A Climate Assessment for the Douro Wine Region: an examination of the Past, Present, and Future Climate Conditions for Wine Production

Gregory Jones
Department of Environmental Studies
South Oregon University
Ashland, Oregon 97520, USA

2012

With collaboration:
Fernando Alves
Technical Department
ADVID - Association for the Development of Viticulture in the Douro Region
Godim – Régua, Portugal

Additional Support Provided by:
Marco Morondo and Roberto Ferrise
Department of Agronomy and Land Management
University of Florence, Italy

João Santos and Aureliano Malheiro
Centre for the Research and Technology of Agro-Environmental and Biological Sciences
University of Trás-os-Montes and Alto Douro
Vila Real, Portugal
PUBLISHING DETAILS

A Climate Assessment for the Douro Wine Region: an examination of the Past, Present, and Future Climate Conditions for Wine Production

Publisher: ADVID – Associação para o Desenvolvimento da Viticultura Duriense
Author: Gregory Jones
Collaboration: Fernando Alves
Additional Support Provided by: Marco Moriondo, Roberto Ferrise, João Santos and Aureliano Malheiro
Year: 2012

Print run: 50 copies
Distribution: ADVID – Associação para o Desenvolvimento da Viticultura Duriense
Cover design: HL Design
Cover photography: © José Marafona | Dreamstime.com

Dep. Legal: 349676/12
## INDEX

Foreword ................................................................................................................................. 9

Executive Summary ............................................................................................................. 11

Introduction .................................................................................................................................................................. 13
  
  Weather and Climate Structure for Wine Quality and Production ............................................ 13
  Climate Suitability for Winegrape Cultivars ................................................................................. 14
  Climate Variability in Wine Regions ............................................................................................ 16
  Climate Change, Viticulture, and Wine ...................................................................................... 18
  The Douro Wine Region .................................................................................................................. 24

Data and Methods ................................................................................................................... 27
  Historic Climate Normals .............................................................................................................. 27
  Douro Wine Region Stations ......................................................................................................... 29
  Regional Circulation and Weather Regimes ............................................................................. 30
  Spatial Climate: Historic ............................................................................................................ 31
  Spatial Climate: Future Projections ............................................................................................. 32

Results and Discussion ........................................................................................................... 33
  Historic Climate Normals .............................................................................................................. 33
  Douro Wine Region Stations ......................................................................................................... 36
  Regional Circulation and Weather Regimes ............................................................................. 50
  Spatial Climate: Historic ............................................................................................................ 54
  Spatial Climate: Future Projections ............................................................................................. 67

Conclusions ............................................................................................................................... 81

Acknowledgements .................................................................................................................. 85

Literature Cited ......................................................................................................................... 85

Appendix ..................................................................................................................................................... 93
foreword
FOREWORD

ADVID - Associação para o Desenvolvimento da Viticultura Duriense (Association for the Development of Viticulture in the Douro Region) is a non-profit association founded in 1982 by a group of companies involved in the production and marketing of wines from the Douro Wine Region (DWR). ADVID aims to study, demonstrate and disseminate vine-growing and wine-making techniques appropriate to the specifics of the region so as to encourage the competitiveness of its wines in the domestic and international markets.

In 2008, the Portuguese government recognized the Douro Region Wine Cluster as a Collective Efficiency Strategy (COMPETE application). Furthermore, the Portuguese government named ADVID the management entity and driving force behind implementing the strategic goals. Under the Plan of Action that was presented, the impact of "Climate Change on Wine Production" was considered one of the Cluster’s Flagship Projects for its economic importance for the wine industry.

This Flagship Project seeks to respond to a number of ADVID’s concerns and activities, underpinned by a diagnosis report published in 2007 containing proposals that provided the basis of the terms of reference of this topic. The report was prepared and duly reflected by the Douro wine industry for an integrated, consequent and consistent approach to the search for solutions working in conjunction with Portuguese and international universities. The intention was to respond to a need determined by the business sector linked to the wine industry in the region, in order to understand the range of potential impacts and possible solutions for climate change scenarios at the regional and local scale.

To document and better understand the characteristics of climate in the Douro Region, ADVID relied on the collaboration of the prestigious American scientist Prof. Gregory Jones (Southern Oregon University)—a specialist in climate structure and suitability for viticulture, and how climate variability and change influence grapevine growth, wine production and quality—to carry out the project. The work consisted of analyzing, stabilizing and lending credibility to existing climate databases and providing new approaches for the interpretation of the regional climate, contributing to its better understanding, a condition essential for the projection of future climate scenarios.

Currently, this Flagship Project is founded on three mutually complementary measures: evaluating the climate of the Douro Region – analysis of the climatic conditions of the past, present and future for wine production; definition of more-effective adaptation strategies; and prediction of the consequences for the quality of the wine. These measures, organized and funded by the Douro Region Wine Cluster, involve key players of the Cluster, particularly in the implementation of the “ClimeVineSafe” projects, directed at short-term measures to mitigate the effect of climate change and also to support the “Modeling the evolution of wine quality in the DWR” project.

Most importantly, the Cluster’s Action Plan has numerous Flagship Projects that are focused on developing strategies aimed at reducing the vulnerability of the wine sector by increasing adaptive capacity. To achieve these goals numerous convergent adaption activities are being implemented in the region, including the study of more efficient use of water by the plants, creation of vineyard mapping (zoning) tools at regional and property scales, encouragement of integrated sustainability of viticulture production, rationalization of the cultivation of hillside vineyards, the study of the behavior of different varieties and rootstocks, and, last but not least, preservation of the genetic biodiversity of the viticultural heritage originating in Portugal.

The Board of ADVID, July 2012
EXECUTIVE SUMMARY

It is evident from the history of growing wine grapes worldwide that they are a climatically sensitive crop whereby quality production is achieved across a fairly narrow geographic range. In addition, wine grapes are grown largely in mid-latitude regions that are prone to high climatic variability that drive relatively large vintage differences in quality and productivity. Furthermore, historic trends and future projections in climate parameters for wine regions have shown that changes have occurred and are likely to continue in the future. This research provides an assessment of numerous aspects of climate in one of the world’s most historic wine regions – the Douro Valley of Portugal – with the goal of documenting and examining the historic, current, and future climatic conditions of the region.

While there is a general understanding of the climate of the Douro Wine Region, a comprehensive, high quality, long term station data set for the region has been limited over both space and time. Therefore this climate assessment utilizes the best available data that are of three main types; 1) historic climate normals, 2) weather stations within the Douro Wine Region, and 3) spatial climate data for observed and future projections of climate in the region. Furthermore, the assessment includes an examination of the relationships between the large-scale regional circulation controls and climate variability in the Douro Wine Region.

Updated spatial climate data for 1950-2000 reveals similar climate conditions to the 1931-1960 climate normal over the Douro Wine Region. For growing season average temperatures the region averages 17.8°C and is spatially classed as 65% a Warm climate type, 24% an Intermediate climate type, and nearly 10% a Hot climate type on the GST index. Observed trends in the region were examined both for individual stations and spatially over the entire region. Differences between the 1931-1960 and 1950-2000 data reveal that the later period was warmer by an average of 0.9°C for annual temperatures over the region with the growing season and winter being 1.2°C and 0.4°C warmer, respectively. Examining three long-term stations in the region shows greater warming in minimum compared to maximum temperatures with rates ranging from 1.2°C to 3.6°C during the time period. Results from an analysis of extreme events for the three stations reveals significant changes for both maximum and minimum temperature extremes, with overall warmer nights, warmer days, a general decline in the diurnal temperature range, a higher number heat stress events, some evidence for longer warm spells, and a clear reduction in cold spell durations.

Future climate conditions in the Douro Wine Region were examined using IPCC SRES projections from the HADCM3 model for three greenhouse gas emission scenarios (B2, A1B, and A2) and three future time slices (2020, 2050, and 2080). Average annual temperatures are projected to warm for all emission scenarios and for each time slice. Projections range from 0.5-1.4°C by 2020, 1.4-3.3°C by 2050, and 2.1-5.1°C by 2080. For GST the region is projected to change from a largely Warm climate suitability (65% of the area) in 1950-2000 to increasing area in Hot climate suitability by 2020 (43%) and even Very Hot climate suitability by 2050 (36%). By 2080 the spatial pattern of GST is projected to have 19% of the landscape becoming Too Hot, 54% Very Hot, 25% Hot, and less than 3% Cool, Intermediate or Warm. The pattern of the changes shows warming increasing most rapidly along the main sections of the river valley, then across the Douro Superior,
and by 2080 up in elevation across much of the region. Precipitation changes for the Douro Wine Region are projected to be fairly low to moderately high depending on the scenario and time period. For annual average precipitation the projected changes are near zero to declines as much as 21.6% in the A1B scenario by 2080. The majority of the changes in precipitation are projected to occur during the growing season where decreases from 10-42% are projected by 2080. The future projections for the climate in the region from this assessment are in general agreement with other research for Europe, the Iberian Peninsula, and Portugal.

Wine regions have developed over time to best match their regional environmental conditions, allowing for generally consistent ripening of the varieties that were found to be best suited to the conditions. While the overall structure of climate in regions drives the suitability and climate variability strongly influences vintage to vintage production and quality variations, the projected rate and magnitude of future climate change will likely bring about numerous potential impacts for the wine industry. However, the Douro Wine Region is rich in landscape and plant characteristics that may help mitigate the deleterious effects of climate change. First of all the region’s geomorphology and relief contribute to multiple meso- and micro-climate situations, which may provide spatial adaptation strategies. Furthermore, the landscape provides growers with choices in cultivation techniques to manage the ecophysiological dimension of the environment. One characteristic that will be very important is how growers can adapt the landscape and vineyards to help balance global photosynthetic activity of the grapevine and water loss by transpiration. A highly significant factor in the management of changes that may be required due to climate change is the genetic heritage of the plant material, particularly the varieties and their oenological performance. Although the general characteristics and aptitude for drought resistance of rootstocks have been studied, it is above all the vast heritage of varieties grown in the Douro Wine Region that will provide some of the most useful tools for wine growers, both through the different thermal requirements of varieties and the elasticity of their phenological behavior and their different physiological responses. By following sustainable approaches and being innovative across the entire production system the Douro Wine Region will undoubtedly reduce its vulnerability and increase its adaptive capacity in the face of a changing climate.
INTRODUCTION

Climate is a pervasive factor in the success of all agricultural systems, influencing whether a crop is suitable to a given region, largely controlling crop production and quality, and ultimately driving economic sustainability. Climate’s influence on agribusiness is never more evident than with viticulture and wine production where overall it is arguably the most critical aspect in ripening fruit to optimum characteristics to produce a given wine style. Any assessment of climate for wine production must examine a multitude of factors that operate over many temporal and spatial scales. Namely climate influences occur at the macroscale (synoptic climate) to the mesoscale (regional climate) to the toposcale (site climate) to the microscale (vine row and canopy climate). In addition, climate influences come from both broad structural conditions and singular weather events manifested through many temperature, precipitation, and moisture parameters. To understand climate’s role in growing winegrapes and wine production one must consider 1) the weather and climate structure necessary for optimum quality and production characteristics, 2) the climate suitability to different winegrape cultivars, 3) the climate’s variability in wine producing regions, and 4) the influence of climate change on the structure, suitability, and variability of climate.

WEATHER AND CLIMATE STRUCTURE FOR WINE QUALITY AND PRODUCTION

Worldwide, the average climatic conditions of wine regions determine to a large degree the grape cultivars that can be grown there, while wine production and quality are chiefly influenced by site-specific factors, husbandry decisions, and short-term climate variability (Jones and Hellman, 2003). Individual weather/climate factors affecting grape growth, production, and wine quality include solar radiation, average temperatures, temperature extremes (including winter freezes and spring and fall frosts and summer heat stress), heat accumulation, wind, and precipitation, humidity, and soil water balance characteristics. While numerous individual and interactive effects between these climate factors can and do occur, the most common characterization of mesoclimates in viticultural areas is commonly done as integrated mathematical expressions of temperature that permit the calculation of bioclimatic indices (Fregoni, 2003; Jones et al. 2010). These indices are typically summed over a period of time important to the vine’s growth and production (usually the 6 or 7 months of the vine’s growth and development cycle). The relationships between heat accumulation, vine growth, and maturation potential was first postulated by A.P. de Candolle in the nineteenth century where he observed that vine growth started when the mean daily temperature reached 10°C. As the various indices were created they were each typically related to the typicity of the wine that can be produced with classes associated with cool climate cultivar wines to warm climate cultivar wines to fortified wines and table grapes. Various forms of these bioclimatic indices have been created and include the degree-day formulation of the Winkler Index (Amerine and Winkler, 1944), different forms of a heliothermal index (Branas, 1974; and Huglin, 1978), the quality index of Fregoni (2003), a
latitude-temperature index (Jackson and Cherry 1988; Kenny and Shao, 1992), and a growing season average temperature index (Jones, 2006) with each helping to define the suitability of a region to the planting of certain winegrape cultivars.

Given its importance to vine balance, fruit quality and yield, and disease pressure, understanding water relationships in any wine region is very important. As such, these factors should be assessed from many viewpoints: 1) ambient atmospheric moisture, 2) local rainfall frequency and timing, and 3) soil water holding capacity. In addition, each of these aspects of water availability can be evaluated in terms of a water balance or budget. While ample precipitation during the early vegetative stage is beneficial (Jones and Davis, 2000a, 2000b), during bloom it can reduce or retard flowering, during berry growth it can enhance the likelihood of fungal diseases, and during maturation it can further fungus maladies, yellow and dilute the berries, which reduces the sugar and flavour levels, and severely limit the yield and quality (Mullins et al. 1992). Examination of the world's viticulture regions suggests that there is no upper limit on the amount of precipitation needed for optimum grapevine growth and production (Gladstones, 1992). On the other hand, grapevine viability seems to be limited in some hot climates by rainfall amounts less than 500 mm, although this can be overcome by regular irrigation, if allowed. Extreme meteorological events, such as thunderstorms and hail, while generally rare in most viticultural regions, are extremely detrimental to the crop. Both events can severely damage the leaves, tendrils, and berries during growth and if they occur during maturation can split the grapes, causing oxidation, premature fermentation, and a severe reduction in volume and quality of the yield.

As an integration of many climate parameters, a soil water balance takes into account seasonal variations in temperature, precipitation, and available soil moisture to give an estimation of water requirements (either natural or via irrigation). A water balance essentially defines the “water need” by plants and the atmosphere in any region. In most grape growing regions there is a period of soil water surplus from late fall through late spring, followed by a period of draw-down of soil moisture through evaporation (by the atmosphere) and transpiration (by plants) during the summer and through the early fall when precipitation begins replenishing the soil. Adequate soil moisture recharge during the spring can drive vine growth and result in more effective bloom and berry set (Williams, 2000). While some soil moisture during the summer growth period can reduce heat stress, too high soil moisture can drive too much vegetative growth and lead to inadequate ripening (Matthews and Anderson, 1988) along with delayed leaf fall putting the vines at risk of late fall frost/freeze events.

**CLIMATE SUITABILITY FOR WINEGRAPE CULTIVARS**

Winegrape cultivar suitability to a given region is controlled by the baseline climate. Historically there have been numerous temperature-based metrics (e.g., degree-days, mean temperature of the warmest month, average growing season temperatures, etc.) that have been used for establishing optimum climates for the range of winegrape cultivars (Gladstones, 1992). At the global scale the general bounds on climate suitability for viticulture are found between 12-22°C for the growing season in each hemisphere (Gladstones, 2004; Jones, 2007; Figure 1). As
seen in Figure 1 the 12-22°C climate bounds depict a largely mid-latitude suitability for winegrape production, however many sub-tropical to tropical areas at higher elevations also fall within these climate zones. Furthermore, any general depiction of average temperatures will also include large areas that have not been typically associated with winegrape production. This is evident in Figure 1 where large areas of eastern Europe, western Asia, China, the mid-western and eastern United States, south-eastern Argentina, south-eastern South Africa, and southern Australia fall within the 12-22°C thresholds. While many of these regions may have the growing season temperatures conducive to growing winegrapes, other limiting factors such as winter minimum temperatures, spring and fall frosts, short growing seasons, and water availability would limit much of the areas mapped to the average conditions.

Figure 1: Global wine regions and 12-22°C growing season temperature zones (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, Geographic Indicators in Australia and Brazil, and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina, and New Zealand). (Jones et al. 2012).

Further refining the climate suitability for many of the world’s most recognizable cultivars, Jones (2006) shows that high quality wine production is limited to 13-21°C average growing season temperatures (Figure 2). The climate-maturity zoning in Figure 2 was developed based upon both climate and plant growth for many cultivars grown in cool to hot regions throughout the world’s benchmark areas for those winegrapes. While many of these cultivars are grown and produce wines outside of their individual bounds depicted in Figure 2, these are more bulk wine (high yielding) for the lower end market and do not typically attain the typicity or quality for those same cultivars in their ideal climate. Furthermore, growing season average temperatures below 13°C are typically limited to hybrids or very early ripening cultivars that do not necessarily have large-scale commercial appeal. At the upper limits of climate, some production can also be found with growing season average temperatures greater than 21°C, although it is mostly limited to fortified wines, table grapes and raisons. Recent research has mapped these climate limits for Europe (Jones et al. 2009), Australia (Hall and Jones, 2010) and the western United States (Jones et al. 2010) detailing the within region climate suitability across the cool, intermediate, warm, and
hot climate types. This work helps depict the true wine region spatial climate structure, instead of the common practice of using stations, which clearly do not properly characterize the climates experienced in the actual vineyard areas.

**Grapevine Climate/Maturity Groupings**

<table>
<thead>
<tr>
<th>Average Growing Season Temperature (NH Apr-Oct; SH Oct-Apr)</th>
<th>Muller-Thurgau</th>
<th>Pinot Gris</th>
<th>Gewurztraminer</th>
</tr>
</thead>
<tbody>
<tr>
<td>13-15°C</td>
<td>Riesling</td>
<td>Pinot Noir</td>
<td>Sauvignon Blanc</td>
</tr>
<tr>
<td>15-17°C</td>
<td></td>
<td>Chardonnay</td>
<td></td>
</tr>
<tr>
<td>17-19°C</td>
<td>Cabernet Franc</td>
<td>Semillon</td>
<td></td>
</tr>
<tr>
<td>19-21°C</td>
<td>Tempranillo</td>
<td>Dolcetto</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Merlot</td>
<td>Malbec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Viosnignier</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Syrah</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cabernet Sauvignon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sangiovese</td>
<td>Table grapes*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grenache</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carignane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zinfandel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nebbiolo</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Raisins*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2**: Climate-maturity groupings based on relationships between phyloenergetic requirements and growing season average temperatures for high to premium quality wine production in the world's benchmark regions for many of the world's most common cultivars. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than +/- 0.2-0.5°C are highly unlikely (Jones, 2006).

**CLIMATE VARIABILITY IN WINE REGIONS**

While the average climate structure in a region determines the broad suitability of winegrape cultivars, climate variability influences issues of production and quality risk associated with how equitable the climate is year in year out. Climate variability in wine regions influences grape and wine production through cold temperature extremes during the winter in some regions, frost frequency and severity during the spring and fall, high temperature events during the summer, extreme rain or hail events, and broad spatial and temporal drought conditions. Climate variability mechanisms that influence wine regions are tied to large scale atmospheric and oceanic interactions that operate at different spatial and temporal scales (Figure 3). The most prominent of these is the large scale Pacific sector El Niño-Southern Oscillation (ENSO) (Glantz, 2001), which has broad influences on wine region climates from North America, Australia and
New Zealand, South Africa, South America, and Europe (Jones et al. 2012). However, the effects of ENSO on wine region climate variability varies tremendously in magnitude and is of opposite sign depending on the location of the wine region and is often coupled with other more influential regional mechanisms (Jones and Goodrich, 2008).

