Vol. 75: 117–130, 2018
https://doi.org/10.3354/cr01513

CLIMATE RESEARCH
Clim Res

Published online May 30

Atmospheric circulation variability and vintage Port wine

Anthony J. Vega[1,*], Sara A. Ates[2], Robert V. Rohli[2]

[1]Department of Biology and Geoscience, Clarion University of Pennsylvania, Clarion, PA 16214, USA
[2]Department of Geography and Anthropology, Louisiana State University, Baton Rouge, LA 70803–4105, USA

ABSTRACT: The success of viticulture is inexorably tied to atmospheric conditions during the growing season. Previous work has tied observed and general circulation model (GCM)-projected changes in atmospheric variables to wine production in Europe. This research uses a synoptic climatological approach to examine the role of atmospheric circulation variability on wine production in the Douro Valley region of Portugal. Of particular interest is the atmospheric contribution to 'vintage Port' production. Vintage Port years are declared periodically and coincide with particularly high quality grape harvests. Results suggest that temperatures and potential evapotranspiration (PET) have increased significantly overall for the region, with the signal being present in both non-vintage and vintage years, while precipitation has remained statistically constant over the study period. Circulation analysis indicates that early winter ridging and drying offset by late winter pressure decreases and frontal cyclone tracking over the region is important during vintage years. Additionally, the analysis suggests that March synoptic drying followed by a significantly reduced PET during summer is important in vintage years. When followed by autumn maximum air temperatures and evapotranspiration rates that are significantly higher than normal, vintage Port results. Such conditions favor summer water retention in grapes, which increases the concentration of sugars through drying immediately prior to harvest. These results may be useful in alerting producers about quality of the upcoming harvest, especially as long-lead climate outlooks continue to improve.

KEY WORDS: Port wine · Viticulture · Atmospheric circulation variability · Portugal

1. INTRODUCTION

The wine industry is a large and growing sector of the Portuguese economy, especially as emerging markets such as China and Brazil increase global wine demand. Portugal ranks among the top 10 wine-exporting countries in the world annually, accounting for approximately 3 % of the total global market share (the Wine Institute, www.wineinstitute.org/). Port wine production is a substantial component of the wine industry in Portugal, comprising 22 % of total wine production (Wines of Portugal, www.winesofportugal.com/en/). Although fortified wines are produced elsewhere, such as sherry from Spain, Marsala from Italy, Madeira from the Madeira Islands (Portugal), Commandaria from the Republic of Cyprus, mistelle from France, and vermouth from Italy and France, all of the world's authentic Port wine is produced in Portugal's Douro River Valley (Fig. 1).

As with any agricultural commodity, the Portuguese Port industry is intricately tied to climate. Although substantial work has been done to describe the atmospheric variables associated with variability in the quantity of Port wine production in Portugal, more should be done to elucidate the effects of atmospheric circulation variability and climate change on the industry, especially regarding Port quality. The purpose of this study is to identify empirical linkages between atmospheric circulation and the historical production of wine in Portugal. Atmospheric features associated with the declaration of the highest quality 'vintage' Port years are of particular interest.

*Corresponding author: avega@clarion.edu

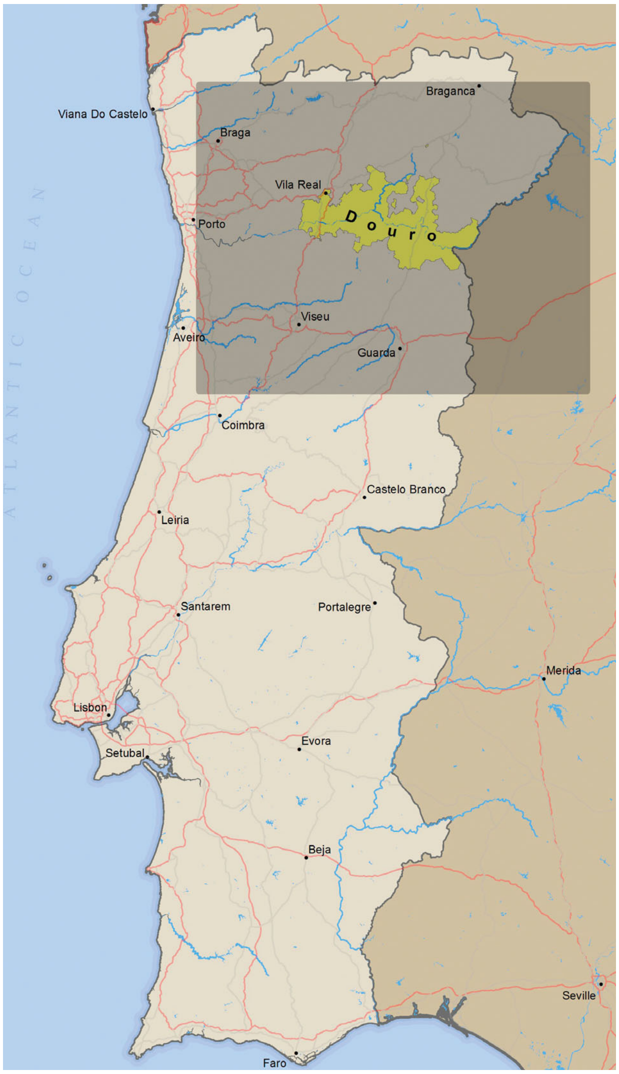

Fig. 1. The Douro River Valley wine region of Portugal (yellow). Surface analysis grid centered over the Douro River wine region (shaded area)

