogeneity. Isolated temporal trends at each station are offset by periods of the year with either no clear climate trend, or the opposite trend. As a result, site-specific approaches will be required to downscale and apply global climate model projections to this region with spatial resolutions on the order of several kilometers, given how the historical response to global climate change over the past century has not been uniform and consistent within the Okanagan Valley even between closely situated sub-regions.

Mean winter temperatures are increasing throughout the valley, and extreme minimum temperatures are also increasing during the winter at the central and northern sites which have historically presented the most risk of winter damage to grapevines. Only the most southern and northern sub-regions are expected to see significant changes in their heat unit accumulations during the growing season. Over the coming century, the southern end of the valley will likely move from Winkler heat unit region 1 to 2, changing its classification from a region similar to the Niagara Peninsula (Canada) and Geneva (New York, USA) closer to the current climates in Sienna (Italy), Napa Valley (California, USA), and the Margaret River region of Australia.

Growing season and dormant season average temperatures in the Okanagan Valley are expected to only change modestly by 2100, and will maintain the existing climate maturity groupings for ripening grape varieties at cool (Vernon, Okanagan Centre, Summerland, and Penticton) and intermediate (Oliver) for all sites except Osoyoos. The observed climate trendings at Osoyoos suggest it will transition from its existing intermediate climate maturity grouping to a warm grouping by about 2050. Although the early to mid-season ripening capacity of the region may improve due to climate changes, there appears to be a risk of the asymmetric late season increases in minimum daily temperatures lowering the daily temperature range at some sites, possibly leading to difficulties in maintaining a balanced between sugar and sensory profiles as wine grapes approach maturity.

The recent industry focus on increasing crop yields and regional market share from Vitis vinifera cv. Merlot and Chardonnay will be best sustained via shifting Chardonnay production north in the next few decades to avoid excessive heat units for this variety in the southern end of the valley where current total

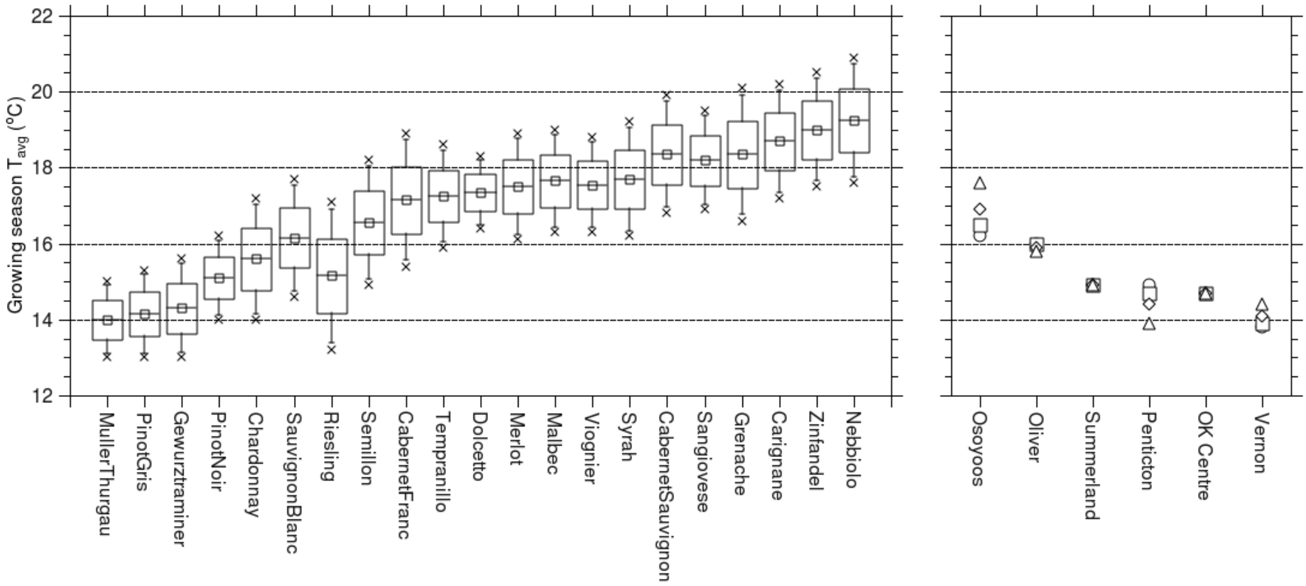

Figure 7: Wine grape climate maturity groupings based on average growing season temperatures and the estimated span of varietal ripening potential that occurs within and across groups for the Okanagan Valley sites under (open circles) the 1971-2000 climate averages period and their respective projected climates in (open squares) 2020, (open diamonds) 2050, and (open up triangles) 2100. Adapted from Jones et al. (2005a) to include the current dataset.

wine grape production is concentrated. The projected warming at the southern end of the valley should favor improved and increased Merlot production and allow more reliable and higher quality yields of warmer varieties such as Syrah/Shiraz, Cabernet Sauvignon, Sangiovese, and perhaps Zinfandel, among others. Increasing winter temperatures throughout the region are also expected to result in increased risk of pests such as Pierces disease.

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