Figure 3: Global wine regions, climate variability mechanisms, and their areas of known influences as described in the text. ENSO – El Niño Southern Oscillation, PDO – Pacific Decadal Oscillation, NAO – North Atlantic Oscillation, IOD – Indian Ocean Dipole, AO – Arctic Oscillation, AAO – Antarctic Oscillation, SST – Sea Surface Temperatures. The wine regions are as described in Figure 1. (Jones et al. 2012).

For Europe the dominant climate variability mechanism is the North Atlantic Oscillation (NAO; Figure 3), which has a large climatic influence on the North Atlantic Ocean and surrounding land masses (Hurrell, 2003). The NAO is associated with changes in the surface westerlies across the North Atlantic due to a large scale seesaw in atmospheric mass between the subtropical high and the polar low. The corresponding index that numerically characterizes the NAO varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years. The positive phase of the NAO index exhibits a stronger than usual subtropical high pressure center (Azores high) and a deeper than normal Icelandic low. The increased pressure difference over the North Atlantic results in more and stronger winter storms crossing the Atlantic Ocean on a more northerly track. For Europe the positive phase results in warmer and wet winters across northern areas and warmer and drier conditions across the Mediterranean basin. In addition, northern Canada and Greenland experience cold and dry winters, while the eastern US experiences mild and wet winter conditions. The negative phase of the NAO index exhibits a weak subtropical high and a weak Icelandic low and the reduced pressure gradient results in fewer and weaker winter storms crossing on a more west-east pathway. The result is typically moist air advection and wetter conditions over the Mediterranean and cold, dry conditions in northern Europe. The eastern US east coast experiences more cold air outbreaks and hence snowy weather conditions, while Greenland, however, will have milder winter temperatures.

Relationships between the NAO and winegrape production in Europe are mixed with most showing little to no correlation (Jones, 1997). This is likely due to the fact that the NAO is largely a
wintertime mechanism and its effects diminish over the growing season. However, there is some
evidence that the positive NAO phase brings drier growing seasons to the Iberian Peninsula and
the Mediterranean that result in lower quality and yield (Esteves and Manso-Orgaz, 2001; Grifoni
et al. 2006). For the northern vineyards of Europe either phase can be problematic, whereby a
positive NAO brings wetter conditions and greater disease pressure and the negative phase brings
greater frost pressure during the spring. In addition, Souriau and Yiou (2001), using historical
grape harvest dates from north-eastern France and Switzerland, showed significant correlations
between harvest dates and the NAO and suggested using the record “as an interesting proxy” to
reconstruct the NAO back in time. Although ENSO plays a significant role in determining the
interannual variability of climate in the lower latitudes, its influence on European climate is weak
(Mathieu et al. 2004) or hard to differentiate from the effects of the NAO (Rodó and Comín, 2000).

While the impacts of climate change on the average climate of wine regions worldwide is
evident (see below), arguably just as important is how that climate varies. Increases in climate
variability in a given region would bring about greater risk associated with climate extremes,
which in turn would strain the economic viability of wine production in any region. Both
observations and models indicate that climates experience changes in both the mean and the
variability of temperatures in wine regions and elsewhere (Jones, 2007). For example, if the
change response of a warming climate was only in the mean, then there would be less cold
weather and more hot and record hot weather. On the other hand, increases in the temperature
variance alone would result in more cold and hot weather and record conditions. However,
evidence points to increases in both the mean and variance which would bring about less change
for cold weather events and much more hot weather and record hot weather (IPCC, 2007). For
example, Schär et al (2004) demonstrate that the European summer climate structure is expected
to experience a pronounced increase in year-to-year variability in response to greenhouse-gas
forcing. While heat waves are caused by entrenched high pressure and blocking patterns, such an
increase in variability might be able to explain the unusual European summer 2003, and would
strongly affect the incidence of heat waves and droughts in the future. Evidence of changing
climate variability in wine regions was also found by Jones (2005) and Jones et al (2005a) where
the coefficient of variability in the growing season climates throughout the western US and many
other wine regions globally has increased over the last 50 years. Jones et al (2005a) also found
that model projections through to 2050 show a continued increase in the coefficient of variability
of growing season temperatures in 20 of 27 wine regions globally.

**Climate Change, Viticulture, and Wine**

From the discussion above on the climate structure, suitability, and variability associated
with regional to global wine production it is clear that viticultural regions are located in relatively
narrow geographical and climatic ranges. In addition, winegrapes have relatively large cultivar
differences in climate suitability further limiting some winegrapes to even smaller areas that are
appropriate for their cultivation. These narrow ‘niches’ for optimum quality and production put
the cultivation of winegrapes at greater risk from both short-term climate variability and long-
term climate changes than more other more broad acre crops (Jones, 2007). In general, the
overall wine style that a region produces is a result of the baseline climate, while climate variability determines vintage quality differences. Climatic changes, which influence both variability and average conditions, therefore have the potential to bring about changes in wine styles (Jones, 2007). Our understanding of climate change and the potential impacts on viticulture and wine production has become increasingly important as the earth system undergoes natural cycles and fluctuations and changing levels of greenhouse gases and alterations in Earth surface characteristics bring about changes in the Earth’s radiation budget, atmospheric circulation, and hydrologic cycle (IPCC, 2007). Observed warming trends over the last hundred years have been found to be asymmetric with respect to seasonal and diurnal cycles with greatest warming occurring during the winter and spring and at night (Karl et al. 1993; Easterling et al. 2000). The observed trends in temperatures have been related to agricultural production viability by impacting winter hardening potential, frost occurrence, and growing season lengths (Carter et al. 1991; Menzel and Fabian, 1999; Easterling et al. 2000; Nemani et al. 2001; Moonen et al. 2002; Jones, 2005).

To place viticulture and wine production in the context of climate suitability and the potential impacts from climate change, Figure 2 provides the framework for examining today’s climate-maturity ripening potential for premium quality wine cultivars grown in cool, intermediate, warm, and hot climates (Jones, 2006). For example, Cabernet Sauvignon is grown in regions that span from intermediate to hot climates with growing seasons that range from roughly 16.8-20.2°C (e.g., Bordeaux or Napa). For cooler climate cultivars such as Pinot Noir, they are typically grown in regions that span from cool to lower intermediate climates with growing seasons that range from roughly 14.0-16.0°C (e.g., Northern Oregon or Burgundy). From the general bounds that cool to hot climate suitability places on high quality wine production, it is clear that the impacts of climate change are not likely to be uniform across all cultivars and regions, but are more likely to be related to climatic thresholds whereby any continued warming would push a region outside the ability to produce quality wine with existing cultivars. For example, if a region has an average growing season temperature of 15°C and the climate warms by 1°C, then that region is climatically more conducive to ripening some cultivars, while potentially less for others. If the magnitude of the warming is 2°C or larger, then a region may potentially shift into another climate maturity type (e.g., from intermediate to warm). While the range of potential cultivars that a region can ripen will expand in many cases, if a region is a hot climate maturity type and warms beyond what is considered viable, then grape growing becomes challenging and maybe even impossible. Furthermore, observations and modelling have shown that changes climate have not and will not likely just be manifested in changes in the mean, but also in the variance where there are likely to be more extreme heat occurrences, but still swings to extremely cold conditions (IPCC, 2007). Therefore, even if average climate structure gets better in some regions, variability will still be very evident and possibly even more limiting than what is observed today.

History has shown that winegrape growing regions developed when the climate was most conducive and that shifts in viable wine-producing regions have occurred in the past due to changes in climate, making production more difficult or easier (Le Roy Ladurie, 1971; Pfister, 1988;
Gladstones, 1992). In Europe, records of dates of harvest and yield have been kept for nearly a thousand years (Penning-Roswell, 1989; Le Roy Ladurie, 1971), revealing periods with more beneficial growing season temperatures, greater productivity, and arguably better quality in some regions. Other evidence has shown that vineyards were planted as far north as the coastal zones of the Baltic Sea and southern England during the medieval “Little Optimum” period (roughly 900-1300 AD) when temperatures were up to 1°C warmer (Gladstones, 1992). During the High Middle Ages (12th and 13th Centuries) harvesting occurred in early September as compared to early to late October during much of the 20th Century (Pfister, 1988; Gladstones, 1992). However during the 14th Century dramatic temperature declines lead to the “Little Ice Age” (extending into the late 19th century), which resulted in most of the northern vineyards dying out and growing seasons so short that harvesting grapes in much of the rest of Europe was difficult. In addition, research has used contemporary grape harvest dates from Burgundy to reconstruct spring-summer temperatures from 1370 to 2003 and, while the results indicate that temperatures as high as those reached in the warm 1990s have occurred several times in the region since 1370, the extremely warm summer of 2003 appears to have been higher than in any other year since 1370 (Chuine et al. 2004).

More recent research of the impacts of climate change on wine quality by Jones et al. (2005a) analyzed growing season temperatures in 27 of arguably the best wine producing regions in the world and found that average growing season temperatures warmed 1.3°C over the last 50 years. However, the warming was not uniform across all regions with greater magnitudes in the western U.S. and Europe and less warming in Chile, South Africa, and Australia. The greatest warming was seen in the Iberian Peninsula, Southern France, and parts of Washington and California with warming greater than 2.5°C. For example, Jones et al. (2005a) found that the observed warming during 1950-1999 for the Burgundy, Rhine Valley, Barolo, and Bordeaux regions ranged from 0.7-1.8°C. More regionally specific and temporally resolved analyses concur with the global observations of wine region temperature trends (Jones and Davis, 2000a,b; Jones et al. 2005b; Jones, 2007; Webb et al. 2008; Hall and Jones, 2009; Ramos et al. 2008). Overall, during the last 30-70 years many of the world’s wine regions have experienced a decline in frost frequency, shifts in the timing of frosts, and warmer growing seasons with greater heat accumulation. In North America research has shown significant changes in growing season climates, especially in the western U.S. For example, during 1948-2002 in the main grape growing regions of California, Oregon, and Washington, growing seasons warmed by 0.9°C, driven mostly by changes in minimum temperatures, with greater heat accumulation, a decline in frost frequency that is most significant in the dormant period and spring, earlier last spring frosts, later first fall frosts, and longer frost-free periods (Jones, 2005). Temporal changes for the Napa Valley since 1930 (Jones and Goodrich, 2008) show that heat accumulation is over 350 units higher (degree-days in °C units) and has been the result of significant warming at night where the minimum temperatures have climbed 3.0°C while daytime temperatures have not changed significantly. Precipitation amounts and timing are highly variable in the western U.S., being more tied to larger scale climate variability mechanisms such as El Niño or the Pacific Decadal Oscillation than structural trends (Jones and Goodrich, 2008). Recent research for Europe shows similar results as those found in North America detailed above (Jones et al. 2005b). An examination of
climate and phenology trends over the last 30-50 years for eleven locations across a range of climate types in Europe (cool to warm) and for 16 cultivars shows that warming occurred across most seasons, but is strongest in the spring and summer. Growing seasons in the wine regions studied warmed by 1.7°C on average, with most of the observed warming coming at night. Heat accumulation increased as well with degree days rising by 250-300 units (°C units) while precipitation frequency and amounts did not change significantly. In Spain, Jones et al. (2005b) found that growing seasons warmed on average by 0.8-1.2°C for the Galicia and Valladolid regions with the warming being much more significant at night (minimum temperatures increasing 1.1-2.1°C) than during the day (not significant). Heat accumulation, either measured by the Huglin Index or Winkler Index (see below), increased inland but did not changed significantly in the more coastal region of Galicia. Ramos et al. (2008) also found overall growing season warming in the Penedès, Priorat, and Segrià wine regions of northeast Spain of 1.0-2.2°C. The work also revealed the potential for added moisture stress where declining precipitation during the spring and summer, combined with the observed warming results in an increased water demand of 6-14% in an already semi-arid region. Along with changes in many temperature parameters in the northeast of Spain there are concomitant changes in vine and wine parameters, including earlier phenological events, higher wine quality with higher ripening diurnal temperature ranges, and reduced production in the warmest vintages (Ramos et al. 2008). Furthermore, for Europe in general, grapevine phenological timing showed strong relationships with the observed warming with trends ranging 6-25 days earlier over numerous cultivars and locations (Jones et al. 2005b).

Projections of future climates are produced through models based upon knowledge of how the climate system works and are used to examine how the environment, in this case viticulture and wine production, are likely to respond to these changes. These climate models are complex 3-D, mathematical representations of our Earth/Atmosphere system that represent spatial and temporal analyses of the laws of energy, mass, moisture, and momentum transfer in the atmosphere and between the atmosphere and the surface of the Earth. Additionally, climate models are based upon IPCC emissions scenarios (IPCC, 2007) which reflect estimates of how humans will emit CO₂ in the future. The many models in use today, combined with the fact that they are modelling a non-linear system and using different emission scenarios, result in a range of potential changes in temperature and precipitation for the planet (IPCC, 2007). Work over the last three decades using model projections show that the observed warming trends in wine regions worldwide are predicted to continue. From one of the early analyses of the impacts climate change on viticulture, it was suggested that growing seasons in Europe should lengthen and that wine quality in Champagne and Bordeaux should increase (Lough et al. 1983). These results have largely been proven correct (Jones et al. 2005a). Furthermore, spatial modelling 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 more stable in terms of consistent ripening climates and/or viable once again (Kenny and Harrison, 1992; Butterfield et al. 2000). Examining specific cultivars (Sangiovese and Cabernet Sauvignon), Bindi et al. (1996) and Bindi and Fibbi (2000) found that climate change in Italy should lead to shorter growth intervals but increases in yield variability. 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 CO2 might have on both vine growth and grape quality and even the texture of oak wood used for making wine barrels (Tate, 2001; Renner, 1989; Schultz, 2000; McInnes et al. 2003).

As discussed in the climate suitability section previously, the broadest scale of global suitability for viticulture shows that optimal zones are found between either the mean annual 10-20°C isotherms (de Blij, 1983; Johnson, 1985) or the growing season 12-22°C isotherms (Gladstones, 2004; Jones, 2006). To examine these global latitudinal bounds of viticulture suitability due to climate, Jones (2007) used output from the Community Climate System Model (CCSM) on a 1.4°x1.4° latitude/longitude resolution and B1 (moderate), A1B (mid-range), and A2 (high) emission scenarios to depict the 12-22°C isotherms shifts for three time periods 2000, 2050, and 2100. Changes from the 2000 base period show both shifts in the amount of area suitable for viticulture and a general latitudinal shift poleward. By 2050, the 12°C and 22°C isotherms shift 150-300 km poleward in both hemispheres depending on the emission scenario (not shown). By 2100, the isotherms shift an additional 125-250 km poleward (see Figure 4 for the mid-range A1B scenario). The shifts are marginally greater on the poleward fringe compared to those on the equatorial fringe in both hemispheres. However, the relative area of land mass that falls within the isotherms across the continents expands slightly in the Northern Hemisphere while contracting in the Southern Hemisphere due to land mass differences (Figure 4). Similar shifting is seen by 2100 for all emission scenarios (not shown).

Figure 4: Changes in general climate zones for viticulture from 2000 to 2100. Climate data is derived from the National Center for Atmospheric Research’s Community Climate System Model (CCSM) for observed (2000) and an A1B (mid-range scenario). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, Geographic Indicators in Australia and Brazil, and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina, and New Zealand). The general climate zones are given by the 12-22°C growing season (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere) average temperatures.
Using Hadley Centre climate model (HadCM3) output and an A2 emission scenario to 2049 for 27 of the world’s top wine producing regions, Jones et al. (2005a) compared the average climates of two periods, 1950-1999 and 2000-2049. The results suggest that mean growing season temperatures could warm by an average 1.3°C over the wine regions studied with notable wine regions such as Burgundy (Beaujolais), Rhine Valley, Barolo, and Bordeaux potentially could see warming ranging from 0.9-1.4°C. Also, the projected changes are greater for the Northern Hemisphere (1.3°C) than the Southern Hemisphere (0.9°C). Examining the rate of change projected for the 2000-2049 period only reveals significant changes in each wine region with trends ranging from 0.2°C to 0.6°C per decade. Overall trends during the 2000-2049 period average 2°C across all regions with the smallest warming in South Africa (0.9°C/50 years) and greatest warming in Portugal (2.9°C/50 years). In addition, Jones et al. (2005a) showed that many of the wine regions may be at or near their optimum growing season temperature for high quality wine production and further increases, as predicted by the differences between the means of the 1950-1999 and 2000-2049 periods, will place some regions outside their theoretical optimum growing season climate. The magnitude of these mean growing season changes indicate potential shifts in climate maturity types for many regions at or near a given threshold of ripening potential for cultivars currently grown in that region.

For the United States as a whole, White et al. (2006) used a high-resolution (25 km) regional climate model forced by an IPCC A2 greenhouse gas emission scenario and estimated that potential premium winegrape production area in the conterminous United States could decline by up to 81% by the late 21st century. The research found that increases in heat accumulation will likely shift wine production to warmer climate cultivars and/or lower-quality wines. Additionally the models show that while frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) in the growing season have the potential to severely challenge or completely eliminate winegrape production in many areas of the United States. Furthermore, grape and wine production will likely be restricted to a narrow West Coast region and the Northwest and Northeast, areas where excess moisture is already problematic (White et al. 2006).

Other regional work in Europe (Kenny and Harrison, 1992; Butterfield et al. 2000; Stock et al. 2005), Australia (McInnes et al. 2003; Webb et al. 2005; Hall and Jones, 2009), and South Africa (Carter, 2006) has examined climate change through different modelling approaches but has come up with similar results as discussed above. Examining changes in the Huglin Index of suitability for viticulture in Europe, Stock (2005) shows increases of 100-600 units that result in broad latitudinal shifts with new areas on the northern fringes becoming viable, changes in varietal suitability in existing regions, and southern regions becoming so hot that overall suitability is challenged. For Spain, deCastro et al. (2005) examined different emission scenarios to place lower and upper bounds on temperature and precipitation changes and found trends of 0.4-0.7°C per decade with summer warming greater than in the winter. Overall the changes result in warming by 2100 of between 5-7°C inland and 3-5°C along the coast. Concomitant with these temperature projections, deCastro et al. (2005) show much drier springs and summers and lower annual rainfall which is less spatially homogeneous across Spain than is temperature.
Furthermore, to examine grapevine responses to climate change, Lebon (2002) used model output to show that the start of Syrah ripening (véraison) in Southern France would shift from the second week of August today to the third week of July with a 2°C warming and to the first week of July with a 4°C warming. Additionally the research found that significant warming during maturation and especially at night would disrupt flavor and color development and ultimately the wine’s typicity.

In Australia, Webb et al. (2005) analyzed climate change scenarios for viticulture showing that temperatures by 2070 are projected to warm in Australia by 1.0-6.0°C increasing the number of hot days and decreasing frost risk, while precipitation changes are more variable but result in greater growing season stress on irrigation. The changes projected for Australia has tied future temperature regimes to reduced wine quality with southerly and coastal shifts in production regions being the most likely alternative to maintaining viability. Hall and Jones (2009) modelling growing season climates for Australia finding that eight of the 61 recognized wine regions in the country would be warmer than the known growing season temperature threshold for suitability by 2030, 12 by 2050, and 21 by 2070 without further adaptive measures. In South Africa, regional projections of rising temperatures and decreased precipitation have been shown to put additional pressure on both the phenological development of the vines and on the necessary water resources for irrigation and production (Carter, 2006). The research implies that the practice of winemaking in South Africa is likely to become riskier and more expensive with the most likely effects being shifts in management practices to accommodate an increasingly limited water supply. The author notes that the situation will likely exacerbate other economic issues such as increases in the price of wine, a reduction in the number of wine growers, and need for implementation of expensive and yet unknown adaptive strategies (Carter, 2006). Together these studies, and those detailed previously, indicate that the challenges facing the wine industry include more rapid phenological development, changes in suitable locations for some cultivars, a reduction in the optimum harvest window for high quality wines, and greater management of already scarce water resources.