1.1. Characteristics of Port

There are a variety of different types of Port, such as white, red, ruby, rose, and tawny, with ruby being the most popular. Most types are normally blended with previous years' wines in order to maintain constancy of style and quality. As such, no date or year appear on most Port bottle labels, as the wines are recognized as blends. However, some Ports do carry an indication of age and a date of harvest. Ports with the date of harvest are usually those made from a single high-quality harvest and these are declared 'vintage Ports'. Vintage year declarations are determined by an independent group that examines wine samples from across the entire Douro region. However, some wineries declare their own vintage years. Samples are drawn from ageing casks at intervals and quality is assessed. After a period of 16 mo of ageing, the wine may be submitted to the Port Wine Institute (IVP) for approval as a vintage Port (Henderson & Rex 2012).

Box 1. Officially declared vintage Port years: 1901–2012. Source: www.vintageport.biz

1904, 1906, 1908, 1912, 1917, 1920, 1924, 1927, 1935, 1940, 1942, 1945, 1948, 1955, 1960, 1963, 1966, 1970, 1975, 1977, 1980, 1983, 1985, 1992, 1994, 1997, 2000, 2003, 2007, 2009, 2011

Vintage Port is produced from a single year's harvest of a higher-quality grape. The wine is usually bottled in the second or third year of wood cask ageing and allowed to mature further in the bottle. The subtleties of the taste features among different varieties and ageing techniques have led to much chemometric research on Port (Ortiz et al. 1996, Rudnitskaya et al. 2007, Agati et al. 2013). Recent research has even suggesting that Port has antiproliferative properties toward human cancer cells that differ among ages and varieties (Oliveira et al. 2015).

Late bottled vintage (LBV) is also generally associated with a particularly good year's single harvest. This wine is usually bottled during the sixth year of ageing and the label expresses both the year of harvest and the date of bottling with the designation 'L.B.V.' This study considers only the officially declared vintage Port and LBV years during the period 1900–2012 (Box 1). It is recognized that some wineries may produce excellent wines during 'non-vintage' years and some wineries may produce lower-quality wines during officially declared vintage years. This study focuses on the official vintage declaration, which includes the majority of regional wineries. Therefore, the study operates under the assumption that the official declarations are consistent.

Traditionally, there are about 3 vintage Port declarations per decade, although variations in frequency have occurred. In the study period, the 1940s and the 2000s saw the most vintage year declarations, with 4 declarations in each of these 2 decades. The fewest occurred in the 1930s and the 1950s, with 1 declaration in each of these decades.

1.2. Physical setting

The 'terroir' refers to all environmental conditions including climate, soil type, and basic geomorphology important to the production of wine (Fraga et al. 2014a, Jones 2015). Resulting wine characteristics such as fruit style, fruit flavors, body, acidity and overall style are reflective of terroir (Jones 2015). Portugal is divided into 12 winemaking regions (Fraga et al. 2014b). For the Douro River Valley winemaking region (see Fig. 1), the oldest demarcated region regulated by law in the world, the terroir allows for the production of primarily astringent and black, fruit flavored, full-bodied dark red wines.

The general climate of the Douro region is classified as Mediterranean warm summer (Csb) in the Köppen-Geiger climate classification system. The wine producing areas of France, Chile, and New Zealand are classified as marine west coast (Cfb), as their climates are cooler and wetter than Csb, and the regions are therefore associated with different grape varieties and resulting wine types. The wine-producing regions of the northern Mediterranean rim, including southern France, Italy, and eastern Spain fall into the Mediterranean (Csa) climate type which is characterized by slightly wetter and cooler summers than Csb climates.

A primary climate control of the Douro region is the significant orographic effect from the surrounding mountains. This geography protects the region from cold incursions from the North Atlantic, resulting in a more continental type of climate normally associated with locations much farther inland. The orographic effect gives rise to a drier overall climate with cool winters and warm summers. Real et al. (2015) showed that accumulated heat through summer is a primary influence on wine production in the Douro region. Soil moisture deficits through the Douro region normally occur from June through October with recharge occurring until January, and a climatological surplus persisting through May.

Soils in the Douro region derive from schist, which is rich in nutrients and ideally suited to wine production, as the soils retain water well during the dry summer period. This water retention is essential for the survival and growth of the various grape varieties. In general, western Douro regions are wetter than areas farther east. The western regions, such as the Marão Mountain area (Baixo Corgo region), tend to produce lighter wines made from higher-yielding grape varieties that mature early. The eastern regions such as the Cima Corgo area and the Douro Superior region are known for deeper, complex, and more intense wines, made from lower-yielding, small, thick-skinned grape varieties that are better adapted to the drier conditions (www.taylor.pt/en/what-is-port-wine/douro-vallay-vineyards). The physical conditions make the region ideally suited to Port wine agriculture, and Mateus et al. (2002) noted that middle- to higher-elevation sites within the Douro River Valley may be the best suited to Port production.

Grapes are well suited to the Douro terroir. The best-known variety, and the one traditionally associated with Port is Touriga Nacional, which is a small, thick-skinned grape that produces a sweet, low juice yield. This results in a dark and concentrated wine dominated by black fruit flavors, abundant structure, and high tannins (Stevenson 2011). Touriga Nacional is planted in very rocky, low-quality soil and along steep regions of the Douro Valley. Touriga Francesa is the fifth most widely planted grape variety, as it produces consistent yield and wines even in poor growing areas. The grape produces a high-quality, intense, fruity essence and bouquet whose characteristics are more subtle that those of Touriga Nacional (Robinson 1986). Tinta Barroca is a grape variety restricted to cooler, typically north-facing slopes, and shady areas. It produces a very sweet, fragrant, and soft wine rich in anthrocyanins that is more astringent than the higher-tannin wines (Robinson 1986). Tinta Roriz (Tempranillo in Spain) was introduced to the Douro region relatively recently. It is a large grape that adapts well to different climate and soil conditions, and produces a high yield, which has motivated increased planting of this variety through the Douro region. It produces a well-structured, elegant, and complex wine (www.taylor.pt/en/what-is-port-wine/douro-valley-vineyards). Due to its adaptability, yield, and flavor profiles, it is grown in many other wine-producing regions such as the west coast of the United States, Australia, New Zealand, Mexico, as well as parts of South America and the Middle East. It is the primary grape used in Rioja, one of the best-known wines of Spain (Mayson 2012). By contrast, Tinta Cão is the oldest grape variety in the region. This variety is very well adapted to the climate conditions of the region, and extremely reliable and consistent across a variety of soil qualities. However, it is a low-yield, small berry variety and, for this reason, it is the least widely planted variety. The grape produces an acidic, velvety, textured wine that greatly improves with age (Robinson 1986).

The primary feature of Port production is the addition of aguardente, a neutral grape spirit (brandy) that halts fermentation while the wine is still sweet, fruity, and robust. Such practices stem from the need to preserve wines on voyages, but fortification typically advances flavor profiles, originally characteristic of the terroir, to otherwise marginal wines. Fortification also increases alcohol content and minimizes further chemical alterations. Typical Port carries an alcohol content of about 20 %, which is much stronger than most other wines, which are normally in the range of 11 to 15% alcohol content. The production of Port also has impacts on the environment as much as it is influenced by the environment, with winery effluents being substantial in the small geographic area of production (Pirra et al. 2010).

1.3. Background: atmospheric conditions and port wine quality and quantity

Many recent studies have examined the relation between changing atmospheric conditions and European wine production. Climate changes are widely recognized to affect European wine production (Jones et al. 2005). The majority of studies indicate that the current changing climate is improving wine quality through increased temperatures and decreased precipitation (Dalu et al. 2013). However, climate change also poses threats to wine producers (Battaglini et al. 2009). Kenny & Harrison (1992) provided an early modern overview of the relationship between climate variability and change and wine grape production across Europe, with both an analysis of conditions from 1951–1980 and projections based on general circulation model (GCM) output. Bindi et al. (1996) was among the first studies to project yield changes based on scenarios of GCM-simulated future climates, including projected changes in CO_2 concentrations; the study found a wide range of projected yields in Italy, depending on the GCM and the variety of grape selected. Since that time, several similar studies have subjected small regions within Europe to closer analysis. Notable examples include studies focused on Greece (Koundouras et al. 1999), France (e.g. Jones & Davis 2000a, Duchêne & Schneider 2005), the Miño River Valley of Spain (Blanco-Ward et al. 2007), the Tokaj region of Hungary (Makra et al. 2009), Baden-Württemberg in Germany (Neumann & Matzarakis 2011), and Douro (Jones & Alves 2012, Fraga & Santos 2017).

Environmental research aimed at predicting yields in the viticulture region of Portugal has been undertaken extensively by a few research groups, but is otherwise sparse. Cunha et al. (2003) used measured pollen concentrations at key times in the growing season to derive a statistical forecast model of wine production. Santos et al. (2013) identified a 3–to 4 mo lagged predictive relationship between atmospheric temperature and precipitation anomalies and harvest in the Douro River valley. Similar models were derived to forecast production in the Lisbon (Malheiro et al. 2013) and Minho (Fraga et al. 2014c) regions of Portugal.