**The Douro Wine Region**

Portugal is the 10th largest wine producing country in the world (FAO, 2010), growing grapes in over 30 different denominations of origin wine regions. Arguably the most known of these wine regions is the Douro Valley (Figure 5) where the physical and cultural landscapes of the Douro Valley are etched by nearly 2,000 years of wine production. Being the oldest demarcated and controlled winemaking region in the world dating to 1757, the Douro Valley has gained notoriety from the quality of its main product Port wine; however the region today is also recognized for the quality of its table wine production as well. The Douro Wine Region covers approximately 252,000 hectares with vineyard area representing roughly 45,600 hectares or 18% of the total land area (Table 1). The region produces both the classic Port wines (approximately 79% of production) and also dry wines (21%), made from 78% red and 22% white cultivars, many of which are indigenous to the region and/or Portugal.
The Douro Wine Region consists of three sub-regions; the Baixo Corgo, the Cima Corgo, and the Douro Superior (Figure 6; Table 1). The western most part of the region is approximately 70 km from the coast and the eastern most areas border with Spain. The Baixo Corgo covers the smallest area with the Cima Corgo the next largest and the Douro Superior the largest sub-region. The landscape is characterized by mountainous terrain rising above the Douro River with moderate to steep slopes and varying exposures. The average elevation over the entire region is 443 m, but ranges from a low near 40 m to a high of just over 1400 m. The highest area is along the Marão Mountain Range, which provides a moderate rain shadow effect from the storms off the Atlantic.
The climate of the Douro Wine Region is Mediterranean and is characterized by a strong inter-annual consistency of total insolation, temperature, and potential evapotranspiration and significant inter-annual variation in precipitation (ADVID, 2007). In the Douro Wine Region, as in most regions with a Mediterranean climate, the high variability in precipitation along with high evapotranspiration during the summer period is normally one of the major factors limiting grapevine development, and production and quality of the harvest (Sotés, 2001). In the case of the Douro wine region, grapevines are subject to a high potential water deficit whereby the difference between evapotranspiration and precipitation can be as high as 730-750 mm throughout the bud break to harvest period (Malheiro et al., 2007). However, it should be noted that an important part of the geographic area of the Douro is subject to low precipitation regimes (33% of the area has less than 700 mm). In addition, the likelihood of experiencing a dry year is...
generally greater than that of years with above-average rainfall. According to (Schultz, 2000) this limitation may be aggravated in the future given that climate change scenarios show a potential reduction of soil moisture conditions of up to 70% which would likely reduce yield in countries in southern Europe, particularly the Iberian Peninsula (Stigliani and Salomons, 1992).

For these reasons, viticulture in the Douro wine region is carried out over a considerable area of the land in moderate to very severe conditions, particularly when climate and topography are associated. Thus with projections of temperature changes over the next 50 years of 1.5-2.5°C, combined with predictions of less rainfall and/or greater variability in the occurrence heat waves or intense rainfall events are realized, the stability of hillside vineyards and sustainability of entire operations will be challenged (Schultz, 2000; Jones et al. 2005). Based on work carried out in other wine regions worldwide, the impact of climate change scenarios on wine production and quality will have different outcomes depending on the characteristics of each sub-region, its location and the capacity of grape varieties and growers/producers to adapt (Jones et al. 2005). It may be beneficial for some regions that traditionally produce white wines, or it may allow them to be produced in areas where grapevines are not traditionally grown, but the changes could create constraints in regions where red wines with high quality potential are traditionally produced. The evolution of these scenarios will condition decision-making on vineyard locations, selection of plant material, the technical management plans to be followed and the typicity and style of wine to be produced. Given these issues there is an urgent need to understand the vulnerability of the Douro wine region to changes in climate and maximize the adaptive capacity of the wine industry.

While much is known about the climate of the Douro Wine Region, an integrated examination of the historical, contemporary and future climate in the region has not been done. Therefore the goals of this work are to examine the historic climate conditions in the Douro Wine Region, better understand the regional suitability of the climate to viticulture, analyze the frequency and trends in climate indices, weather/climate extremes, and regional climate variability mechanisms, and depict and summarize climate change projections for the region.

DATA AND METHODS

While there is a general understanding of the climate of the Douro Wine Region, a comprehensive, high quality, long term station data set for the region has been limited over both space and time. Therefore this climate assessment utilizes the best available data that are of three main types; 1) historic climate normals, 2) weather stations within the Douro Wine Region, and 3) spatial climate data for observed and future projections of climate. Furthermore, the assessment includes an examination of the relationships between the large-scale regional circulation controls and climate variability in the Douro Wine Region.

HISTORIC CLIMATE Normals

The most relevant historic data for the region comes from the 1931-1960 climate normals developed by Ferreira (1965). The data consist of monthly averages of annual precipitation, maximum and minimum temperature, relative humidity, evapotranspiration, and solar radiation for numerous stations in Portugal. These station data have been digitized to national contours
(Figure 7) by the Serviço Meteorológico Nacional, Direcção Geral do Ambiente, 1974, Edição Digital - Instituto do Ambiente (2002). However, the data has limited accuracy in that the generalized contours do not take into account local scale topographical effects. Furthermore, the data were not consistently updated, so no future climate normals have been created. For this assessment only precipitation, temperature, and evapotranspiration data are included.

For the Douro Wine Region (both inside and within 25 km of the boundary) there are 76 stations for precipitation and 57 stations for temperature and evapotranspiration in the 1931-1960 data of Ferreira (1965). These stations will be used in this analysis to quantify the general historical climate structure in the region, examine the relationship between these stations and other locational attributes, and be used to qualify other climate data used in the assessment.

Figure 7: Map of average temperature from the 1931-1960 climate normals developed by Ferreira (1965) and digitized to national contours by the Instituto do Ambiente (2002).
DOURO WINE REGION STATIONS

While the 1931-1960 climate normals station data described above provides reasonable insight into historic conditions over Portugal and within the Douro Wine region, the current climate station data in Portugal is limited to fewer qualified main stations (e.g., Lisboa, Oporto, Braganca, Coimbra, Beja, Tavira, etc.). These stations provide good general spatial coverage for the country and are available from a number of sources (Instituto de Meteorologia, Portugal, the European Climate Assessment & Dataset, and Instituto da Água, Portugal). Unfortunately, stations at this scale are not useful for a climate assessment for the Douro Wine Region. However, the Portuguese Instituto de Meteorologia does have three stations within the region – Vila Real, Régua, and Pinhão. These stations are used for this assessment for the common data availability period of 1967-2010. Other climate stations in the region, operated by ADVID and others, have shorter records and were used for quality control.

Of course quality control is an important aspect of analyzing climate station data. Climate data are the records of observed climate conditions taken at specific sites and times with particular instruments under a set of standard procedures. A climate dataset therefore contains climate information at the observation sites, as well as other non-climate-related factors such as the environment of the observation station, and information about the instruments and observation procedures under which the records were taken. An assumption is made that the station records are representative of climate conditions over a region when the data are used in climate analysis. This is, unfortunately, not always the case (Peterson et al. 1998). Station moves, instrument changes, calibration issues, recorder errors, etc. can all cause issues with climate station data. To account for potential issues with station data, numerous tools have been developed to manage and/or correct these issues. This climate assessment uses one such tool created by the CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI). The main goal of the tool is to check for data homogeneity and the quality control of outliers (unrealistic values, bad data points, etc.). The aim of climate data homogenization is to adjust observations, if necessary, so that the temporal variations in the adjusted data are caused only by climate processes. An authoritative review on climate data homogenization can be found in Peterson et al. (1998).

The CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) has also developed a suite of indices for understanding the behavior of climate at a given station (Karl et al. 1999; Wang et al. 2003; Peterson 2005). The analysis of average climate conditions, while important, may not be as critical as understanding the change in the frequency or severity of extreme climate events. However, little standardization of appropriate indices for developing a global picture of conditions and trends has been done until ETCCDI developed a suite of 27 core indices (Table 2). These indices provide a common framework by which the frequency or severity of extreme climate events can be assessed worldwide. Therefore, the 27 indices are calculated for Vila Real, Régua, and Pinhão for 1967-2010 after data quality control and homogenization has been properly assessed.
Table 2: Indicator name, ID, definitions and units for the 27 core climate indices used in the Douro Wine Region assessment. Indices are as originally developed by CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI). A complete description of how each index is calculated is given in the Appendix.

<table>
<thead>
<tr>
<th>ID</th>
<th>Indicator name</th>
<th>Definitions</th>
<th>UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD0</td>
<td>Frost days</td>
<td>Annual count when TN(daily minimum)&lt;0°C</td>
<td>Days</td>
</tr>
<tr>
<td>SU25</td>
<td>Summer days</td>
<td>Annual count when TX(daily maximum)&gt;25°C</td>
<td>Days</td>
</tr>
<tr>
<td>SU35</td>
<td>Stress days</td>
<td>Annual count when TX(daily maximum)&gt;35°C</td>
<td>Days</td>
</tr>
<tr>
<td>TR20</td>
<td>Tropical nights</td>
<td>Annual count when TN(daily minimum)&gt;20°C</td>
<td>Days</td>
</tr>
<tr>
<td>GSL</td>
<td>Growing season Length</td>
<td>Annual (1st Jan to 31st Dec in NH) count between first span of at least 6 days with TG&gt;5°C and first span after July 1 (NH) of 6 days with TG&lt;5°C</td>
<td>Days</td>
</tr>
<tr>
<td>TXx</td>
<td>Max Tmax</td>
<td>Monthly maximum value of daily maximum temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Tnx</td>
<td>Max Tmin</td>
<td>Monthly maximum value of daily minimum temperature</td>
<td>°C</td>
</tr>
<tr>
<td>TXn</td>
<td>Min Tmax</td>
<td>Monthly minimum value of daily maximum temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Tnn</td>
<td>Min Tmin</td>
<td>Monthly minimum value of daily minimum temperature</td>
<td>°C</td>
</tr>
<tr>
<td>TN10p</td>
<td>Cool nights</td>
<td>Percentage of days when TN&lt;10th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>TX10p</td>
<td>Cool days</td>
<td>Percentage of days when TX&lt;10th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>TN90p</td>
<td>Warm nights</td>
<td>Percentage of days when TN&gt;90th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>TX90p</td>
<td>Warm days</td>
<td>Percentage of days when TX&gt;90th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>WSDI</td>
<td>Warm spell duration indicator</td>
<td>Annual count of days with at least 6 consecutive days when TX&gt;90th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>CSDI</td>
<td>Cold spell duration indicator</td>
<td>Annual count of days with at least 6 consecutive days when TN&lt;10th percentile</td>
<td>Days</td>
</tr>
<tr>
<td>DTR</td>
<td>Diurnal temperature range</td>
<td>Monthly mean difference between TX and TN</td>
<td>°C</td>
</tr>
<tr>
<td>RX1day</td>
<td>Max 1-day precipitation amount</td>
<td>Monthly maximum 1-day precipitation</td>
<td>mm</td>
</tr>
<tr>
<td>Rx5day</td>
<td>Max 5-day precipitation amount</td>
<td>Monthly maximum consecutive 5-day precipitation</td>
<td>mm</td>
</tr>
<tr>
<td>SDII</td>
<td>Simple daily intensity index</td>
<td>Annual total precipitation divided by the number of wet days (defined as PRCP&gt;=1.0mm) in the year</td>
<td>mm/day</td>
</tr>
<tr>
<td>R10</td>
<td>Number of heavy precipitation days</td>
<td>Annual count of days when PRCP&gt;=10mm</td>
<td>Days</td>
</tr>
<tr>
<td>R20</td>
<td>Number of very heavy precipitation days</td>
<td>Annual count of days when PRCP&gt;=20mm</td>
<td>Days</td>
</tr>
<tr>
<td>Rnn</td>
<td>Number of days above nn mm</td>
<td>Annual count of days when PRCP&gt;nn mm, nn is user defined threshold</td>
<td>Days</td>
</tr>
<tr>
<td>CDD</td>
<td>Consecutive dry days</td>
<td>Maximum number of consecutive days with RR&lt;1mm</td>
<td>Days</td>
</tr>
<tr>
<td>CWD</td>
<td>Consecutive wet days</td>
<td>Maximum number of consecutive days with RR&gt;1mm</td>
<td>Days</td>
</tr>
<tr>
<td>R95p</td>
<td>Very wet days</td>
<td>Annual total PRCP when RR&gt;95th percentile</td>
<td>mm</td>
</tr>
<tr>
<td>R99p</td>
<td>Extremely wet days</td>
<td>Annual total PRCP when RR&gt;99th percentile</td>
<td>mm</td>
</tr>
<tr>
<td>PRCPTOT</td>
<td>Annual total wet-day precipitation</td>
<td>Annual total PRCP in wet days (RR&gt;=1mm)</td>
<td>mm</td>
</tr>
</tbody>
</table>

**REGIONAL CIRCULATION AND WEATHER REGIMES**

The large seasonal and daily changes in mid-latitude weather are related to changes in atmospheric circulation and air mass dominance from Arctic, polar and subtropical source regions (Wallace and Gutzler, 1981 and others). While studies have shown that various teleconnection indices such as the North Atlantic Oscillation have prominent relationships with weather and climate in Europe and elsewhere (Hurrell, 2003), the use of weather typing (Santos et al. 2005) or synoptic classifications (Jones and Davis, 2000a) have proven effective in establishing a daily calendar of events and their relationships to regional agriculture. Given the coupling of air masses
and circulation, a study of the daily frequencies of air masses and the various circulation regimes that control their movements could prove useful in understanding influences on the climate of the Douro Wine Region. To accomplish this portion of the Douro Wine Region climate assessment the work uses a recent update to the work of Santos et al. (2005) is used. The update using NCEP/NCAR Reanalysis data from 1948-2011 to classify weather regimes affecting Portugal. The weather regimes are created from daily mean anomalies of sea level pressure (SLP) over the 30°W-20°E - 25-65°N domain over the eastern Atlantic, Western Europe and the Mediterranean. The weather regimes are created through a two-stage process by which the SLP field is subjected to a Principal Component Analysis (PCA) and the resulting PCs clustered into groups using K-means clustering. The results are six weather regimes; anticyclone (A); ridge (R); northwesterly flow (NW); easterly flow (E); Azores and Europe anticyclone (AA, two anticyclones); and cyclone (C) that are in general agreement with previous studies (Santos et al. 2005). Each day during 1948-2011 is classed to one of these six weather regimes, providing a calendar by which to establish the seasonal and annual structure of the regional circulation and examine its effects on local scale climate variability.

**Spatial Climate: Historic**

This climate assessment for the Douro Wine Region also uses a global database called ‘WorldClim’ developed by Hijmans et al (2005). The WorldClim data was created by gathering data from numerous sources (e.g., GHCN, WMO, FAOCLIM, etc.) and stations were interpolated using a thin-plate smoothing spline algorithm implemented in the ANUSPLIN package for interpolation (Hutchinson, 2004), using latitude, longitude, and elevation as independent variables. The station data is interpolated to a 30 arc second spatial resolution; which is equivalent to about 0.86 km² at the equator and less elsewhere, but is close to 1 km in a mid-latitude area such Portugal. The gridded data set provides monthly maximum temperatures, minimum temperatures, and precipitation for 1950-2000, representing the highest resolution available at the global scale for spatial climate analyses.

The WorldClim data was also thoroughly assessed for uncertainty issues such as those arising from the input station data and the interpolation routine (Hijmans et al. 2005). This was done by mapping weather station density, elevation bias in the weather stations, and elevation variation within grid cells and through data partitioning and cross validation. The results showed that station elevation bias tended to be negative (stations were lower than expected) at high latitudes but positive in the tropics. Uncertainty was overall found to be highest in very mountainous areas and in those that have low station density. Furthermore, data partitioning showed high uncertainty of the gridded surfaces over isolated islands such as in the Pacific. A comparison with an existing data set at 10 arc min resolution showed overall agreement, but with significant variation in some regions (New et al. 2002). A comparison with two high-resolution data sets for the United States (Daymet and PRISM) also identified areas with large local differences, particularly in very mountainous regions (Thornton et al. 1997; Daly et al. 2002). However, compared to previous global climatologies, WorldClim has the advantages of being 1) the data are at a higher spatial resolution (400 times greater or more), 2) incorporated more
weather station records, 3) used improved elevation data, and 4) more extensively documented the spatial patterns of uncertainty in the data.

To ensure the accuracy and usefulness of the WorldClim data, it is compared to the 57 station network for the 1931-1960 climate normal described above. A spatial correlation between the two data sets (stations compared to grids) is applied to assess their relationship. Furthermore, the WorldClim data is also compared to the station data from Vila Real, Régua, and Pinhão for 1967-2010. Even though these three data sets are from slightly different time periods their relationships should remain stable over time, resulting in a high correlation between the station values and grids, indicating the relevance of their use in a regional assessment such as for the Douro Wine Region.

**SPATIAL CLIMATE: FUTURE PROJECTIONS**

The examination of the potential future changes in climate is typically done through the use of General Circulation Models (GCMs). GCMs are representations of the physical processes in the atmosphere, ocean, polar ice masses and land surfaces, and are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations and other bio-physical changes in the earth-atmosphere system. GCMs depict the climate using a three dimensional grid over the globe, typically having a horizontal resolution of between 250 and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans. However, the spatial scales available in GCMs are simply not practical for assessing agricultural landscapes, particularly where orographic and climatic conditions vary significantly across relatively small distances such as in the Douro Wine Region. Large-scale future projections of climate, while very useful for general approaches, present limitations for more precise interpretations of the effects of climate and future scenarios on wine quality especially in a region with such topographic, climatic, and landscape use variation as the Douro wine region.

Future climate model data (GCM) is normally available from many sources (e.g., the Hadley Centre in England or the Intergovernmental Panel on Climate Change [IPCC]), but typically cover a single 2.5° x 2.5° latitude/longitude grid that would represent all of Portugal. Even the best GCM resolutions of 0.5° x 0.5° latitude/longitude grids are still quite large and often do not adequately characterize heterogeneous areas. To adequately represent a wine region such as the Douro, regional downscaled models are necessary (Moriondo and Bindi, 2004; Jones et al. 2005) to facilitate appropriate assessments at scales of 25-50 km or less. To examine future climate conditions in the Douro Wine Region, this assessment uses datasets developed by the International Centre for Tropical Agriculture’s (CIAT) Decision and Policy Analysis (DAPA) program. The data were originally acquired from the IPCC data portal and re-processed using an spline interpolation algorithm of the anomalies (Ramirez and Jarvis, 2010) and the current distribution of climates from the WorldClim database developed by Hijmans et al. (2005).

These data represent GCMs from the fourth IPCC Assessment Reports (IPCC, 2007) that are downscaled to the same WorldClim grid described above (~close to 1 km for Portugal). The method assumes that the geographies of changes in climates do not vary much at regional scales.
and that the relationships between the different variables will remain basically the same in the future. The new climate surfaces are thus generated using an empirical downscaling approach instead of re-modeling the climate patterns using an RCM (Regional Climate Model). The downscaling method used is based on a thin plate spline spatial interpolation of anomalies of original GCM outputs. The anomalies are interpolated between GCM cell centroids and are then applied to the 1950-2000 baseline climate given by WorldClim (Hijmans et al., 2005). For this assessment the three future time slices (2020, 2050, and 2080) for three greenhouse gas emission scenarios (B2, A1B, and A2) using the HADCM3 model are compared to historic conditions (1950-2000). These emission scenarios represent a range of population and economic growth, differing efficiencies in technologies, and the social structure between countries and regions. The B2 scenario represents conditions of continuously increasing population, intermediate levels of economic development and technological change, and a more divided world but with lower energy requirements. The A1B scenario represents a more integrated world with rapid economic growth, global population that peaks in 2050 and then gradually declines, rapid spread of new and efficient technologies, and extensive social and cultural interactions worldwide that leads to a balanced emphasis on all energy sources. The A2 scenario is of a more divided world with regionally oriented economic development, driven by continuously increasing population that is reliant on fewer energy sources and maintains high energy requirements.