Several recent studies have used atmospheric model projections to assess the future of Portuguese viticulture. Simulation using an ensemble of 16 regional climate model (RCM) experiments led Fraga et al. (2012, 2013, 2016) to conclude that a significant reshaping of the wine-growing region of Portugal is underway, as higher temperatures and lower precipitation are forecasted for the 2011–2070 period, especially across southern and inland Portugal. These results generally corroborate those of Malheiro et al. (2010), who projected substantial changes in European wine geography as a whole. Fraga et al. (2014b) provided evidence of projections of mesoscale climatic shifts through the use of downscaling.

Future projections of wine grape yield in Portugal are conflicting. Santos et al. (2011) used predictive modeling to project a slightly increasing trend in yield in the Douro region until about 2050, with a subsequent sharper increase to 2100. Follow-up research by Santos et al. (2013) projected a 10% increase in production by 2100, based on output from the ensemble of 16 RCM experiments. However, Schultz (2000) cautioned that concurrent changes in solar radiation could actually decrease yields, and, along with projected precipitation decreases, could have deleterious impacts on flavor development, with the Iberian Peninsula feeling the effects more than elsewhere in Europe. Jones & Alves (2012) concluded that projected future warming will have both positive and negative impacts in the region simultaneously. Real et al. (2015, 2017) agreed with Baciocco et al. (2014) that accumulated heat through the growing season is important to wine quality, in the Douro region and France, respectively.

The relationship between wine production and broad-scale atmospheric circulation variability has been actively studied recently. Rodó & Comín (2000) related increased Iberian Peninsula precipitation to ENSO events to resulting higher-quality wine production for the region. Souriau & Yiou (2001) used French and Swiss grape harvest data as a paleoenvironmental proxy for the NAO index. Esteves & Orgaz (2001) related Portugal wine quality to monthly air temperature and precipitation amounts, as well as monthly circulation fluxes driven by the Southern Oscillation Index and NAO. Grifoni et al. (2006) related temperature, precipitation and teleconnection indices to Italian wine quality.

Long-term circulation changes bring changes in temperature, precipitation, and other atmospheric variables that are known to impact viticulture. Moreover, GCMs are increasingly able to predict circulation changes, including those associated with long-term modes of atmospheric variability in the form of atmospheric teleconnections (Karnauskas et al. 2012, Song & Zhang 2014). Therefore, improved understanding of the circulation patterns that are known to have dominated in high-quality versus low-quality seasons, or high-quantity versus low-quantity ones, may enable long-lead climate predictions to inform viticulture forecasts in the world's primary Port wine producing region.

A rich literature exists on the use of synoptic climatological methodologies to derive the major modes of atmospheric circulation variability. While Santos et al. (2007) employed *k*-means clustering to identify atmospheric circulation patterns conducive to drought in Portugal, eigenvector-based map pattern classifications (e.g. Yarnal 1993) have been more traditionally used for such purposes. In general, the object is to minimize the within-group variability in atmospheric flow, as defined by geopotential height patterns, and maximize the between-group variability. This work is along the lines of that of Jones & Davis (2000a), who used a spatial surface pressure analysis and a temporal air mass analysis to link circulation patterns to surface weather parameters important to Bordeaux region viticulture. Specifically, Jones & Davis (2000b) identified that viticulture grape quality and wine production improve with increased frequency of episodes involving lower temperatures, and higher precipitation totals along with increased winds to delay plant phenology during flowering and berry setting times. Santos et al. (2012) employed a similar technique, using principal components analysis to identify major modes of variability in bioclimatic indices that pertain to viticulture across Europe.

It is widely accepted (e.g. Vintage Port 2016) that vintage years in the Douro region generally occur after a cold and wet winter followed by a warm and dry spring then a very hot summer. It is thought that such conditions allow grapes to sweeten to greater levels than in other conditions. Also, some rain in August and September is ideal, as this helps increase grape water content. This study tests this generalized model relative to Port quality, in addition to attempting to discern important circulation flow regimes and/or circulation changes coincident with vintage Port years.

2. DATA AND METHODS

A generalized surface analysis of atmospheric conditions is combined with a monthly mean circulation analysis that also includes an examination of the NAO and Arctic Oscillation (AO) teleconnection indices using data obtained from the Climate Prediction Center (www.cpc.ncep.noaa.gov). Surface data are obtained from The Climatic Research Unit (http://badc.nerc.ac.uk/data/cru) for a grid centered over the Douro River valley of Portugal bounded by latitudes 41.25° to 41.75° N and longitudes 7.25° to 8.25° W (Fig. 1). Surface data include mean monthly precipitation (PPT), monthly PET, maximum monthly temperature (T_{max}), minimum monthly temperature (T_{min}), and monthly average air temperatures (TMP) from 1901 to 2012. The surface analysis includes calculation of general descriptive statistics and testing of means, in addition to linear trend analysis to identify changes over time for annual and seasonal (winter = DJF) components of non-vintage years separately from vintage years.

In addition, an examination of the sea level pressure (SLP = 1000 hPa), along with 850, 700, 500, and 300 hPa geopotential height levels is performed. This is in contrast to previous research on the effects of climate on viticulture in the region, which has primarily focused on teleconnections (Redó & Comín 2000, Esteves & Orgaz 2001, Souriau & Yiou 2001) and/or surface climatic components (Grifoni et al. 2006, Malheiro et al. 2013, Baciocco et al. 2014, Real et al. 2015, 2017). Geopotential height data are obtained from NCEP/NCAR Reanalysis (Kalnay et al. 1996) and cover the period 1948–2012 for a grid that extends from 20° to 70° N and from 90° W to 40° E (Fig. 2). This 2.5° × 2.5° grid, centered over the North Atlantic, includes 1113 grid points. The use of upper-level data is intended to reveal general circulation flow patterns and their link to the quality of wine production by separating generalized circulation during vintage Port years, and analyzing circulation anomalies during those seasons and years as compared to other years ('non-vintage') which did not produce a vintage declaration.

Monthly composites of the gridded circulation data are constructed for SLP, and the 850, 700, 500, 300, and 300 hPa geopotential height surfaces for both vintage and non-vintage years. Seasonal composites are also produced, as are difference maps between vintage and non-vintage years by month and season.

3. RESULTS AND DISCUSSION

3.1. Surface atmospheric features

A Spearman correlation analysis was performed on the surface variables and year to identify linear trends over time. Statistically significantly ($\alpha < 0.05$)

Fig. 2. Sea level pressure and geopotential height surface analysis grid. Area for which data is shown in Figs. 3–6

increasing linear trends for non-vintage years were identified for all seasons for PET, T_{max}, and TMP, while T_{min} showed a significantly increasing trend during the summer and autumn seasons. Temperature results update those of Luterbacher et al. (2004), who determined that Europe was warmer in the late 20th century than at any time during the past 500 yr, and supports findings by van den Besselaar et al. (2015). The analysis also confirms the findings of Kürbis et al. (2009), who investigated temperature and moisture trends for Europe, and those of the study by Scherrer et al. (2006) of Swiss temperatures.

Spearman analysis of only the vintage years suggests no change in precipitation for any season, which supports Briffa et al. (2009), who showed that increasing water stress in Europe was due to higher recent temperatures rather than precipitation changes. Significantly increasing vintage-year trends ($\alpha < 0.05$) through the study period occur for PET, T_{max}, and TMP for all seasons. For T_{min}, significant vintage-year change occurred only in summer.

The similarity or difference in thermal and precipitation-related variables in the non-vintage and vintage year data sets becomes more apparent when several simple seasonal descriptive statistics are generated and tested. A Student's *t*-test for difference of means revealed no statistically significant seasonal differences between non-vintage and vintage years for PPT. The *t*-test revealed that autumn T_{max} was significantly greater during vintage years than during non-vintage years. This suggests that statistically warmer temperatures during the harvest season aid grape development and lead to higher-quality Port production.

No statistically significant differences in T_{min} or TMP were found between non-vintage versus vintage years. However, difference of means testing revealed that PET is significantly lower during vintage-year summers than during non-vintage-year summers, but higher in vintage-year autumns than during non-vintage-year autumns. A lower summer PET is indicative of lower crop heat/water stress, which aids in producing higher-quality grapes and resulting wine. During autumn, a higher PET is indicative of dry ripening at harvest, which favors a more balanced fruit product.

3.2. Teleconnection analysis

To provide insights into linkages between surface atmospheric variables and broad-scale atmospheric flow, Spearman correlations were calculated between the non-vintage and vintage year surface variables and teleconnection indices. The NAO and AO indices were chosen given their proximity to and direct influence on European climatology (Rodwell et al. 1999, Luterbacher et al. 2004, Scaife et al. 2008) and known links to wine quality (Dalu et al. 2013). It is recognized that the NAO is likely a regional manifestation of the AO (Deser 2000, Rogers and McHugh 2002) but, since the indices differ, both were examined. Considering the amount of fluctuation in flow during individual months, it is necessary to determine whether a seasonal mean is truly reflective of the overall flow during that season; use of both indices is more robust in this context. The time period 1950–2012 was examined in this part of the analysis due to the limited availability of reliable teleconnection indices.

Results suggest that Douro River regional precipitation is correlated significantly to the NAO in the spring and winter of non-vintage years, while during vintage years, a significant correlation occurs only in winter (Table 1). The correlations are negative in all cases. Significant negative correlations also occur with the AO for spring and winter for non-vintage years, and with winter during vintage years (Table 1). The negative sign of the correlations for the NAO index indicates that negative (positive) precipitation anomalies occur during cool season positive NAO periods when zonal (meridional) flow regimes occur. The negative correlations for the AO index suggest that retreat (amplification) of the circumpolar vortex during cool seasons with a positive (negative) AO phase drives the polar front towards the pole (equator), leaving negative (positive) precipitation anomalies over the study region. The teleconnection analysis indicates that the relationship is present at all times (both vintage years and non-vintage years) with no correlation to resulting wine quality.