RESULTS AND DISCUSSION

HISTORIC CLIMATE NORMALS

For the 1931-1960 climate normal time period the stations representing the Douro Wine Region show a relatively heterogeneous climate structure with generally wetter and cooler areas to the west and higher in elevation, and drier and warmer areas to the east (Figures 6, 8 & 9). The stations average 487 m in elevation, but range from a low of 65 m in Régua to a high of 940 m in Penedono. The stations lie from approximately 60 km from the coast at Barqueiros to over 160 km at Fornos de Lagoaça. In terms of annual precipitation the 76 stations range from 385 mm at Barca d’Alva to 1953 mm at Lamas de Alvadia, with a median value of 694 mm (Table 3). During the dormant season of November through March median precipitation is 442 mm ranging over 1000 mm from the driest (218 mm) to the wettest locations (1223 mm; same stations as for annual precipitation). During the growing season (Apr-Oct), the median precipitation is 257 mm with a low of 162 mm at Freixo de Numão to a high of 730 mm at Lamas de Alvadia. During 1931-1960 winter and growing season precipitation averaged 64% and 36% of annual precipitation over these stations.

Average annual temperatures across the 57 stations during 1931-1960 had a median value of 14.3°C, ranging 5.4 degrees from a low of 11.4°C at Castanheiro do Sul to a high of 16.8°C at Vesúvio (Table 3). The broad patterns of annual temperatures within the region shows that the warmest zones are generally along the lower elevations following the main river valley and to the east (Figure 9). Dormant season average temperatures also range nearly 5 degrees from a low at
Table 3: Summary statistics for the 1931-1960 climate normals for the stations in the Douro Wine Region. Each variable is summarized over the annual, growing season (Apr-Oct), and dormant season (Nov-Mar) for 76 stations for precipitation and 57 stations for temperature and evapotranspiration.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Period</th>
<th>Mean</th>
<th>Median</th>
<th>Std. Dev.</th>
<th>Max.</th>
<th>Min.</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm)</td>
<td>Annual</td>
<td>794</td>
<td>694</td>
<td>311</td>
<td>1953</td>
<td>385</td>
<td>1568</td>
</tr>
<tr>
<td></td>
<td>Growing Season (Apr-Oct)</td>
<td>287</td>
<td>257</td>
<td>96</td>
<td>730</td>
<td>162</td>
<td>568</td>
</tr>
<tr>
<td></td>
<td>Dormant Season (Nov-Mar)</td>
<td>506</td>
<td>442</td>
<td>218</td>
<td>1223</td>
<td>218</td>
<td>1005</td>
</tr>
<tr>
<td>Average Temperature (°C)</td>
<td>Annual</td>
<td>14.3</td>
<td>14.3</td>
<td>1.3</td>
<td>16.8</td>
<td>11.4</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Growing Season (Apr-Oct)</td>
<td>18.7</td>
<td>18.7</td>
<td>1.5</td>
<td>21.8</td>
<td>15.3</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Dormant Season (Nov-Mar)</td>
<td>8.1</td>
<td>8.2</td>
<td>1.1</td>
<td>10.0</td>
<td>5.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Maximum Temperature (°C)</td>
<td>Annual</td>
<td>20.7</td>
<td>20.5</td>
<td>1.7</td>
<td>24.1</td>
<td>16.6</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>Growing Season (Apr-Oct)</td>
<td>26.3</td>
<td>26.1</td>
<td>2.0</td>
<td>30.3</td>
<td>22.4</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>Dormant Season (Nov-Mar)</td>
<td>12.8</td>
<td>12.6</td>
<td>1.5</td>
<td>15.4</td>
<td>8.4</td>
<td>7.0</td>
</tr>
<tr>
<td>Minimum Temperature (°C)</td>
<td>Annual</td>
<td>7.9</td>
<td>7.9</td>
<td>1.2</td>
<td>10.5</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Growing Season (Apr-Oct)</td>
<td>11.2</td>
<td>11.0</td>
<td>1.3</td>
<td>14.2</td>
<td>7.8</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Dormant Season (Nov-Mar)</td>
<td>3.4</td>
<td>3.4</td>
<td>1.1</td>
<td>6.0</td>
<td>1.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Evapotranspiration (mm)</td>
<td>Annual</td>
<td>781</td>
<td>777</td>
<td>56</td>
<td>917</td>
<td>673</td>
<td>244</td>
</tr>
<tr>
<td></td>
<td>Growing Season (Apr-Oct)</td>
<td>677</td>
<td>675</td>
<td>55</td>
<td>814</td>
<td>575</td>
<td>239</td>
</tr>
<tr>
<td></td>
<td>Dormant Season (Nov-Mar)</td>
<td>104</td>
<td>103</td>
<td>9</td>
<td>127</td>
<td>79</td>
<td>48</td>
</tr>
</tbody>
</table>

**Figure 8:** Distribution of average annual precipitation in the Douro, 1931-1960 period, scale 1:1,000,000. Serviço Meteorológico Nacional, Direção Geral do Ambiente, 1974, Edição Digital - Instituto do Ambiente, 2002. Carta Administrativa Oficial de Portugal, scale 1:250.000, Instituto Geográfico Português (2004).

Castanheiro do Sul of 5.1°C to a high of 10°C at Pinhão. During the growing season, average temperatures are highest at Vesúvio reaching 21.8°C and lowest at Moimenta da Beira (15.3°C). Annual maximum temperatures reveal similar structure and characteristics with Castanheiro do Sul the lowest and Ribalonga the highest during all time periods (Table 3). During 1931-1960 the growing season range in average maximum temperatures was nearly 8 degrees, from 22.4 to 30.3°C. For the warmest month of the summer, August, maximum values reach 37.0°C in Ribalonga (Figure 10). Annual minimum temperatures average 7.9°C and do not vary from station to station as much as maximum temperatures, ranging from a low of 5.0°C at Moimenta da Beira.
to a high of 10.5°C at Moncorvo (Table 3). Winter lows average 3.4°C with the lowest observed at Chavães (1.1°C) and the highest at Barqueiros (6.0°C), while growing season minimum temperatures range from a low of 7.8°C at Moimenta da Beira to a high of 14.2°C at Moncorvo.

**Figure 9:** Average annual temperature in the Douro, based on the mean series for 1931-1960, scale 1:1,000,000 (Adapted from Ferreira, 1965), digital version, kindly provided by Vicente Sousa (UTAD). Carta Administrativa Oficial de Portugal, scale 1:250.000, Instituto Geográfico Português (2004).

**Figure 10:** Average growing season temperature (Growth Cycle - in green) and average maximum temperature in August (in red) for the Douro, based on the mean series for 1931-1960. Source: Ferreira, 1965.

Similar to the structure and characteristics with temperatures and precipitation, evapotranspiration (ET) rates over the Douro Wine Region show strong heterogeneity. Median
annual ET over the stations is 777 mm, or slightly more than the median annual precipitation (Table 3). During the growing season, when ET rates largely determine soil-moisture stresses, the median ET rate is 675 mm or over 250% of the median precipitation inputs during the period of vine growth. The highest growing season ET value was in Vesúvio (917 mm) while the lowest was in Moimenta da Beira (575 mm).

**DOURO WINE REGION STATIONS**

Within the Douro Wine Region three climate stations have reasonably long records with good quality data: Régua, Pinhão, and Vila Real (Figures 11-16). Daily data for maximum and minimum temperatures and precipitation covering 1967-2010 were subjected to extensive quality control to examine outliers, assess missing data, and examine the homogeneity (station moves, changes, etc.) using the CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI) tools. Some outliers (< 0.1% of all data) were encountered in each station’s time series with most being unrealistic values (bad data points) and were adjusted either manually when the error was obvious (inverted values) or by taking the average of ± three days from the data point. Missing data was limited to less than 1% of the time period (Figures 11-16) and if the data had two or less missing days they were replaced with the average of ± three days from the data point. In terms of data change points, during 1967-2010 the Vila Real and Pinhão stations showed no signs of inhomogeneity in their temperature data records. Régua however exhibited a break point in minimum temperatures (sharp decrease) during 2003-04. This was corrected using the Q-M adjustment and the Vila Real station as a reference in the ETCCDI RHtests procedure (Wang, 2003).

Figure 11: Time series of daily maximum temperatures (left panel) and daily minimum temperatures (right panel) for Régua for 1967-2010. Red circles represent missing observations.
Figure 12: Time series of daily precipitation for Régua for 1967-2010. Red circles represent missing observations.

Figure 13: Time series of daily maximum temperatures (left panel) and daily minimum temperatures (right panel) for Pinhão for 1967-2010. Red circles represent missing observations.
Figure 14: Time series of daily precipitation for Pinhão for 1967-2010. Red circles represent missing observations.

Figure 15: Time series of daily maximum temperatures (left panel) and daily minimum temperatures (right panel) for Vila Real for 1967-2010. Red circles represent missing observations.
Over the 1967-2010 time period Régua averaged 22.1°C for average annual maximum temperatures and 10.1°C for average annual minimum temperatures. For the same time period Pinhão was slightly cooler in average annual maximum (21.9°C) and minimum temperatures (10.0°C) compared to Régua, while Vila Real is the coolest of the three stations, averaging 18.6°C and 8.3°C for average annual maximum and minimum temperatures, respectively. For annual maximum temperatures the coolest year was 1993 across all three stations with values 2°C or more lower than average. The warmest years were 1995 for Régua, 1998 for Pinhão, and 1989 for Vila Real. Annual minimum temperatures were lowest during 1970-80 for all three stations, while highest during either 1997 or 2003. During the growing season (Apr-Oct) Régua averaged 26.8°C and 13.2°C for average maximum and minimum temperatures, respectively. Pinhão was slightly warmer than Régua for both average maximum (27.1°C) and minimum (13.3°C) temperatures during the growing season while Vila Real was moderately cooler averaging 23.3°C and 11.3°C for maximum and minimum temperatures, respectively. Similar to annual averages, the coolest growing season maximum temperatures occurred in 1993 (2°C or more lower). The years with the warmest maximum temperatures during the growing season were 2006 in Régua (28.7°C), 1995 in Pinhão (28.7°C), and 2010 in Vila Real (24.9°C). For growing season minimum temperatures, 1974 was the coolest across all three stations, while either 2003 or 2006 was the warmest. During the dormant season Régua averaged 15.3°C for maximum temperatures, while Pinhão averaged 14.6°C and Vila Real 12.0°C (Table 4). Vila Real is the coolest for minimum temperatures during the winter, averaging 4.2°C while Régua and Pinhão average 5.9°C and 5.4°C, respectively. During 1967-2010 the coldest winter minimum temperatures occurred during the 1974-1976 winters at all three stations while the warmest occurred during the 1988-1990 winters. Maximum temperatures during the winter were warmest during 1997 for both Régua and Pinhão, but 1981...
for Vila Real, while the lowest maximums were seen in 1990 for Pinhão and Régua, but 2004 for Vila Real.

Temperature trends for the three stations show that both annual maximum and minimum temperatures have warmed. Annual average maximum temperatures warmed significantly at both Régua and Pinhão, at 0.03°C per year or 1.2-1.3°C over the 1967-2010 time period (Table 5; Figure 17). While annual average maximum temperatures warmed in Vila Real the changes were not statistically significant. Annual average minimum temperatures warmed significantly at all three sites and at yearly rates of 0.03-0.08°C, with the greatest warming of 3.3°C coming at Régua followed by 2.1°C and 1.3°C at Pinhão and Vila Real, respectively. For the growing season similar changes were seen with Régua and Pinhão warming significantly in both maximum and minimum temperatures and Vila Real showing a significant trend in minimum temperatures only (Table 5; Figure 17). Maximum temperatures changed 1.7°C and 1.6°C over the entire time period for Régua and Pinhão, while minimum temperatures warmed 1.5°C in Vila Real, 2.5°C in Pinhão, and 3.6°C in Régua. During the winter none of the stations exhibited significant changes in maximum temperatures, however all three showed significant warming in minimum temperatures with Vila Real increasing 0.9°C, Pinhão 2.0°C, and Régua 3.0°C during 1967-2010.

For annual precipitation during 1967-2010 Pinhão was the driest of the three stations averaging 652 mm, followed by Régua with 835 mm, and Vila Real with 1034 mm (Table 4). Each station exhibited substantial year to year variation in precipitation, with ranges nearly as large as the average values (743, 772, and 1018 mm, respectively). The driest year during the time period was 2005 with 370 mm at Pinhão, 476 mm at Régua, and 570 mm at Vila Real (Figure 18; 2007 was the second driest with similar values). The wettest year was different for each station with 2001 seeing 1113 mm at Pinhão, 1977 having 1248 mm at Régua, and 1978 seeing 1588 mm in Vila Real. Growing season precipitation (Apr-Oct) is 38-41% of annual precipitation for the three stations during the time period, with Pinhão averaging 268 mm, Régua 315 mm, and Vila Real 403 mm (Table 4). The driest growing seasons during 1967-2010 were 1970 and 1991 where precipitation amounts were nearly half of average (Figure 19). The wettest growing season occurred in 1993 with near double the average precipitation at each station. Dormant season precipitation is approximately 60% of the annual amount, with Pinhão averaging 384 mm, Régua 520 mm, and Vila Real 632 mm (Table 4). The driest winter during the time period was 1999-00 for Régua with 187 mm and 2004-05 for Pinhão (109 mm) and Vila Real (168 mm). All three stations had their wettest winter in 2000-01 with 1402 mm at Pinhão, 1326 mm at Régua, and 1629 mm in Vila Real (Figure 20). No trends were found for annual, dormant season, or growing season precipitation at any of the three stations (Table 5).
Table 4: Descriptive statistics for annual, growing season (Apr-Oct), and dormant season (Nov-Mar) maximum and minimum temperatures and precipitation for Régua, Pinhão, and Vila Real for 1967-2010.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Régua</th>
<th></th>
<th>Pinhão</th>
<th></th>
<th>Vila Real</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Maximum Temperature (°C)</td>
<td>22.1</td>
<td>0.7</td>
<td>23.6</td>
<td>20.4</td>
<td>21.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Annual Minimum Temperature (°C)</td>
<td>10.1</td>
<td>1.1</td>
<td>11.9</td>
<td>8.2</td>
<td>10.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Annual Precipitation (mm)</td>
<td>835</td>
<td>194</td>
<td>1248</td>
<td>476</td>
<td>652</td>
<td>185</td>
</tr>
<tr>
<td>Growing Season Maximum Temperature (°C)</td>
<td>26.8</td>
<td>0.9</td>
<td>28.7</td>
<td>24.6</td>
<td>27.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Growing Season Minimum Temperature (°C)</td>
<td>13.2</td>
<td>1.2</td>
<td>15.2</td>
<td>10.7</td>
<td>13.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Growing Season Precipitation (mm)</td>
<td>315</td>
<td>96</td>
<td>635</td>
<td>150</td>
<td>268</td>
<td>103</td>
</tr>
<tr>
<td>Dormant Season Maximum Temperature (°C)</td>
<td>15.3</td>
<td>0.8</td>
<td>17.0</td>
<td>13.9</td>
<td>14.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Dormant Season Minimum Temperature (°C)</td>
<td>5.9</td>
<td>1.5</td>
<td>8.9</td>
<td>2.8</td>
<td>5.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Dormant Season Precipitation (mm)</td>
<td>520</td>
<td>269</td>
<td>1326</td>
<td>187</td>
<td>384</td>
<td>233</td>
</tr>
</tbody>
</table>

Table 5: Trend parameters for annual, growing season (Apr-Oct), and dormant season (Nov-Mar) maximum and minimum temperatures and precipitation for Régua, Pinhão, and Vila Real for 1967-2010.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Régua</th>
<th></th>
<th>Pinhão</th>
<th></th>
<th>Vila Real</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>P-Value</td>
<td>Slope</td>
<td>$R^2$</td>
<td>P-Value</td>
<td>Slope</td>
</tr>
<tr>
<td>Annual Maximum Temperature (°C)</td>
<td>0.29</td>
<td>0.000</td>
<td>0.031</td>
<td>0.18</td>
<td>0.004</td>
<td>0.027</td>
</tr>
<tr>
<td>Annual Minimum Temperature (°C)</td>
<td>0.75</td>
<td>0.000</td>
<td>0.076</td>
<td>0.58</td>
<td>0.000</td>
<td>0.051</td>
</tr>
<tr>
<td>Annual Precipitation (mm)</td>
<td>NS</td>
<td>0.524</td>
<td>-1.51</td>
<td>NS</td>
<td>0.573</td>
<td>1.265</td>
</tr>
<tr>
<td>Growing Season Maximum Temperature (°C)</td>
<td>0.29</td>
<td>0.000</td>
<td>0.040</td>
<td>0.24</td>
<td>0.001</td>
<td>0.037</td>
</tr>
<tr>
<td>Growing Season Minimum Temperature (°C)</td>
<td>0.74</td>
<td>0.000</td>
<td>0.083</td>
<td>0.58</td>
<td>0.000</td>
<td>0.057</td>
</tr>
<tr>
<td>Growing Season Precipitation (mm)</td>
<td>NS</td>
<td>0.611</td>
<td>0.602</td>
<td>NS</td>
<td>0.294</td>
<td>1.298</td>
</tr>
<tr>
<td>Dormant Season Maximum Temperature (°C)</td>
<td>NS</td>
<td>0.097</td>
<td>0.016</td>
<td>NS</td>
<td>0.327</td>
<td>0.012</td>
</tr>
<tr>
<td>Dormant Season Minimum Temperature (°C)</td>
<td>0.35</td>
<td>0.000</td>
<td>0.069</td>
<td>0.19</td>
<td>0.003</td>
<td>0.046</td>
</tr>
<tr>
<td>Dormant Season Precipitation (mm)</td>
<td>NS</td>
<td>0.537</td>
<td>-2.07</td>
<td>NS</td>
<td>0.907</td>
<td>-0.34</td>
</tr>
</tbody>
</table>
Figure 17: Growing season average temperature (Apr-Oct) trends for the climate stations from Régua, Pinhão, and Vila Real in the Douro Wine Region between 1967 and 2010 (ADVID, 2007).

Figure 18: Annual precipitation for the climate stations from Régua, Pinhão, and Vila Real in the Douro Wine Region between 1967 and 2010 (ADVID, 2007). The black line is the moving average across all stations.
Figure 19: Growing season (Apr-Oct) precipitation for the climate stations from Régua, Pinhão, and Vila Real in the Douro Wine Region between 1967 and 2010 (ADVID, 2007). The black line is the moving average across all stations.

Figure 20: Dormant season (Nov-Mar) precipitation for the climate stations from Régua, Pinhão, and Vila Real in the Douro Wine Region between 1967 and 2010 (ADVID, 2007). The black line is the moving average across all stations. Note that the data is on the two year period for winter (e.g., 1997 represents the 1997-98 winter).
General trends similar to those detailed above have been observed over the Iberian Peninsula and Europe by other researchers. Miranda et al. (2002) found that recent warming trends for Portugal were greatest in winter and spring and more pronounced for minimum than for maximum values of temperature. Examining climate and phenology over multiple regions in Europe, Jones et al. (2005) found that changes were typically greater for minimum temperatures than maximum temperatures across the stations studied. For the station closest to the Douro Wine Region, Pontevedra, Spain, the results pointed to significant increases in minimum temperatures (1.1°C from 1952-2004) while maximum temperatures did not change significantly. Averaged over all of the locations studied, warming during 1960-2005 was 1.7°C during the growing season with increases in GDD and HI of nearly 300 units, which were strongly tied to earlier phenology (6-18 days) and shorter intervals between events (4-14 days) averaged across the regions. Ramos et al. (2008) found overall growing season warming of 1.0-2.2°C in NE Spain during 1952-2006. The authors also found that heat accumulation indices (Winkler and Huglin indices) increased significantly, driven mostly by maximum temperatures and maximum temperature extremes. The changes showed moderate to strong relationships with phenology (earlier events), wine quality (higher with increasing DTR), and production (reduced due to heat and/or moisture stress). The authors also found that a 1°C warmer growing season increased water demands by 6-14% in the conditions in NE Spain. Across the wine regions of NW Spain and the Miño River Valley, Blanco-Ward et al. (2007) found GST that averaged 17.3°C, ranging from 14.7 to 19.1°C; GDD that averaged 1382, ranging from 872 to 1858; found HI that averaged 2049, ranging from 1454 to 2512. The authors also showed that the spatial variability in climates over the region was largely defined by variations in growing season precipitation, GDD, HI, and the DI. Using GHCN data for 1950-1999, Jones et al. (2005) found average warming during the growing season of 1.3°C over 27 wine regions worldwide. A grid cell over Northern Portugal found a time period average of 17.7°C in GST (Warm climate suitability) and a significant trend of 0.9°C from 1950-1999.