For T_{max}, a significant positive correlation with NAO occurs with spring and winter for vintage years (Table 2). Significant correlations between T_{max} and AO appear with autumn for non-vintage years, and winter for vintage years. The positive correlations in all cases indicate an increase (decrease) in T_{max} during the associated cool seasons when the flow regime is predominantly zonal (meridional) across the North Atlantic Ocean and Europe. This result is logical, as zonal flow would advect milder air toward Portugal than meridional flow, given the position of the normal ridge axis over the North Atlantic Ocean. This result does not extend to the more central wine region of Italy as that area shows decreased wine quality during meridional flow in spring (Dalu et al. 2013).

For T_{min}, the only significant correlation is to the NAO in spring of vintage years (r = 0.482, p = 0.050), suggesting that zonal (meridional) flow increases (decreases) T_{min}. No significant correlations were identified between the teleconnection indices and TMP for the region.

Table 1. Significant correlations between seasonal composites of monthly North Atlantic Oscillation/Arctic Oscillation indices and precipitation in the Douro region of Portugal, in vintage (Vin) and non-vintage (NV) Port years, 1950–2012

Years (vintage or non-vintage)	Season	R	p-value
NAO			
NV	Spring	−0.340	0.021
NV	Winter	−0.568	<0.001
Vin	Winter	−0.762	<0.001
AO			
NV	Spring	−0.397	0.006
NV	Winter	−0.591	<0.001
Vin	Winter	−0.809	<0.001

Table 2. Significant correlations between seasonal composites of monthly North Atlantic Oscillation/Arctic Oscillation (NAO/AO) indices and maximum temperature in the study region, in vintage (Vin) and non-vintage (NV) Port years, 1950–2012

Years (vintage or non-vintage)	Season	R	p-value
NAO			
Vin	Spring	0.624	0.007
Vin	Winter	0.537	0.026
AO			
NV	Autumn	0.352	0.016
Vin	Winter	0.498	0.042

3.3. Pressure and geopotential height analysis

Composites were created of the monthly and seasonal geopotential height field means for the SLP (1000 hPa) and 850, 700, 500, and 300 hPa levels, for both non-vintage and vintage years. Difference maps were also created by subtracting the non-vintage-year mean heights from the vintage-year means, for each level. Fig. 3 displays the differences between the monthly composites for vintage and non-vintage years for mean SLP, with non-vintage year heights subtracted from vintage year heights. Similarly, Fig. 4 maps the differences between the monthly composites of 500 hPa geopotential heights. To save space, only SLP and the 500 hPa levels are depicted; the other levels resemble the patterns shown by the SLP and 500 hPa composites, except for the tilting of the major features with height.

January and February show a general decrease (increase) in SLP and geopotential heights over the study region during vintage (non-vintage) years. Differences between vintage and non-vintage years at the surface and upper levels (Figs. 3 & 4) are most apparent over the western North Atlantic, where anomalies of opposite sign are maximized. The difference maps indicate pressure increases over the eastern Mediterranean, suggesting an enhanced trough (ridge) over Portugal during vintage (non-vintage) years. Such a situation would relate to the frequency and/or intensity of mid-latitude cyclones over the study region, resulting in precipitation and temperature changes.

During March, vintage (non-vintage) year SLP and upper-level heights indicate ridging (troughing) westward of and over the study area. Such a situation would generally dampen (enhance) precipitation while supporting higher (lower) temperatures. This result supports the findings of Dalu et al. (2013), who noted that Italian wines increase in quality during springs having decreased mid-latitude cyclone activity; such cyclones (and their accompanying frontal precipitation) would be blocked from reaching southern Europe by western North Atlantic ridging. The differences in SLP and heights for vintage versus non-vintage years for April through August are subtle. However, during September, a small increase in 500 hPa composite height differences occurs, with maximum differences exceeding 30 m higher (lower) during vintage (non-vintage) years; differences in the Douro Valley are approximately 25 m. Such a situation would promote clearer (cloudier) skies, higher

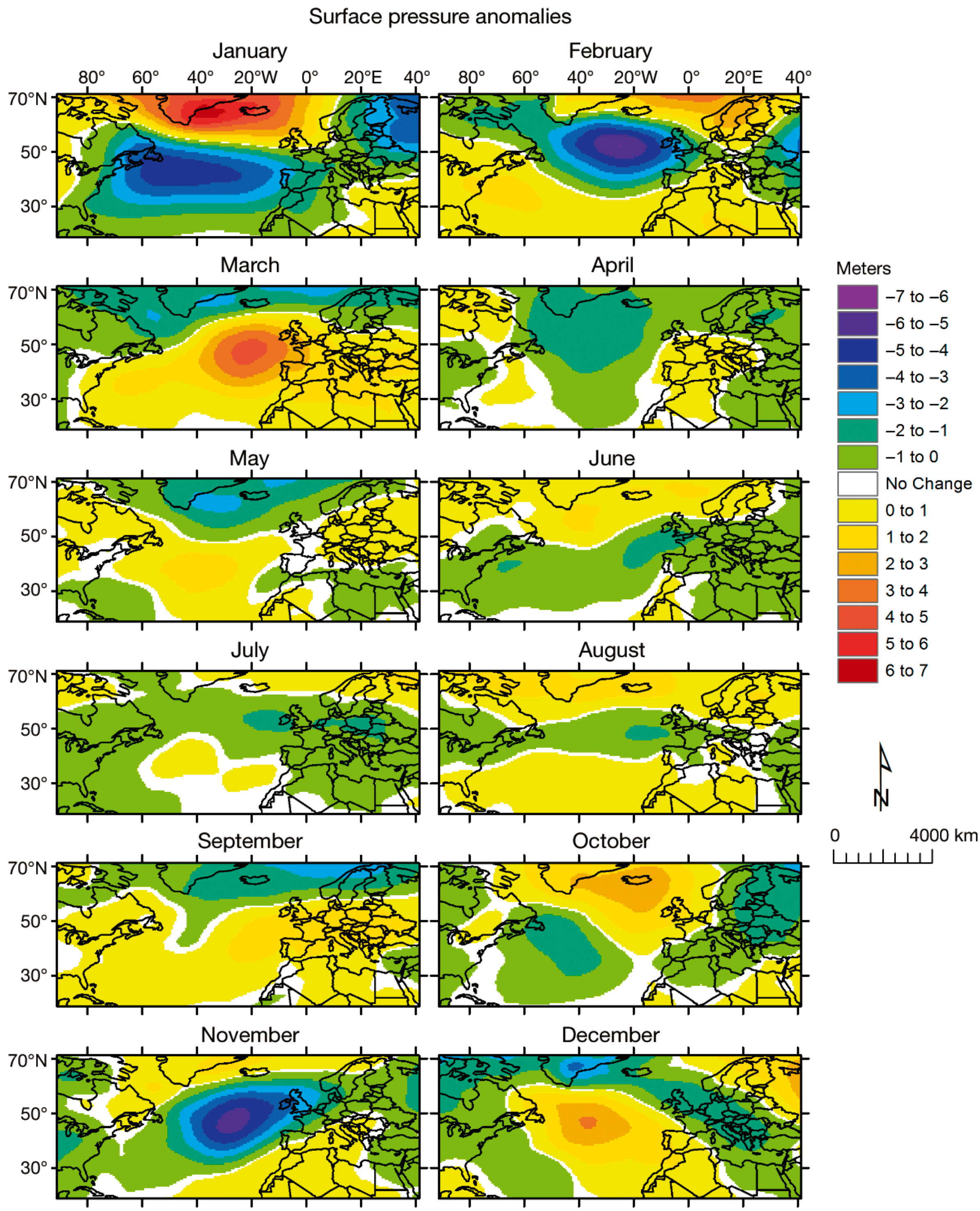

Fig. 3. Difference in mean sea level pressure (vintage years minus non-vintage years) by month, 1901–2012

(lower) temperatures and less (more) precipitation during vintage (non-vintage) years.

Although October differences in SLP and upper-level heights are minor, the November patterns indicate much lower (higher) SLP and deeper troughing (ridging) over the central North Atlantic during vintage (non-vintage) years. The pattern favors warm and moist air advection and the development of mid-latitude cyclones into southern Europe. Subsequent increases (decreases) in precipitation and decreases