Gimeno et al. (2011) provide a summary of the state of the climate and climate change for the NW Iberian Peninsula, detailing regional changes in atmospheric and oceanic parameters that have influenced changes in the region’s hydrologic cycle and coastal zone upwelling. de Castro et al. (2005) in a detailed report for Spain showed that temperatures during the 20th Century showed a general warming that was at a slightly greater magnitude that the global average. Temperature trends were shown to be greater during the winter, with a slight decrease in precipitation over the country, but at very high variability. Brunet et al. (2007) examined the temporal and spatial patterns of temperature changes at the longest and most reliable stations over Spain during 1850-2005. The results found significant warming of 0.10°C per decade over the period with slightly greater changes in maximum versus minimum temperatures, resulting in a larger diurnal temperature range. Differences between Spain, especially NW Spain, and Portugal and the Douro Wine Region would be expected show regional similarity, although geographic position and coastal proximity might produce some differences. In a comprehensive assessment of the NW Iberia climate Gómez-Gesteira et al (2011) detail the structure and trends in numerous climate parameters. The authors note that the region’s land temperatures have warmed on average 0.50°C since 1974, with Régua showing a higher warming trend than other regional cities.
(i.e., Porto, Vigo, Coruña). Regional sea surface temperatures have also warmed during this period, averaging 0.24°C since 1974 and sea level rise has been significant in the coastal waters of the peninsula. Both de Castro et al. (2005) and Gómez-Gesteira et al (2011) note that the warming over Iberia is slightly greater than that for Europe as a whole, which is in turn greater that global trends.

Examining precipitation patterns and trends over Spain during 1961-2006 Del Rio et al. (2011) found significant decreases in late winter through early summer precipitation. González-Hidalgo et al. (2011) find similar results to Del Rio et al. (2011) with trends in monthly precipitation however their greater density of stations reveals great temporal and spatial variability over Spain. However, de Lima et al. (2010) found no significant trend in long term annual precipitation amounts over the main climate stations in Portugal over the last 75-110 years. Some partial trends over shorter time periods were found, indicating variable periods of increasing or decreasing amounts that have led to the redistribution of precipitation amounts for Portugal. Gómez-Gesteira et al (2011) also note that no significant trends in annual precipitation are evident, although some minor seasonal changes are apparent. Examining precipitation trends in southern Portugal Costa and Soares (2009) found pronounced trends in an index of aridity during 1950-1999, indicating increasing threats of drought and desertification in the region. While wetness indices do not show significant trends over southern Portugal, the authors found evidence for increasing short-term precipitation intensity during the last three decades of the 20th Century. Costa and Soares (2009) also find evidence for greater extreme precipitation variability over the region. Briffa et al. (2009) found a tendency toward increasing drought conditions over most of Europe and that the trend over the last few decades is strongly coupled to increasing temperatures more so that decreasing precipitation.

Using the ETCCDI tools, a collection of core climate indices were calculated for the three long term climate stations in the Douro Wine Region (Table 2). In general, common trends were found more between Régua and Pinhão than with Vila Real (Table 6). Below is a summary of the changes for the three stations with the trends given as the total change over the 1967-2010 time period and examples of the trends can be found in Figures 21-23:

**Absolute-Based Extreme Indices:**
- Maximum Tmax (°C) – significant warming for Régua (2.2°C) and Pinhão (2.5°C)
- Minimum Tmax (°C) – significant warming for all three stations, ranging from 2.9°C for Vila Real (Figure 23), 3.3°C for Pinhão, and 4.3°C for Régua
- Maximum Tmin (°C) – no significant trends
- Minimum Tmin (°C) – significant warming for Régua (1.9°C) and Pinhão (2.2°C)

**Percentile- Based Extreme Indices:**
- % of Days Tmax < 10th Percentile – significant trend of a decline of 4% for Régua only
- % of Days Tmax > 90th Percentile – significant trend of an increase of 8% for Régua and 7% for Pinhão
- % of Days Tmin < 10th Percentile – significant decrease across all stations of 6% for Vila Real, 13% for Pinhão, and 20% for Régua (Figure 21)
% of Days Tmin > 90th Percentile – significant increase across all stations of 9% for Vila Real, 12% for Pinhão, and 19% for Régua (Figure 21)

Threshold-Based Extreme Indices:
- # of Days Tmax > 35°C – Régua and Pinhão (Figure 22) exhibited significant trends of an increasing number of days over 35°C, 19 and 16 days respectively
- # of Days Tmax > 25°C – Régua and Pinhão exhibited significant trends of an increasing number of days over 25°C, 26 and 21 days respectively
- # of Days Tmax < 0°C – not observed at Régua and Pinhão and no significant trend at Vila Real
- # of Days Tmin > 20°C – significant trends of increasing days with nighttime temperatures over 20°C at all three stations; 6, 10, and 13 days at Vila Real (Figure 23), Pinhão, and Régua, respectively
- # of Days Tmin < 0°C – Régua and Pinhão exhibited significant trends of a decreasing number of days below 0°C, 19 and 12 days respectively

Duration-Based Extreme Indices:
- Warm Spell Duration Index – only Pinhão exhibited a significant trend toward more warm spells (when the daily maximum temperature exceeds the 90th percentile for six straight days)
- Cold Spell Duration Index – Régua and Pinhão (Figure 22) exhibited significant trends toward fewer cold spells (when the daily minimum temperature falls below the 10th percentile for six straight days)
- Growing Season Length (days) – only Régua exhibited a significant trend toward longer growing seasons (8 days)

Other Temperature-Based Indices:
- Diurnal Temperature Range (°C) – all three stations showed trends of a decreasing DTR, ranging from -0.6°C for Vila Real, -1.0°C for Pinhão, and 1.9°C for Régua

Precipitation-Based Average and Extreme Indices:
- Maximum 1-Day Precipitation – no significant trends
- Maximum 5-Day Precipitation – no significant trends
- Simple Precipitation Intensity Index – Pinhão exhibited a significant increase in the ratio of annual precipitation to the number of days of precipitation during the year
- Annual # of Days Precipitation > 10 mm – no significant trends
- Annual # of Days Precipitation > 20 mm – Pinhão exhibited a significant trend in the total number of days with precipitation greater than 20 mm
- Maximum Length of Dry Spell – no significant trends
- Maximum Length of Wet Spell – no significant trends
- Annual # of Days with Precipitation > 95 Percentile – no significant trends
- Annual # of Days with Precipitation > 99 Percentile - no significant trends
- Annual Precipitation Total – no significant trends
<table>
<thead>
<tr>
<th>Indices</th>
<th>Régua</th>
<th>P-Value</th>
<th>Slope</th>
<th>Pinhão</th>
<th>P-Value</th>
<th>Slope</th>
<th>Vila Real</th>
<th>P-Value</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Days Tmax &gt; 35°C (days)</td>
<td>0.28</td>
<td>0.000</td>
<td>0.432</td>
<td>0.23</td>
<td>0.001</td>
<td>0.374</td>
<td>0.145</td>
<td>0.082</td>
<td></td>
</tr>
<tr>
<td># of Days Tmax &gt; 25°C (days)</td>
<td>0.23</td>
<td>0.001</td>
<td>0.595</td>
<td>0.16</td>
<td>0.007</td>
<td>0.481</td>
<td>0.376</td>
<td>0.136</td>
<td></td>
</tr>
<tr>
<td># of Days Tmax &lt; 0°C (days)</td>
<td>Not Observed</td>
<td></td>
<td></td>
<td>Not Observed</td>
<td></td>
<td></td>
<td>NS</td>
<td>0.322</td>
<td>-0.003</td>
</tr>
<tr>
<td># of Days Tmin &gt; 20°C (days)</td>
<td>0.42</td>
<td>0.000</td>
<td>0.312</td>
<td>0.24</td>
<td>0.001</td>
<td>0.220</td>
<td>0.30</td>
<td>0.000</td>
<td>0.143</td>
</tr>
<tr>
<td># of Days Tmin &lt; 0°C (days)</td>
<td>0.42</td>
<td>0.000</td>
<td>-0.436</td>
<td>0.15</td>
<td>0.008</td>
<td>-0.264</td>
<td>NS</td>
<td>0.106</td>
<td>-0.139</td>
</tr>
<tr>
<td>Growing Season Length (days)</td>
<td>0.13</td>
<td>0.017</td>
<td>0.189</td>
<td>NS</td>
<td>0.097</td>
<td>0.186</td>
<td>NS</td>
<td>0.208</td>
<td>-0.227</td>
</tr>
<tr>
<td>Maximum Tmax (°C)</td>
<td>0.24</td>
<td>0.001</td>
<td>0.051</td>
<td>0.18</td>
<td>0.004</td>
<td>0.058</td>
<td>NS</td>
<td>0.292</td>
<td>0.018</td>
</tr>
<tr>
<td>Minimum Tmax (°C)</td>
<td>0.41</td>
<td>0.000</td>
<td>0.099</td>
<td>0.20</td>
<td>0.003</td>
<td>0.076</td>
<td>0.25</td>
<td>0.000</td>
<td>0.067</td>
</tr>
<tr>
<td>Maximum Tmin (°C)</td>
<td>NS</td>
<td>0.530</td>
<td>0.013</td>
<td>NS</td>
<td>0.678</td>
<td>-0.008</td>
<td>NS</td>
<td>0.970</td>
<td>0.001</td>
</tr>
<tr>
<td>Minimum Tmin (°C)</td>
<td>0.20</td>
<td>0.002</td>
<td>0.045</td>
<td>0.18</td>
<td>0.004</td>
<td>0.051</td>
<td>NS</td>
<td>0.072</td>
<td>0.028</td>
</tr>
<tr>
<td>% of Days Tmax &lt; 10th Percentile (%)</td>
<td>0.10</td>
<td>0.033</td>
<td>-0.097</td>
<td>NS</td>
<td>0.085</td>
<td>-0.089</td>
<td>NS</td>
<td>0.540</td>
<td>-0.028</td>
</tr>
<tr>
<td>% of Days Tmax &gt; 90th Percentile (%)</td>
<td>0.26</td>
<td>0.000</td>
<td>0.184</td>
<td>0.16</td>
<td>0.007</td>
<td>0.151</td>
<td>NS</td>
<td>0.125</td>
<td>0.077</td>
</tr>
<tr>
<td>% of Days Tmin &lt; 10th Percentile (%)</td>
<td>0.70</td>
<td>0.000</td>
<td>-0.460</td>
<td>0.61</td>
<td>0.000</td>
<td>-0.312</td>
<td>0.29</td>
<td>0.000</td>
<td>-0.136</td>
</tr>
<tr>
<td>% of Days Tmin &gt; 90th Percentile (%)</td>
<td>0.65</td>
<td>0.000</td>
<td>0.439</td>
<td>0.39</td>
<td>0.000</td>
<td>0.279</td>
<td>0.33</td>
<td>0.000</td>
<td>0.217</td>
</tr>
<tr>
<td>Warm Spell Duration Index (days)</td>
<td>NS</td>
<td>0.100</td>
<td>0.127</td>
<td>0.14</td>
<td>0.012</td>
<td>0.272</td>
<td>NS</td>
<td>0.867</td>
<td>0.018</td>
</tr>
<tr>
<td>Cold Spell Duration Index (days)</td>
<td>0.37</td>
<td>0.000</td>
<td>-0.390</td>
<td>0.18</td>
<td>0.004</td>
<td>-0.244</td>
<td>NS</td>
<td>0.108</td>
<td>-0.074</td>
</tr>
<tr>
<td>Diurnal Temperature Range (°C)</td>
<td>0.50</td>
<td>0.000</td>
<td>-0.045</td>
<td>0.22</td>
<td>0.005</td>
<td>-0.024</td>
<td>0.13</td>
<td>0.018</td>
<td>-0.015</td>
</tr>
<tr>
<td>Monthly Maximum 1-Day Precipitation (mm)</td>
<td>NS</td>
<td>0.954</td>
<td>0.010</td>
<td>NS</td>
<td>0.140</td>
<td>0.207</td>
<td>NS</td>
<td>0.572</td>
<td>-0.103</td>
</tr>
<tr>
<td>Monthly Maximum 5-Day Precipitation (mm)</td>
<td>NS</td>
<td>0.667</td>
<td>-0.125</td>
<td>NS</td>
<td>0.102</td>
<td>0.496</td>
<td>NS</td>
<td>0.147</td>
<td>-0.703</td>
</tr>
<tr>
<td>Simple Precipitation Intensity Index (mm/day)</td>
<td>NS</td>
<td>0.182</td>
<td>0.022</td>
<td>0.14</td>
<td>0.011</td>
<td>0.053</td>
<td>NS</td>
<td>0.081</td>
<td>-0.036</td>
</tr>
<tr>
<td>Annual # of Days Precipitation &gt; 10 mm (days)</td>
<td>NS</td>
<td>0.366</td>
<td>-0.094</td>
<td>NS</td>
<td>0.200</td>
<td>0.121</td>
<td>NS</td>
<td>0.405</td>
<td>-0.093</td>
</tr>
<tr>
<td>Annual # of Days Precipitation &gt; 20 mm (days)</td>
<td>NS</td>
<td>0.681</td>
<td>0.020</td>
<td>0.09</td>
<td>0.050</td>
<td>0.080</td>
<td>NS</td>
<td>0.843</td>
<td>-0.014</td>
</tr>
<tr>
<td>Maximum Length of Dry Spell (days)</td>
<td>NS</td>
<td>0.295</td>
<td>0.181</td>
<td>NS</td>
<td>0.916</td>
<td>-0.024</td>
<td>NS</td>
<td>0.286</td>
<td>-0.188</td>
</tr>
<tr>
<td>Maximum Length of Wet Spell (days)</td>
<td>NS</td>
<td>0.122</td>
<td>-0.058</td>
<td>NS</td>
<td>0.165</td>
<td>-0.052</td>
<td>NS</td>
<td>0.626</td>
<td>0.018</td>
</tr>
<tr>
<td>Annual # of Days with Precipitation &gt; 95 Percentile (days)</td>
<td>NS</td>
<td>0.346</td>
<td>1.254</td>
<td>NS</td>
<td>0.226</td>
<td>3.167</td>
<td>NS</td>
<td>0.234</td>
<td>-2.071</td>
</tr>
<tr>
<td>Annual # of Days with Precipitation &gt; 99 Percentile (days)</td>
<td>NS</td>
<td>0.821</td>
<td>-0.158</td>
<td>NS</td>
<td>0.418</td>
<td>2.062</td>
<td>NS</td>
<td>0.198</td>
<td>-1.083</td>
</tr>
<tr>
<td>Annual Precipitation Total (mm)</td>
<td>NS</td>
<td>0.524</td>
<td>-1.512</td>
<td>NS</td>
<td>0.573</td>
<td>1.265</td>
<td>NS</td>
<td>0.404</td>
<td>-2.513</td>
</tr>
</tbody>
</table>
Figure 21: Example time series of the percentage of days when the minimum temperature is above the 90th percentile (left panel) and below the 10th percentile (right panel) for Régua during 1967-2010. Trends are computed by linear least squares (solid line) and locally weighted linear regression (dashed line).

Figure 22: Example time series of the cold spell duration index (left panel; when the daily minimum temperature falls below the 10th percentile for six straight days) and the number of days per year when the maximum temperature is greater than 35°C (right panel) for Pinhão during 1967-2010. Trends are computed by linear least squares (solid line) and locally weighted linear regression (dashed line).

Figure 23: Example time series of the number of days per year when the minimum temperature is greater than 20°C (left panel) and the highest minimum daily temperature observed each year (right panel) for Vila Real during 1967-2010. Trends are computed by linear least squares (solid line) and locally weighted linear regression (dashed line).
Changes in temperature extremes have been noted by others as well. In general, recent trends in temperature extremes reflect the general warming with fewer cold extremes, more warm extremes, and a lengthening of the freeze-free season in most mid- and high latitude regions (IPCC, 2007). Alexander et al. (2006) examining global climate extremes using the same ETCCDMI method used in this assessment, found widespread and significant changes in temperature extremes with the overall warming, which was especially evident in minimum temperatures. Both the spatial area and magnitude of trends in minimum temperatures are greater than maximum temperatures during 1951-2003. The work of Alexander et al. (2006) shows significant trends in decreases in cold nights, increases in warm nights, and increases in warm days over the Iberian Peninsula during this time period. Other regional research examining temperature extremes show projections in maximum temperature extremes (Tmax > 90th percentile) later in the 21st Century that could reach values 7°C more than today over much of the Iberian peninsula and that they increase more in the spring and summer, than fall and winter (de Castro et al. 2005). The authors also found that the frequency of days with extreme minimum temperatures (Tmin < 10th percentile) tends to decrease. Trends in precipitation extremes were less consistent, with some minor changes in dry periods, but no significant changes in heavy precipitation events (de Castro et al. 2005). Brunet et al. (2007) also examined extremes over Spain during 1850-2005 and noted that the overall warming has been more associated with reductions in cold extremes as opposed to warm extremes. Also using the same ETCCDMI method used in this assessment, Ramos et al. (2011) examined extremes for 23 main climate stations in Portugal. Generalized trends averaged over all stations revealed that both maximum and minimum temperatures declined during the 1941-1975 period, then increased by 0.49°C and 0.54°C per decade during 1976-2006 for maximum and minimum temperatures, respectively. The authors noted that the warming rates were significantly higher than similar trends computed at the global and European scales. For extremes Ramos et al. (2011) found similar results to the Douro Wine Region assessment, with statistically significant positive trends in the warm extremes (e.g., tropical nights, summer days, warm spells, warm nights and warm days).

While this assessment of the three stations in the Douro Wine Region during 1967-2010 did not show any broad evidence of significant changes in precipitation or dry spells, other regional research over a longer time period has. Vicente-Serrano et al. (2011a) examined drought severity and surface water resources over the NW Iberian Peninsula during 1930-2006. The results from variability and trends in the standardized precipitation index (SPI) and the standardized precipitation evaporation index (SPEI) show that precipitation has generally increased over the region, however potential evapotranspiration has increased as well due to warming. Vicente-Serrano et al. (2011) did not find any evidence for increasing drought severity during 1930-2006, however the mean duration of drought episodes has increased by approximately a month over the last three decades. River discharge over NW Iberia was shown to be largely driven by precipitation variability with less influence from regional warming during the time period.
For 1948-2011 the regional circulation over the eastern Atlantic Ocean, Western Europe, and the Mediterranean have been classed into six dominant weather regimes (Figure 24). Ridging conditions (R) are the most frequent during the time period representing 28.6% of all days and seasonally is more common from April through September when it represents 27 to 62% of the days in each month (Figure 25). Ridging typically represents days of clear skies, high solar radiation potential, and moderate to extreme high temperatures. Anticyclonic conditions (AA), with centers over the Azores and Europe, occurs 17.9% of all days and is more evenly distributed over the months with a September maximum at 27% of the days in the month. Anticyclonic conditions also tend to be clear skies, but can represent more moderate temperatures depending on the time of the year. Easterly flow (E) is next most frequent, occurring 16.3% of all days and having a maximum occurrence during the winter where it represents 21-25% of all days during the months of December through March (Figure 25). Easterly flow often brings cold air off of Eastern Europe, resulting in cold events over Iberia when it occurs during the winter and spring. Flow from the northwest (NW) occurs 14.6% of all days during 1948-2011 and tends to be more frequent during the fall and early winter (September-December) when it represents up to 21% of the days in the month. Northwest flow typically represents frontal passages from a low pressure area centered over the British Isles and is often the prominent pattern during the shift from late summer stable conditions to the transition to fall/winter. General anticyclonic conditions (A) occur 12.2% of all days (Figure 25) with strong seasonality to the winter months when it represents from 10-22% of all days in the months. Over Portugal the conditions associated with anticyclonic conditions (A) are often the clear, cold days between frontal transitions. The weather regime that is least frequent during the time period is the cyclonic regime (C) which occurs 10.3% of all days and has little seasonality varying by 7-14% of the days in each month (Figure 25). The cyclonic regime (C) is a transient flow associated with the passage of fronts and is typically the wettest of the six regimes.

The annual, growing season (Apr-Oct) and dormant season (Nov-Mar) frequency of each of the six weather regimes often ranges from nearly 25% of the mean to nearly twice the mean occurrence. For example, cyclonic conditions (C) during the growing season has averaged 20 days during April through October, but varied from a low of 4 days in 1970 to high of 47 days in 1993. The result was that precipitation during 1970 was the lowest during the 1967-2010 period at Régua, while 1993 was the highest. A winter example is with anticyclonic conditions (A), which during the 1975-76 winter were nearly twice as frequent and resulted in the coldest winter during 1967-2010 at Régua.

While it is evident that the daily weather regimes result in the daily weather over the Douro Wine Region, the complexity in the region’s terrain potentially results in less obvious relationship between the regional circulation and local weather. Correlations between annual, growing season, and dormant season weather regimes and average maximum and minimum temperatures and precipitation detail these characteristics. On an annual basis during 1967-
2010, average maximum temperatures do not exhibit significant correlations with the climate data from Régua. Average minimum temperatures do show a significant relationship with ridging conditions (R), where increased ridging brings about generally cooler years ($R^2=0.11$). In terms of annual precipitation amounts, cyclonic conditions are related to higher amounts in Régua during 1967-2010, but only explains 12% of the variation. Similar relationships are found with increased ridging conditions during the growing season resulting cooler years, although the cooling effect comes more from the increased frequency of spring events rather summer events. The most prominent influence during the growing season where 27% of the variation in precipitation is described by variations is cyclonic conditions (C). During the winter correlations between regional circulation and the local weather increase. Average maximum temperatures during the winter are significantly lower when easterly flow (E) increases. Average minimum temperatures during the winter in the region are influenced by ridging (R), cyclonic (C), and northwest flow (NW) conditions, which together explain 43% of the variation. Increased ridging typically brings colder winters, while increased cyclonic and northwest flow generally bring warmer winters. Winter precipitation levels exhibit the strongest correlation with the weather regimes with cyclonic (C) and northwest flow (NW) conditions explaining 84% of the variation during 1967-2010. The effect is for higher rainfall during winters with increased cyclonic conditions from both regimes. The increased relationships between weather regimes and local weather variations during the winter are common in circulation studies (Jones and Davis, 2000a).

Over the period of the circulation analysis (1948-2010) some of the weather regimes exhibit significant trends. For the annual period, anticyclone (A) conditions have increased slightly ($R^2=0.09$) and ridging (R) has declined moderately ($R^2=0.22$). Most of the annual decline in ridging (R) conditions has come during the growing season ($R^2=0.20$). During the winter only a slight decline in the dual anticyclone conditions (AA) has been seen ($R^2=0.08$). Given the few trends in weather regimes, but significant trends in annual, growing season, and dormant season temperatures, the results point to a general warming that is not being significantly driven by regional circulation changes.
Figure 24: Mean sea level pressure fields for the six weather regimes derived from the PCA-Cluster Analysis. A-Anticyclone; R-Ridge; NW-Northwesterly Flow; E-Easterly Flow; AA-Anticyclones over the Azores and Europe; and C-Cyclone.

Figure 25: Monthly frequencies of the six weather regimes derived from the PCA-Cluster Analysis. A-Anticyclone; R-Ridge; NW-Northwesterly Flow; E-Easterly Flow; AA-Anticyclones over the Azores and Europe; and C-Cyclone.
Other work examining synoptic conditions that affect Europe and other wine regions has found similar results to those described above. Jones and Davis (2000b) found that regional circulation and air mass synoptic climatologies were effective at describing the variability of the local climate for Bordeaux, France. The authors noted that frequencies in certain synoptic events influenced grapevine phenology, wine production, and wine quality for the region. Jones and Davis (2000b) found that increased frequencies of late spring anticyclones tended to bring cold events that delayed growth, that higher frequencies of cyclonic events during bloom were related to lower production, while higher frequencies of ridging and stable air masses lead to full ripeness and higher wine quality in Bordeaux. Examining both olive and wine production in Portugal, Gouveia et al. (2007) find that both show significant relationships to winter and spring NAO index variability, but that the results are more significant for high quality olive production and for some areas of Portugal more than others. Another recent study by Gouveia et al. (2011) also found that higher temperatures during late spring were beneficial to wine production in the DV. Furthermore, evidence has been given for the presence of cycles in the wine production time series in the DV that can be mostly attributed to springtime temperature variability (Cunha and Richter, 2011). Port wine vintage quality has been shown to be related to maximum temperature and precipitation during spring and summer (Gouveia et al. 2010). Gómez-Gesteira et al (2011) also note shifts in the synoptic conditions over the region with a general decline in winter cyclone frequency, which strongly controls wintertime precipitation, and a decline in winter/spring blocking which is related to warmer spring conditions.

Santos et al. (2012) found spatially coherent structure and trends in heat accumulation over Europe (Huglin and Winkler indices) that is strongly controlled by the large-scale atmospheric circulation during the growing season (April-September). Andrade et al. (2011) found that the anomalously wet 2009-2010 winter in Portugal was characterized by an anomalously strong westerly flow component over the North Atlantic that resulted in an increased frequency of cyclonic events. Vicente-Serrano et al. (2011b) shows how the heaviest rain events were tied to the most extreme negative NAO index values and that 21st Century projections show that NAO trends to more positive values. However, the authors note that extreme negative NAO values such as observed during 2009-2010 will likely still occur.

Santos et al. (2011) found that roughly 50% of the variation in yield during 1986-2008 could be explained by monthly temperatures and precipitation in statistical grapevine yield model. The most important climate factors were temperatures and precipitation during the early growth stages (bud break and bloom). Ensemble projections under the A1B scenario indicated that yield will likely increase throughout the 21st Century. Santos et al. (2012) updated the previous study by including a longer wine production series covering 1932-2010 finding that high rainfall and cool temperatures during bud break, shoot and inflorescence development (February-March) and warm temperatures during flowering and berry development (May) are generally favorable to high production. Examining the probabilities associated with low, normal, and high wine production years, the authors find early season (3-4 month lead time) predictability in overall production volume. Using the same ensemble
projections under the A1B scenario in Santos et al. (2011) but including 16 transient experiments with different GCM / RCMs model chains, the updated study indicated that wine production is expected to increase by approximately 10% by the end of the 21st Century and that high production years will be more common in the future (from 25% of all years currently to over 60% by the end of the 21st Century). However, the modeling efforts need to account for other climate aspects that affect production such as increasing heat stress and/or changes in ripening conditions that could the projected increases (Santos et al., 2012).

**Spatial Climate: Historic**

The analysis of the WorldClim for 1950-2000 at a 1km resolution shows a more detailed spatial framework of the climate parameters (e.g., annual precipitation in Figure 26) compared to the generalized mapped station data from the 1931-1960 time period (Figure 8) or the individual station analyses (Table 4). Even though the 1931-1960 station data and the 1950-2000 WorldClim gridded data only overlap by ten years, a comparison of the values should show relatively high correlation and would further indicate the usefulness of the WorldClim data for this assessment. Comparing the 1931-1960 station data and the WorldClim grid that covers the same latitude and longitude point of the stations finds that maximum temperatures ($r > 0.80$) are higher correlated than minimum temperatures ($r > 0.70$). The difference is expected as minimum temperatures typically vary more over a heterogeneous area such as the Douro Wine Region. The correlation for precipitation is lower ($r > 0.50$) than for temperature, but overall shows the general similarity in the two data sets.

Overall the region experiences a median annual precipitation of 950 mm (Figure 26); however this ranges from 1190 mm in the Baixo Corgo to 832 mm in the Douro Superior (Table 7). The driest location in Douro Superior experiences 643 mm per year on average, while the wettest area is in the mountains along the western boundary of the Baixo Corgo with 1625 mm (Figure 26, Table 7). Winter precipitation amounts (November through March) are approximately 60-65% of the annual total (Figure 27), while growing season precipitation is roughly 35-40% (Figure 28), however similar west to east, wet to dry conditions are evident (Appendix Table 1). Breaking down the annual precipitation into monthly totals (Figure 29) shows a consistent spatial variation in the region, with January and February being the wettest months, and the strong seasonality with the driest months of July and August experiencing very little precipitation over the entire region. The Baixo Corgo is the wettest in every month (Figure 30) owing to the upland areas to the west which receive most of the precipitation.

Table 7: Quartile statistics for annual precipitation and average annual temperatures for the three sub-regions of the Douro Wine Region. The values represent the spatial statistics of each variable; absolute minimum, 25%, median, 75%, and absolute maximum. Data Source: WorldClim Database (Hijmans et al. 2005).

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baixo Corgo</td>
<td>971</td>
<td>1128</td>
<td>1190</td>
<td>1282</td>
<td>1625</td>
</tr>
<tr>
<td>Cima Corgo</td>
<td>778</td>
<td>938</td>
<td>1026</td>
<td>1089</td>
<td>1314</td>
</tr>
<tr>
<td>Douro Superior</td>
<td>643</td>
<td>776</td>
<td>832</td>
<td>927</td>
<td>1123</td>
</tr>
</tbody>
</table>
Figure 27: Winter precipitation (November through March) for the Douro Wine Region during 1950-2000. Data Source: WorldClim Database (Hijmans et al. 2005).

Figure 28: Growing season precipitation (April through October) for the Douro Wine Region during 1950-2000. Data Source: WorldClim Database (Hijmans et al. 2005).
Figure 29: Average monthly precipitation during 1950-2000 for the Douro Wine Region. Data Source: WorldClim Database (Hijmans et al. 2005).
The WorldClim data also shows a much finer scale structure and characteristics of annual temperature (Figure 31) compared to the earlier 1931-1960 maps (Figure 9). On an annual basis, the Douro Wine Region averages 13.7°C, with higher values in the lower elevations and toward the east and lower values in the upper elevations throughout the region (Figure 31). By sub-region, annual average temperatures do not vary much (13.5-13.8°C; Table 8) but there is relatively large variation over the seasons. For example, average monthly maximum temperatures show that during the winter the sub-regions show similar values (Figure 32) while during the summer Douro Superior has a larger area of higher maximum temperatures than the other two sub-regions. During the growing season maximum temperatures average 23.8°C over the entire region while minimum temperatures average 11.6°C (Appendix Figures 2 & 3 and Appendix Table 1). Douro Superior, on average, has warmer maximum and minimum temperatures during the growing season compared to Baixo Corgo and Cima Corgo. Winter maximum temperatures average 12.2°C over the entire region while minimum temperatures average 3.9°C (Appendix 5 & 6 and Appendix Table 1). During the winter, Baixo Corgo tends to be slightly warmer due to its proximity to the coast, but the higher elevations in the sub-region tend to be some of the coolest seen in the entire Douro Wine Region. In both monthly maximum and minimum temperatures similar monthly progressions are seen with the main stem of the Douro Valley and its tributary valleys warming first and/or staying warmer longer (Figures 32 and 33). As plotted in Figure 34, the differences between the three sub-regions on average do not appear to be that great, however the larger area of the Douro Superior and its numerous high elevation zones, reduce the differences seen in the averages.
Table 8: Quartile statistics for average annual temperatures for the three sub-regions of the Douro Wine Region. The values represent the spatial statistics of each variable; absolute minimum, 25%, median, 75%, and absolute maximum. Data Source: WorldClim Database (Hijmans et al. 2005).

<table>
<thead>
<tr>
<th>Region</th>
<th>Minimum (°C)</th>
<th>25% (°C)</th>
<th>Median (°C)</th>
<th>75% (°C)</th>
<th>Maximum (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baixo Corgo</td>
<td>8.6</td>
<td>12.7</td>
<td>13.6</td>
<td>14.1</td>
<td>15.5</td>
</tr>
<tr>
<td>Cima Corgo</td>
<td>11.0</td>
<td>12.8</td>
<td>13.5</td>
<td>14.2</td>
<td>15.7</td>
</tr>
<tr>
<td>Douro Superior</td>
<td>11.5</td>
<td>13.0</td>
<td>13.8</td>
<td>14.4</td>
<td>15.5</td>
</tr>
</tbody>
</table>
Figure 32: Average monthly maximum temperatures during 1950-2000 for the Douro Wine Region. Data source: WorldClim database (Hijmans et al., 2005).

Map Scale: 1:350,000

Region: Wine Region Douro

1950-2000 Maximum Temperatures

Average Monthly Average
Figure 33: Average monthly minimum temperatures during 1950-2000 for the Douro Wine Region. Data Source: WorldClim Database (Hijmans et al. 2005).
Figure 34: Average monthly maximum and minimum temperatures for the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) for the Douro Wine Region. Values are the spatial median temperatures over the regions as depicted in Figures 32 and 33.

Examining the spatial characteristics of three commonly used indices for assessing viticultural suitability finds that historically the Douro Wine Region has been mostly a warm to warm temperate climate for wine production. For growing season average temperatures (GST) the overall Douro Wine Region spatial average for 1950-2000 is 17.8°C. However, GST varies over the region with warmer conditions along the Douro River and its main tributaries and cooler areas in the upper elevations (Figure 35). GST ranges 7.6°C from a low of 12.1°C, which would be considered too cool for viticulture, to a high of 19.7°C (Table 9). While the median GST values in Table 9 show somewhat similar conditions across the three sub-regions, the best statistical measure to use for assessing spatial suitability over these areas is the inter-quartile range (IQR; 25% to 75%). These values show that the Baixo Corgo is the coolest with an IQR from 16.5°C to 17.9°C, the Cima Corgo with an IQR from 16.8°C to 18.3°C, and the Douro Superior the warmest with an IQR from 17.1°C to 18.6°C (Table 9). Overall the region is 65% a Warm climate, 24% an Intermediate climate and nearly 10% a Hot climate type on the GST (Figure 36). By sub-region each area is predominately a Warm climate type with 76%, 63%, and 71% percent of the area in the Baixo Corgo, the Cima Corgo, and the Douro Superior respectively. The Cima Corgo has more area as an Intermediate climate type that the other two regions and the Douro Superior has twice the area in a Hot climate type as the other two regions.

Figure 36: Percentage of the Douro Wine Region and the three sub-regions in each class of the growing season average temperature index during 1950-2000. Data Source: WorldClim Database (Hijmans et al. 2005).
Table 9: Quartile statistics for growing season average temperatures (April-October), growing degree-days (April-October), and the Huglin Index (April-September) for the three sub-regions of the Douro Wine Region. The values represent the spatial statistics of each variable; absolute minimum, 25%, median, 75%, and absolute maximum. Data Source: WorldClim Database (Hijmans et al. 2005).

<table>
<thead>
<tr>
<th>Growing Season Average Temperature</th>
<th>Region</th>
<th>Minimum (°C)</th>
<th>25% (°C)</th>
<th>Median (°C)</th>
<th>75% (°C)</th>
<th>Maximum (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>12.1</td>
<td>16.5</td>
<td>17.5</td>
<td>17.9</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>14.9</td>
<td>16.8</td>
<td>17.5</td>
<td>18.3</td>
<td>19.7</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>15.6</td>
<td>17.1</td>
<td>18.0</td>
<td>18.6</td>
<td>19.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growing Degree-Days</th>
<th>Region</th>
<th>Minimum</th>
<th>25%</th>
<th>Median</th>
<th>75%</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>615</td>
<td>1411</td>
<td>1606</td>
<td>1708</td>
<td>1977</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>1084</td>
<td>1474</td>
<td>1622</td>
<td>1781</td>
<td>2081</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>1207</td>
<td>1537</td>
<td>1717</td>
<td>1855</td>
<td>2090</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Huglin Index</th>
<th>Region</th>
<th>Minimum</th>
<th>25%</th>
<th>Median</th>
<th>75%</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>978</td>
<td>1900</td>
<td>2087</td>
<td>2175</td>
<td>2370</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>1537</td>
<td>1968</td>
<td>2118</td>
<td>2263</td>
<td>2515</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>1709</td>
<td>2034</td>
<td>2200</td>
<td>2327</td>
<td>2542</td>
</tr>
</tbody>
</table>

Growing degree-days (GDD) during 1950-2000 average 1680 over the entire Douro Wine Region, with a similar pattern to that seen in GST. However, while GST and GDD are functionally identical indices (Jones et al. 2010), note that the index classes are not equivalent and not directly comparable. GDD accumulation is highest along the main valley and its tributary valleys and in the Douro Superior (Figure 37). The range in GDD observed over the region is 1475 units from the lowest GDD of 615 in the mountains along the western boundary of the Baixo Corgo, to a high of 2090 observed just south of Barca d’Alva in Douro Superior (Table 9). The entire area is just over 41% a Winkler Region II, just under 40% a Winkler Region III, and 10% a Winkler Region IV (Figure 38). As mentioned above for GST, the IQR is a good measure of describing the main structural area of the sub-regions and with GDD the results shows the Baixo Corgo with an IQR of 1411 to 1708, Cima Corgo with an IQR of 1474 to 1781, and Douro Superior with an IQR of 1537 to 1855. These values place Baixo Corgo as predominately (50%) a Winkler Region III, while the Cima Corgo is mostly a Winkler Region II (48%) (Figure 38). Douro Superior is largely a Winkler Region III (45%), but contains twice as much area in Winkler Region IV (15%) than the other two sub-regions (Figure 38; Table 9).
Figure 37: Growing degree-days for the Douro Wine Region during 1950-2000. Values calculated with a base temperature of 10°C with no upper cut-off and summed over the months of April through October. The legend has both values and Winkler Index regions of suitability (Winkler et al. 1974) with an update to Region I and upper and lower limits implemented by Jones et al. (2011). Also note the class limits are rounded to equivalent °F units as the Winkler Index was originally developed. Data Source: WorldClim Database (Hijmans et al. 2005).

Figure 38: Percentage of the Douro Wine Region and the three sub-regions in each class of the Winkler Region index based upon growing degree-day classes during 1950-2000. Data Source: WorldClim Database (Hijmans et al. 2005).
For the Huglin Index (HI), the Douro Wine Region spatially averages 2160 or just over 50% a Warm Temperate climate, 35% a Temperate climate, 10% a Warm climate, and 4% a cool climate for viticulture (Figures 39 and 40). The range in HI over the Douro Wine Region is 1564 with a similar pattern of lower values in the higher elevations and west to higher values along the rivers and east (Figure 39). The HI IQR for the Baixo Corgo is 1900 to 2175, while for the Cima Corgo the IQR is 1968 to 2263 and for the Douro Superior the IQR is 2034 to 2327 (Table 9). By percentage, the Baixo Corgo is 65% Warm Temperate, 25% Temperate, and less than 5% for Cool and Warm climate types (Figure 40). The Cima Corgo is also largely Warm Temperate (47%) and Temperate (41%), but has nearly twice the area in Warm (8%) as Baixo Corgo. The Douro Superior sub-region is predominately Warm Temperate (55%), but has over twice the area in Warm (16%) as does Cima Corgo. While the HI and the GDD are summing similar heat accumulation characteristics, the addition of a day length factor and weighting maximum temperatures higher makes them not directly comparable. Also, the class limits on the GST, GDD, and HI are not equivalent (e.g., a Warm GST is not necessarily a Warm HI, etc.).

Figure 39: Huglin Index for the Douro Wine Region during 1950-2000. Values calculated with a base temperature of 10°C with no upper cut-off, with a latitude correction applied, and summed over the months of April through September. The legend has both values and Huglin Index categories of suitability as given in Huglin (1978). Data Source: WorldClim Database (Hijmans et al. 2005).
Spatial Climate: Future Projections

Future climate for the Douro Wine Region is assessed for three future time slices (2020, 2050, and 2080), for three greenhouse gas emission scenarios (B2, A1B, and A2) using the HADCM3 model and are compared to historic conditions (1950-2000). For annual average precipitation the projected changes are near zero to declines as much as 21.6% (Figures 41 and 45). The B2 scenario projects little change with minor decreases by 2020 and 2050, but slight increases by 2080. The A1B scenario projects 6-7% declines in annual precipitation by 2020, 13-15% by 2050, and 18-22% by 2080. The A2 scenario has slightly lower magnitudes of the projected changes, with nearly no change through 2050 and 15-17% by 2080. Winter precipitation is not projected to change as much and is even projected to increase in some scenarios (Figure 45 and Appendix Figure 1). Projections for the B2 scenario show increase on the order of 7-17% increases in winter precipitation from current conditions through 2080. The A1B scenario predicts slight decreases on the order of 1-7% over the same time period, while the A2 scenario is mixed with increases of 8-10% through 2050 and slight decreases near 2% by 2080. It is in the growing season that the greatest changes are projected for precipitation (Figure 45 and Appendix Figure 2). All scenarios for the growing season project decreases with the B2 scenario showing declines up 19% by 2050 and then lower declines on the order of 8-10% by 2080. The A1B scenario projects declines in growing season precipitation that range from 13-14% by 2020 to nearly 42% in the Douro Superior by 2080. The A2 scenario predicts similar declines in growing season precipitation, but at a slightly lower rate of 4-40%.
Average annual temperatures, which spatially average between 13.5-14.0°C for the Douro Wine Region during 1950-2000 are projected to warm across all emission scenarios and time periods (Figures 42 and 46). By 2020 warming is projected to range from 0.5-0.7°C for the A2 scenario, 0.7-0.9°C in the B2 scenario, and 1.3-1.4°C in the A1B scenario. For 2050 projected warming is similar for the B2 and A2 scenarios, ranging 1.4-1.9°C, but up to 3.3°C for the A1B scenario (Figure 42). By 2080 the projections indicate potential warming of 2.1-2.6°C with the B2 scenario, 3.1-3.8°C for the A2 scenario, and 4.9-5.1°C for the A1B scenario. By sub-region, the A1B shows nearly equal average annual temperature warming while the B2 and A2 scenarios projects greater warming from west to east with the Douro Superior warming the most.

During the dormant season (November through March) projected warming in average maximum temperatures ranges from 0.4-0.9°C by 2020, 1.1-2.0°C by 2050, and 1.5-3.2°C by 2080 (Appendix Figure 5). Similar to annual temperatures, the A1B scenario exhibits higher warming than does the A2 and B2 scenarios. Average minimum temperatures during the dormant season are also projected to warm with ranges of 0.4-0.8°C by 2020, 1.0-1.8°C by 2050, and 1.5-2.8°C by 2080. For the HADCM3 model and across the three emission scenarios there is a slight difference in projected warming during the dormant season, with maximum temperatures warming more than minimum temperatures (Appendix Figures 5 & 6). The warming patterns over the Douro Wine Region show greater increases initially in the main stem of the river valley, followed by broad warming over the Douro Superior, then warming in the upland zones throughout most of the region.

For the growing season (April-October) the Douro Wine Region spatially averages 17.0-18.0°C for growing season average temperatures (GST) (Figure 43; Table 9). Future changes in these three indices are evident with projected warming in GST of 0.6-1.8°C by 2020, 1.8-4.3°C by 2050, and 2.5-6.6°C by 2080 (Figure 43). The spatial pattern of warming within the region is similar to that observed in annual or dormant season temperatures. The greatest GST warming is projected to occur with the A1B scenario by 2080. Breaking the GST into maximum and minimum temperatures finds greater projected warming for daytime maximum temperatures during the growing season with rates of 0.8-7.9°C across all emission scenarios and time slices compared to 0.4-5.1°C for nighttime minimum temperatures (Appendix Figures 3 & 4). This would imply a potential increase in the diurnal temperature range, but at higher overall values. Averaged over the entire region, GST changes of these magnitudes would move the Douro Wine Region from a Warm climate suitability region to Hot climate suitability or at the upper limits of the Very Hot climate suitability, depending on scenario (Figure 47). Spatially, the 1950-2000 climate structure for GST for the region was approximately 65% a Warm climate suitability, 25% Intermediate, and 10% Hot (Figure 38). Averaged across all three emission scenarios for each time slice, projections show the potential for large changes the percentage of area in each GST class with the region 50% Warm and 43% Hot by 2020 (Figure 48). Further changes by 2050 could result in only 14% of the Douro Wine Region in the Warm climate suitability, 50% in the Hot, and 36% in the Very Hot. By 2080 GST changes potentially could result in nearly 19% of the landscape becoming Too Hot, 54% Very Hot, 25% Hot, and less than
3% Cool, Intermediate or Warm (Figure 48). The pattern of the changes shows warming increasing most rapidly along the main sections of the river valley, then across the Douro Superior, and by 2080 up in elevation across much of the region (Figure 43).

Growing degree-days (GDD) for the Douro Wine Region have spatially averaged 1600-1725 during 1950-2000 (Figure 44; Table 9). The future assessment of GDD in the region shows projections of increases from 100 to nearly 400 units by 2020, 350 to 900 units by 2050, and 500 to 1400 units by 2080 (Figure 44). Projected changes in GDD are lowest with the B2 scenario and highest with the A1B scenario. While GST and GDD are functionally different (i.e., one is a summation of heat and the other an average of temperature), the result presents virtually the same result with the only difference being the class breaks (Jones et al. 2010). Therefore one would expect the modeling results to show similar results and they do in terms of the overall pattern of the projected changes. Average GDD for the entire Douro Wine Region in 1950-2000 places it in Region III on the Winkler Index, with projected changes in GDD moving it to the upper limits of Region III for the B2 and A2 scenarios and into Region IV for the A1B scenario (Figure 47). By 2050 the projections move the area into Region IV for the B2 and A2 scenarios and into Region V for the A1B scenario. For 2080 the projections diverge to a lower Region V in the B2 scenario, to a middle Region V in the A2 scenario, to potentially becoming too hot for the A1B scenario (Figure 47). Spatially the results for GDD are similar to GST, where by 2020 the area is projected to be 13% a Region II, 40% a Region III, 36% a Region IV, and 9% a Region V (Figure 48). Further changes through 2050 project the area to be largely a Region V (45%), with 32% a Region IV, 13% a Region III, and 9% too hot. By 2080 the area that becomes too hot increases to 44%, while 42% of the area is projected to be in Region V, 12% in Region IV, and again less than 3% in Region I to Region III (Figure 48).

The Huglin Index (HI) during the observed period of 1950-2000 has spatially averaged 2000-2200 over the Douro Wine Region (Figure 45; Table 9). While the HI and GDD are both heat accumulation indices, two issues need to be highlighted; 1) the class limits are not equal (e.g., a Temperate HI does not necessarily equate to a Region III in GDD), and 2) the HI weights maximum temperatures more than GDD. Therefore, given the larger projected increases in maximum temperatures in the region, it is expected that the magnitude of the changes in the HI will be different than the GDD. However, for the baseline projections HI increases similar to GDD with changes of 125 to 375 units by 2020, 375 to 900 units by 2050, and 500 to 1400 units by 2080 (Figure 45). Projected changes are again lowest in the B2 scenario and highest with the A1B scenario. The general pattern of warming is similar to both the GST and GDD patterns. For the present period (1950-2000) the Douro Wine Region spatially averages a lower Warm Temperate HI class and is projected to increase to the high Warm Temperate class range for the B2 and A2 scenarios and even into the Warm HI class for the A1B scenario (Figure 47). By 2050 the B2 and A2 scenarios push the region into the upper Warm HI class while the A1B scenario moves the region to the class divide between Very Warm HI and what would be considered too hot on the HI. Further changes in the HI are projected by 2080 with the B2 scenario moving the region into a lower Very Warm HI, the A2 at the limit of the Very Warm HI and too hot, and the A1B moving the entire region into what would be considered too hot on
the HI (Figure 47). Spatial shifts within the Douro Wine Region are also evident with significant changes across all time slices (Figure 48). During 1950-2000 the region was 50% Warm Temperate, 35% Temperate, 10% Warm, and 5% Cool or Very Cool. By 2020 the region’s landscapes are projected to still have a large area as Warm Temperate (40%), but with significant changes to 43% Warm, 8% Very Warm, and less than 10% Temperate to Very Cool. By 2050 and 2080 the differential warming in maximum versus minimum temperature shows with greater changes in the HI compared to GDD. By 2050 nearly 22% of the region is projected to become too hot, while 34% of the area is found in both Very Warm and Warm, and nearly 10% is Very Cool to Warm Temperate (Figure 48). Averaged across all scenarios, the projections show that by 2080 the region potentially could be largely too hot (55%), leaving 30% of the landscape as Very Warm, 13% as Warm, and only 2% from Very Cool to Warm Temperate.
Figure 41: Average annual precipitation for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in % from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Figure 42: Average annual temperatures for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower row representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in °C from the 1950-2000 base period. Data source: WorldClim Database (Hijmans et al. 2005).
Figure 42: Growing season average temperatures (April through October) for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in °C from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Figure 43: Growing degree-days (Winkler Regions) for the Douro Wine Region from 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The legends represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior). The projected changes from 1950-2000 and possible future emission scenarios for BB2, A1B, and A2 emission scenarios for the Douro Wine Region (Winkler Index).

<table>
<thead>
<tr>
<th>Region</th>
<th>B2 Scenario</th>
<th>A1B Scenario</th>
<th>A2 Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baixo Corgo</td>
<td>693-699</td>
<td>687-689</td>
<td>697-699</td>
</tr>
<tr>
<td>Cima Corgo</td>
<td>668-676</td>
<td>686-696</td>
<td>676-686</td>
</tr>
<tr>
<td>Douro Superior</td>
<td>562-581</td>
<td>588-609</td>
<td>562-581</td>
</tr>
</tbody>
</table>

Projected changes from 1950-2000 and future emission scenarios for the Douro Wine Region (Winkler Index).
Figure 44: Huglin Index values for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in HI units from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Figure 45: Spatially averaged projected changes in annual (A), winter (B), and growing season (C) precipitation for the Baixo Corgo (BC), Cima Corgo (CC), and Douro Superior (DS). The data cover the present period (1950-2000) through 2020, 2050, and 2080 for the B2, A1B, and A2 emission scenarios from the HADCM3 model.
Figure 46: Spatially averaged projected warming trends in average annual temperatures over the entire Douro Wine Region. The data cover the present period (1950-2000) through 2020, 2050, and 2080 for the B2, A1B, and A2 emission scenarios from the HADCM3 model.

Figure 47: Spatially averaged projected warming trends in average growing season temperatures (A), growing degree-days (B) and the Huglin Index (HI) over the entire Douro Wine Region. The data cover the present period (1950-2000) through 2020, 2050, and 2080 for the B2, A1B, and A2 emission scenarios from the HADCM3 model. The class levels given in each figure are as defined for each index (see text for more details).
Figure 48: Percentage of the Douro Wine Region in each class of the growing season average temperature index during 1950-2000, 2020, 2050, and 2080. The three future periods are averages across the B2, A1B, and A2 scenarios.

Figure 49: Percentage of the Douro Wine Region in each class of the growing degree-day Winkler Index during 1950-2000, 2020, 2050, and 2080. The three future periods are averages across the B2, A1B, and A2 scenarios.
Figure 50: Percentage of the Douro Wine Region in each class of the Huglin Index during 1950-2000, 2020, 2050, and 2080. The three future periods are averages across the B2, A1B, and A2 scenarios.

The results from this assessment using the WorldClim data from a single climate model (HADCM3) are found to be similar in magnitude to the multi-model chain of regional models from ENSEMBLES and COSMO-CLM used by Santos et al. (2012). The 16 regional climate models in the chain have spatial resolutions of 18-25 km, resulting in fewer grids representing the Douro Wine Region compared to the WorldClim data at 1 km resolution. The ensemble average for 16 regional climate model experiments following the SRES A1B scenario projects warming rates in average annual temperatures of 0.34°C per decade or a total change of 3.1°C from 2010 to 2100. Growing season (April-October) warming is projected to be nearly twice that of warming in the winter. Winter (November-March) average temperatures are projected to warm 0.24°C per decade, resulting in an overall warming of 2.2°C from 2010 to 2100. Average temperatures during the growing season are projected to warm 0.42°C per decade, with an overall warming of 3.8°C from 2010 to 2100. Changes of this magnitude indicate that the GST warms from around 17°C, which is an Intermediate to Warm climate suitability, to approximately 21°C or a Hot to Very Hot climate suitability by the end of the 21st Century in the Douro Valley region. Precipitation changes projected across the 16 regional climate model ensemble are much more variable across the models and over the 21st Century. However, the ensemble average projects significant declines in annual precipitation of 17 mm per decade or a reduction of approximately 15% by 2100. The reduction in annual precipitation shown by the model ensemble is largely driven by significant decreases in growing season precipitation while winter precipitation remains highly variable over the projection time period. An examination of monthly precipitation projections shows significant declines in monthly precipitation across each month of the growing season, but slightly greater values during the late spring, early summer (May and June).
Other recent work examining climate change in wine regions worldwide, over Europe, and specifically in the Iberian Peninsula have found similar projected changes to those found in this assessment. For example, Jones et al. (2005) found projected average warming of 2.0°C during the growing season in 27 wine regions worldwide by 2050 using the A2 scenario in the HADCM3 model. However, the results showed that the Iberian Peninsula warmed more than other regions with GST warming of 2.4°C by 2050 (0.5°C decadal rate) for Northern Portugal. Webb et al. (2008) found similar warming for Australia that was associated with potential wine quality reductions in the already warm regions. Hall and Jones (2009) found warming across Australian wine regions of 1.3-2.7°C by 2070, likely pushing many regions outside of what would be suitable for high quality wine production. For the United States as a whole, White et al. (2006) used a high-resolution (25 km) regional climate model forced by an IPCC A2 greenhouse gas emission scenario and estimated that potential premium winegrape production area in the conterminous United States could decline by up to 81% by the late 21st Century. The research found that increases in heat accumulation will likely shift wine production to warmer climate cultivars and/or lower-quality wines. Additionally the models show that while frost constraints will be reduced, increases in the frequency of extreme hot days (>35°C) in the growing season have the potential to severely challenge or completely eliminate winegrape production in many areas of the United States.

For Europe, Malheiro et al. (2010), using transient ensemble simulations with the COSMO-CLM regional model for the B1 and A1B scenarios, show that the geography of viticulture in Europe will likely change substantially by the end of the 21st Century. Increased dryness and cumulative thermal effects are shown to impact wine regions throughout southern Europe, while northern Europe is projected to see new areas suitable for viticulture. Moriondo et al. (2011) conducted a similar study to this one in Tuscany, Italy and found, that as a consequence of a progressive increase in temperature and a reduction in precipitation, the region was likely to see 1) increases in the area suitable to viticulture (higher elevations), 2) a shorter grapevine growth cycle, 3) a reduction in yield, and 4) premium wine quality zones will shift to higher elevations. Santos et al. (2012) detailed for the Douro Valley that ensemble mean temperatures during February-March increase 3°C from 2000 to the end of the 21st Century, whereas May mean temperatures increase 4°C over the same time period. Spring precipitation is not expected to undergo any long-term change with increasing GHG forcing. However, vegetation-climate feedbacks over Europe, as examined by Wramneby et al. (2010), shows that over southern Europe (including most of the Iberian Peninsula) increasing summer dryness could restrict plant growth and survival, which in turn would cause a positive warming feedback through reduced evapotranspiration. The authors state that the vegetation-climate feedbacks over the European study area will likely be modest compared to the radiative forcing of increased global CO2 concentrations but that the interactions may modify warming projections locally, regionally, and seasonally.

Iberian Peninsula future projections using six IPCC models show continued warming of 0.4°C per decade during the winter and 0.6°C per decade during the summer with a small difference between the B2 and A2 scenarios (de Castro et al. 2005). While the results point to
non-uniform projections among the different climate models, the authors show that overall the results point to a significant reduction in annual precipitation, which is higher in the A2 compared to the B2 scenario, with peak reductions coming in the late spring. Using the PROMES regional climate model (50 km resolution), de Castro et al. (2005) show projections from 2070-2100 of continued warming of 5.0-7.0°C in the summer and 3.0-4.0°C in winter, with lower warming rates the closer to the coast and higher warming rates inland. Although there is large geographic variability in the frequency and range of monthly temperature anomalies, the authors detail increases in temporal variability in all seasons and with both the B2 and A2 scenarios. Changes in precipitation in the PROMES regional climate model are more heterogeneous over the Iberian Peninsula, with a strong gradient in average precipitation from the wetter northwest to the drier southeast. The clearest signal in precipitation is for less spring/summer precipitation over most of Iberia.

Other work for Portugal used the HadRM3 regional model and examined changes in maximum and minimum temperature distributions and associated changes in the likelihood of extreme events for 2071-2100 for two emission scenarios (Ramos et al. 2011). Projected changes for 2071-2100 were found to be consistent with those found during 1976-2006 in Portugal with an increase in maximum temperature of 3.2°C (4.7°C) for the B2 (A2) scenario in summer and 3.4°C in both scenarios for spring. Similar changes were seen for minimum temperatures, with increases for summer (spring) ranging from 2.7°C (2.5°C) in the B2 scenario to 4.1°C (2.9°C) in the A2 scenario. The general changes in maximum and minimum temperatures for Portugal predicted for the end of the 21st Century were accompanied by changes in the occurrence of extreme events where hot extremes increased in frequency, while cold extremes declined in frequency in Portugal (Ramos et al. 2011).

CONCLUSIONS

It is evident from the history of growing winegrapes worldwide that they are a climatically sensitive crop whereby quality production is achieved across a fairly narrow geographic range (Jones, 2006). In addition, winegrapes are grown largely in mid-latitude regions that are prone to high climatic variability that drive relatively large vintage differences in quality and productivity. Furthermore, historic trends and future projections in climate parameters for wine regions has shown that changes have occurred and are likely to continue in the future (Jones et al. 2005). This assessment has examined numerous aspects of climate in one of the world’s most historic wine regions – the Douro Valley of Portugal – with the goal of documenting and examining the historic, current, and future climatic conditions of the region.

The Douro Wine Region covers an area of over 250,000 hectares in mountainous east-west oriented valley, with moderate to steep slopes and varying exposures, and is drained by the Douro River and its tributaries. The area is planted to over 45,000 hectares of winegrapes in three sub-regions: Baixo Corgo, Cima Corgo, and Douro Superior. Historic climate conditions in the Douro Wine Region reveal the area’s largely Mediterranean climate structure with moderately high intra-annual variation in temperature and precipitation. Temperatures over
the region are typically cooler to the west and up in elevation, while the warmest zones are along the main stem of the valley and to the east. Precipitation is highest in the upper elevations and in the mountains along the western boundary, which produce a prominent rain shadow effect as one heads east along the river. Historic data from numerous stations during 1931-1960 shows that the region has areas that range from Cool climate suitability in the higher elevations to Hot climate suitability in some locations in the Douro Superior. Over 1931-1960 winter and growing season precipitation are 64% and 36% of annual precipitation, respectively, and is very similar to what is experienced today. During the growing season, when evapotranspiration rates largely determine soil-moisture stresses, the median evapotranspiration rate over the region is over 250% of the median precipitation inputs during the period of vine growth. Updated spatial climate data for 1950-2000 reveals similar climate conditions to the 1931-1960 climate normals. For growing season average temperatures the region averages 17.8°C and is spatially classed as 65% a Warm climate type, 24% an Intermediate climate type, and nearly 10% a Hot climate type on the GST index. Growing degree-days show a similar pattern with a region-wide average of 1680 and the overall area being just over 41% a Winkler Region II, just under 40% a Winkler Region III, and 10% a Winkler Region IV. For the Huglin Index the region spatially averages 2160 and ranges from over 50% a Warm Temperate climate, 35% a Temperate climate, 10% a Warm climate, and 4% a cool climate for viticulture.

Observed trends in the region were examined both for individual stations and spatially over the entire region. Differences between the 1931-1960 and 1950-2000 data reveal that the later period was warmer by an average of 0.9°C for annual temperatures over the region with the growing season and winter being 1.2°C and 0.4°C warmer, respectively. Examining individual stations with relatively long term and quality data records finds trends for many climate parameters during 1967-2010. During this period Régua, Pinhão, and Vila Real have shown trends in annual, growing season, and winter temperatures. In general the stations all show greater warming in minimum compared to maximum temperatures with rates ranging from 1.2°C to 3.6°C during the time period. Results from an analysis of extreme events for the three stations reveals significant changes for both maximum and minimum temperature extremes, with overall warmer nights, warmer days, a general decline in the diurnal temperature range, a higher number heat stress events, some evidence for longer warm spells, and a clear reduction in cold spell durations. No trends were found for annual, dormant season, or growing season precipitation at any of the three stations. The structure and frequency of large scale weather regimes over the eastern Atlantic Ocean, Western Europe, and the Mediterranean were found to show some influence on the region’s climate variability, however the results point to a general warming that is not being significantly driven by regional circulation changes. Other research globally, in Europe, over the Iberian Peninsula, and in Portugal has found similar trends in average and extremes as those found in this assessment.

Future climate conditions in the Douro Wine Region were examined using IPCC SRES projections from the HADCM3 model for three greenhouse gas emission scenarios (B2, A1B, and A2) and three future time slices (2020, 2050, and 2080). The larger scale global model
results are empirically downscaled using a thin plate spline spatial interpolation of anomalies of original GCM outputs allowing for a direct comparison to the historic spatial climate structure in the region from the WorldClim database (1950-2000). Average annual temperatures are projected to warm for all emission scenarios and for each time slice. Projections range from 0.5-1.4°C by 2020, 1.4-3.3°C by 2050, and 2.1-5.1°C by 2080. Projected warming is lowest with the B2 emission scenario and highest with the A1B scenario, although the A2 scenario is the warmest from 2080-2100. Breaking the year into the dormant (Nov-Mar) and growing seasons (Apr-Oct), shows warming in both periods although temperatures during the growing season (0.6-6.6°C )are projected to warm more than during winter (0.4-3.2°C ) across all scenarios and time slices. During the winter projections are slightly higher for minimum temperatures, while during the growing season maximum temperatures are projected to warm substantially more than minimum temperatures. For the three thermal indices for viticulture suitability examined in this assessment – growing season average temperature (GST), growing degree-days or Winkler Index (GDD), and Huglin Index (HI) – projections show significant changes in each over the Douro Wine Region. For GST the region is projected to change from a largely Warm climate suitability (65% of the area) in 1950-2000 to increasing area in Hot climate suitability by 2020 (43%) and even Very Hot climate suitability by 2050 (36%). By 2080 the spatial pattern of GST is projected to have 19% of the landscape becoming Too Hot, 54% Very Hot, 25% Hot, and less than 3% Cool, Intermediate or Warm. Similar results are found for both GDD and HI, with significant changes across suitability classes over each time slice, although changes in the HI are projected to be greater due to greater warming in maximum temperatures during the growing season. By 2080 the area that becomes too hot in GDD (on the Winkler Index) increases to 44%, while 42% of the area is projected to be in Region V, 12% in Region IV, and again less than 3% in Region I to Region III. For the HI the projections show that by 2080 the region potentially could be largely too hot (55%), leaving 30% of the landscape as Very Warm, 13% as Warm, and only 2% from Very Cool to Warm Temperate. The pattern of the changes shows warming increasing most rapidly along the main sections of the river valley, then across the Douro Superior, and by 2080 up in elevation across much of the region.

Precipitation changes for the Douro Wine Region are projected to be fairly low to moderately high depending on the scenario and time slice. For annual average precipitation the projected changes are near zero to declines as much as 21.6% in the A1B scenario by 2080. Winter precipitation is not projected to change as much and is even projected to increase in some scenarios. The B2 scenario projects winter precipitation increases of 15-17% by 2080, while the A1B and A2 scenarios show slight declines in winter precipitation over the time slices. Most the of the change in precipitation is projected to occur during the growing season where decreases from 10-42% are projected by 2080. Spatially over the Douro Wine Region, the projected changes in growing season precipitation show that the already dry summer regime in the Douro Superior will only get drier, while moderate decreases in summer rainfall will be widespread over the region.

The future projections for the climate in the region from this assessment are in general agreement with other research for Europe, the Iberian Peninsula, and Portugal. Previous work
by de Castro et al. (2005) noted a range of certainty in projected changes (most to least certain from 1 to 10 in the list below) for the Iberian Peninsula that is largely supported by this regional assessment for the Douro Wine Region:

1. A progressive tendency for an increase in mean temperatures throughout the 21st Century.
2. A tendency towards more warming in the scenarios with higher emissions.
3. Increases in mean temperatures that are more significant in the summer than in winter.
4. Warming in summer that increases more inland than it does closer to the coast.
5. A generalized tendency towards less annual accumulated rainfall.
6. A greater range and frequency of monthly temperature anomalies.
7. A greater frequency of days with extreme maximum temperatures, especially in summer.
8. For the last third of the 21st Century, a greater reduction of rainfall is projected in the spring months.
9. Overall projections of increased rainfall in the Western part of Iberia in winter.
10. Projections in rainfall tend to be more significant in the higher emission scenarios.

Wine regions have developed to best match their regional environmental conditions, allowing for generally consistent ripening of the varieties that were found to be best suited to the regions. While the overall structure of climate in regions drives the suitability and climate variability strongly influences vintage to vintage production and quality variations, the projected rate and magnitude of future climate change will likely bring about numerous potential impacts for the wine industry (Bisson et al. 2002). These include added pressure on increasingly scarce water supplies, additional changes in grapevine phenological timing, further disruption or alteration of balanced composition in grapes and wine, regionally-specific needs to change the types of varieties grown, necessary shifts in regional wine styles, and spatial changes in viable grape growing regions (Jones et al. 2005). While this assessment did not include a direct examination of CO2 effects, Gonçalves et al. (2009) found no negative effects on the quality of grapes and the resulting wine; however much more work is needed in this area. In a review of climate change effects on wine production and quality, de Orduña (2010) finds that the most important issues are advanced harvest times and temperatures, increased grape sugar concentrations that lead to high wine alcohol levels, lower acidities and modification of varietal aroma compounds. Anderson et al. (2008) detail that while the wine industry is particularly sensitive to variations and changes in climate, that the industry has a high level of adaptability. However, developing appropriate adaptive mechanisms across the vine, vineyard, winery, and consumer levels will take time and significant research and development investment.

The Douro Wine Region is rich in landscape and plant characteristics that may help mitigate the deleterious effects of climate change. First of all the region’s geomorphology and relief contribute to multiple meso- and micro-climate situations, which may provide spatial adaptation strategies. Furthermore, the landscape provides growers with choices in cultivation techniques to manage the ecophysiological dimension of the environment. One characteristic that will be very important is how growers can adapt the landscape and vineyards to help
balance global photosynthetic activity of the grapevine and water loss by transpiration. A highly significant factor in the management of changes that may be required due to climate change is the genetic heritage of the plant material, particularly the varieties and their oenological performance (Almeida, 1998). Although the general characteristics and aptitude for drought resistance of rootstocks have been studied (Alves and Magalhães, 2001; Sousa et al. 1998), it is above all the vast heritage of varieties grown in the Douro Wine Region that will provide some of the most useful tools for wine growers, both through the different thermal requirements of varieties and the elasticity of their phenological behavior (Lopes et al. 2007) and their different physiological responses (Brito et al. 2004; Moutinho-Pereira et al. 2007).

While uncertainty exists in the exact rate and magnitude of climate change in the future, it would be advantageous for the Douro Wine Region to continue to be proactive in assessing the impacts, invest in appropriate plant breeding and genetic research, be ready to adopt suitable adaptation strategies, be willing to alter varieties and management practices or controls, or mitigate wine quality differences by developing new technologies. With a sound sustainable approach to today’s conditions the region is better prepared to optimize available resources in order to guarantee environmentally responsible viticulture (Malavolta and Boller, 1999). By following sustainable approaches and being innovative across the entire production system the region will undoubtedly reduce its vulnerability and increase its adaptive capacity in the face of a changing climate.

**ACKNOWLEDGEMENTS**

This work was made possible by funding and collaborative support from the Association for the Development of Viticulture in the Douro Region (ADVID). ADVID’s work with producers and growers in the Douro Wine Region since 1982 has been instrumental in developing initiatives that examine and better understand the region’s issues and potential, delivering strategies to the industry that help it become more sustainable and economically viable. Special thanks goes to Fernando Alves of ADVID who did much of the initial work with the historic climate data and provided collaborative support throughout the project. Additional thanks goes to Marco Moriondo and Roberto Ferrise of the University of Florence in Italy for their help with the future climate scenarios and João Santos and Aureliano Malheiro of the University of Trás-os-Montes and Alto Douro for providing the weather regime updates and regional ESEMBLES results. Finally, this work would have not been possible without the vision and confidence of Antonio Graça who brought me to this project and region.

**LITERATURE CITED**


de Orduña, R.M. (2010). Climate change associated effects on grape and wine quality and production, Food Research International, 43(7): 1844-1855.


APPENDIX
Appendix Figure 1: Winter precipitation (November through March) for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in percent from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Appendix Figure 2: Growing season precipitation (April through October) for the Douro wine region. Upper row is historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time-slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in percent from the 1950-2000 base period. Data source: WorldClim database (Hijmans et al., 2005).
Appendix Figure 3: Growing season average maximum temperatures (April through October) for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in °C from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Appendix Figure 4: Growing season average minimum temperatures (April through October) for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The labels represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in °C from the 1950-2000 base period (data source: WorldClim database (Hijmans et al. 2005)).

Data Source: WorldClim Database (Hijmans et al. 2005).
Appendix Figure 5: Winter average maximum temperatures (November through March) for the Douro Wine Region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior) and the projected changes in °C from the 1950-2000 base period. Data Source: WorldClim Database (Hijmans et al. 2005).
Appendix Figure 6: Winter average minimum temperatures (November through March) for the Douro wine region. Upper row is the historic conditions during 1950-2000 with the lower rows representing the B2, A1B, and A2 SRES emission scenarios for three future time slices (2020, 2050, and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo, and Douro Superior), and the projected changes in °C from the 1950-2000 base period. Data source: Worldclim database (Hijmans et al. 2005).
Appendix Table 1: Quartile statistics for annual precipitation, winter precipitation (November through March), growing season precipitation (April-October), and average annual temperatures for the three sub-regions of the Douro Wine Region. The values represent the spatial statistics of each variable; absolute minimum, 25%, median, 75%, and absolute maximum. Data Source: WorldClim Database (Hijmans et al. 2005).

<table>
<thead>
<tr>
<th>Winter Precipitation</th>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>607</td>
<td>726</td>
<td>774</td>
<td>829</td>
<td>1035</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>486</td>
<td>599</td>
<td>661</td>
<td>703</td>
<td>849</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>395</td>
<td>484</td>
<td>524</td>
<td>587</td>
<td>719</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growing Season Precipitation</th>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>363</td>
<td>424</td>
<td>448</td>
<td>479</td>
<td>608</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>299</td>
<td>355</td>
<td>386</td>
<td>408</td>
<td>485</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>249</td>
<td>298</td>
<td>317</td>
<td>350</td>
<td>421</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growing Season Maximum Temperature</th>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>16.8</td>
<td>22.8</td>
<td>23.8</td>
<td>24.2</td>
<td>25.1</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>20.2</td>
<td>22.8</td>
<td>23.7</td>
<td>24.5</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>21.3</td>
<td>23.2</td>
<td>24.0</td>
<td>24.8</td>
<td>26.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growing Season Minimum Temperature</th>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>7.6</td>
<td>10.7</td>
<td>11.4</td>
<td>11.9</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>9.7</td>
<td>10.8</td>
<td>11.4</td>
<td>12.0</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>9.9</td>
<td>11.1</td>
<td>11.9</td>
<td>12.4</td>
<td>13.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winter Maximum Temperature</th>
<th>Region</th>
<th>Minimum (mm)</th>
<th>25% (mm)</th>
<th>Median (mm)</th>
<th>75% (mm)</th>
<th>Maximum (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>7.0</td>
<td>11.7</td>
<td>12.6</td>
<td>13.2</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>9.0</td>
<td>11.1</td>
<td>11.9</td>
<td>12.7</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>9.5</td>
<td>11.2</td>
<td>12.0</td>
<td>12.8</td>
<td>14.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Winter Minimum Temperature</th>
<th>Region</th>
<th>Minimum (°C)</th>
<th>25% (°C)</th>
<th>Median (°C)</th>
<th>75% (°C)</th>
<th>Maximum (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baixo Corgo</td>
<td>0.5</td>
<td>3.5</td>
<td>4.2</td>
<td>4.7</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Cima Corgo</td>
<td>2.0</td>
<td>3.2</td>
<td>3.7</td>
<td>4.3</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Douro Superior</td>
<td>1.9</td>
<td>3.2</td>
<td>3.9</td>
<td>4.5</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Climate Change Indices

Complete definitions of the 27 core indices used from the CCI/CLIVAR/JCOMM Expert Team (ET) on Climate Change Detection and Indices (ETCCDI)

1. FD, Number of frost days: Annual count of days when TN (daily minimum temperature) < 0°C.
   Let TN$_{ij}$ be daily minimum temperature on day i in year j. Count the number of days where: TN$_{ij}$ < 0°C.

2. SU, Number of summer days: Annual count of days when TX (daily maximum temperature) > 25°C.
   Let TX$_{ij}$ be daily maximum temperature on day i in year j. Count the number of days where: TX$_{ij}$ > 25°C.

3. ID, Number of icing days: Annual count of days when TX (daily maximum temperature) < 0°C.
   Let TX$_{ij}$ be daily maximum temperature on day i in year j. Count the number of days where: TX$_{ij}$ < 0°C.

4. TR, Number of tropical nights: Annual count of days when TN (daily minimum temperature) > 20°C.
   Let TN$_{ij}$ be daily minimum temperature on day i in year j. Count the number of days where: TN$_{ij}$ > 20°C.

5. GSL, Growing season length: Annual (1st Jan to 31st Dec in Northern Hemisphere (NH), 1st July to 30th June in Southern Hemisphere (SH)) count between the first occurrence of at least 6 consecutive days with: TG$_{ij}$ > 5°C and the first occurrence after 1st July (1st Jan. in SH) of at least 6 consecutive days with: TG$_{ij}$ < 5°C.

6. TX$_{x}$, Monthly maximum value of daily maximum temperature:
   Let TX$_{k}$ be the daily maximum temperatures in month k, period j. The maximum daily maximum temperature each month is then: TX$_{x_k}=$max(TX$_{kj}$)

7. TN$_{x}$, Monthly maximum value of daily minimum temperature:
   Let TN$_{k}$ be the daily minimum temperatures in month k, period j. The maximum daily minimum temperature each month is then: TN$_{x_k}=$max(TN$_{kj}$)

8. TX$_{n}$, Monthly minimum value of daily maximum temperature:
   Let TX$_{k}$ be the daily maximum temperatures in month k, period j. The minimum daily maximum temperature each month is then: TX$_{n_k}=$min(TX$_{kj}$)

9. TN$_{n}$, Monthly minimum value of daily minimum temperature:
   Let TN$_{k}$ be the daily minimum temperatures in month k, period j. The minimum daily minimum temperature each month is then: TN$_{n_k}=$min(TN$_{kj}$)

10. TN10p, Percentage of days when TN < 10th percentile:
    Let TN$_{ij}$ be the daily minimum temperature on day i in period j and let TNin10 be the calendar day 10th percentile centered on a 5-day window for the base period 1961-1990. The percentage of time for the base period is determined where: TN$_{ij}$ < TNin10

11. TX10p, Percentage of days when TX < 10th percentile:
    Let TX$_{ij}$ be the daily maximum temperature on day i in period j and let TXin10 be the calendar day 10th percentile centered on a 5-day window for the base period 1961-1990. The percentage of time for the base period is determined where: TX$_{ij}$ < TXin10

12. TN90p, Percentage of days when TN > 90th percentile:
    Let TN$_{ij}$ be the daily minimum temperature on day i in period j and let TNin90 be the calendar day 90th percentile centered on a 5-day window for the base period 1961-1990. The percentage of time for the base period is determined where: TN$_{ij}$ > TNin90

13. TX90p, Percentage of days when TX > 90th percentile:
    Let TX$_{ij}$ be the daily maximum temperature on day i in period j and let TXin90 be the calendar day 90th percentile centered on a 5-day window for the base period 1961-1990. The percentage of time for the base period is determined where: TX$_{ij}$ > TXin90
14. WSDI, Warm spell duration index: Annual count of days with at least 6 consecutive days when TX > 90th percentile. Let TXij be the daily maximum temperature on day i in period j and let TXin90 be the calendar day 90th percentile centered on a 5-day window for the base period 1961-1990. Then the number of days per period is summed where, in intervals of at least 6 consecutive days: TXij > TXin90

15. CSDI, Cold spell duration index: Annual count of days with at least 6 consecutive days when TN < 10th percentile. Let TNij be the daily maximum temperature on day i in period j and let TNin10 be the calendar day 10th percentile centered on a 5-day window for the base period 1961-1990. Then the number of days per period is summed where, in intervals of at least 6 consecutive days: TNij < TNin10

16. DTR, Daily temperature range: Monthly mean difference between TX and TN
Let TXij and TNij be the daily maximum and minimum temperature respectively on day i in period j. If i represents the number of days in j, then:

\[ DTR_i = \frac{\sum_{i=1}^{j} (TX_{ij} - TN_{ij})}{I} \]

17. Rx1day, Monthly maximum 1-day precipitation:
Let RRij be the daily precipitation amount on day i in period j. The maximum 1-day values for period j are:
Rx1dayj = max (RRij)

18. Rx5day, Monthly maximum consecutive 5-day precipitation:
Let RRkj be the precipitation amount for the 5-day interval ending k, period j. Then maximum 5-day values for period j are: Rx5dayj = max (RRkj)

19. SDII Simple precipitation intensity index: Let RRwj be the daily precipitation amount on wet days, w (RR ≥ 1mm) in period j. If W represents number of wet days in j, then:

\[ SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W} \]

20. R10mm Annual count of days when PRCP ≥ 10mm: Let RRij be the daily precipitation amount on day i in period j. Count the number of days where: RRij ≥ 10mm

21. R20mm Annual count of days when PRCP ≥ 20mm: Let RRij be the daily precipitation amount on day i in period j. Count the number of days where: RRij ≥ 20mm

22. Rnnmm Annual count of days when PRCP ≥ nnmm, nn is a user defined threshold: Let RRij be the daily precipitation amount on day i in period j. Count the number of days where: RRij ≥ nnmm

23 CDD. Maximum length of dry spell, maximum number of consecutive days with RR < 1mm: Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where: RRij < 1mm

24 CWD. Maximum length of wet spell, maximum number of consecutive days with RR ≥ 1mm: Let RRij be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where: RRij ≥ 1mm

25. R95pTOT. Annual total PRCP when RR > 95p. Let RRwj be the daily precipitation amount on a wet day w (RR ≥ 1.0mm) in period i and let RRwn95 be the 95th percentile of precipitation on wet days in the 1961-1990 period. If W represents the number of wet days in the period, then:

\[ R95p_i = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn95} \]
26. **R99pTOT.** Annual total PRCP when RR > 99p: Let RR\textsubscript{w} be the daily precipitation amount on a wet day \( w \) (RR \geq 1.0\text{mm}) in period \( i \) and let RR\textsubscript{w99} be the 99th percentile of precipitation on wet days in the 1961-1990 period. If \( W \) represents the number of wet days in the period, then:

\[
R99p_i = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{w99}
\]

27. **PRCPTOT.** Annual total precipitation in wet days: Let RR\textsubscript{ij} be the daily precipitation amount on day \( i \) in period \( j \). If \( i \) represents the number of days in \( j \), then

\[
PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}
\]