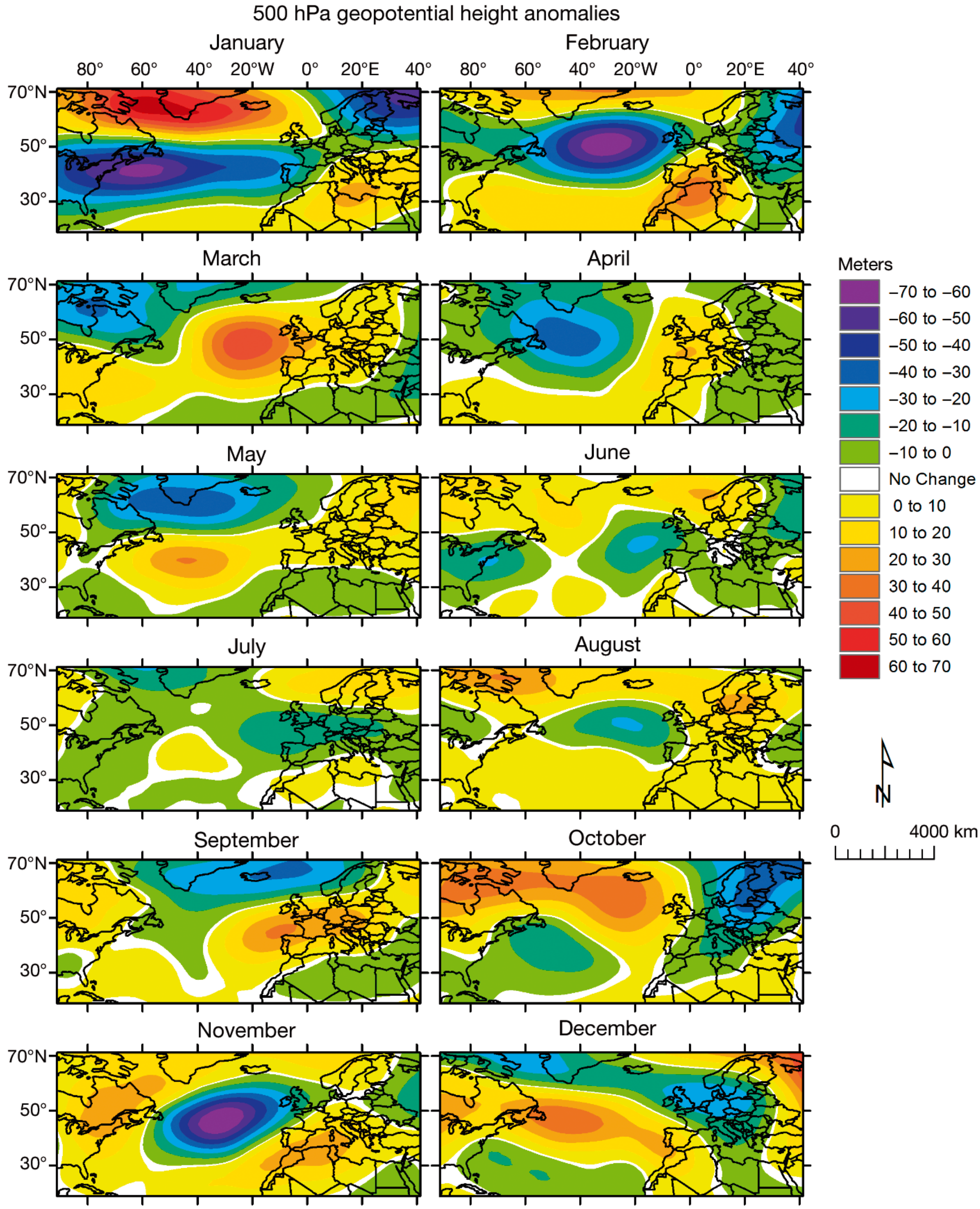

Fig. 4. Difference in mean 500 hPa geopotential height (vintage years minus non-vintage years) by month, 1901–2012

(increases) in temperature are normally coincident with such a flow pattern. Interestingly, December SLP and height differences show an opposite pattern to those of November, as vintage (non-vintage) years are characterized by SLP and 500 hPa heights that increase (decrease) over the west-central North Atlantic. This pattern would produce ridging (troughing) and blocking (enhancement) of frontal cyclone trajectories into central and southern Europe. The SLP and 500 hPa height patterns for a few critical months of the year therefore appear to be conducive to higher-quality Port production. The deep winter (J F) pattern for vintage (non-vintage) years reverses in March as SLPs and 500 hPa heights (Figs. 5 & 6, respectively) increase (decrease) over the study region and the adjacent North Atlantic. Such a situation dampens (enhances) frontal cyclone activity for Portugal. During September, the calm pressure fields of summer give way to pressure and height changes that are somewhat similar to March. Specifically, SLPs and 500 hPa heights (Figs. 5 & 6) increase (decrease) over the study region and neighboring ocean basin during vintage (non-vintage) years. Such a situation would increase (decrease) solar radiation and decrease (increase) clouds and precipitation during this month, which is the time of grape harvest. The final critical month is December, when the pressure and height pattern (Figs. 5 & 6) is the reverse of that present in November and again in January and February. During December of vintage (non-vintage) years, heights increase (decrease) across the mid-Atlantic, extending over the study region, suggesting a decrease (increase) frontal cyclone activity over the Port-producing region. The present study agrees that high-quality wine production for the Douro is tied to amplified ridging over the eastern North Atlantic and western Europe, thus producing meridional conditions that favor higher pressures and heights over the wine-producing regions, but this study is the first to assert that March, September, and December are the months when that ridging is critical.

Despite the rather strong relationships described above, it is important to note that the Douro winemaking region is a complex region in terms of topography and weather. Additionally, there are other oenological, management and even political aspects (e.g. related to winery associations and land ownership) that should be considered. As such, the limitations of the synoptic approach undertaken here should be acknowledged. Microscale work, both in space and time (e.g. Fraga & Santos 2017), should be continued, to 'fine tune' observations made at the synoptic climatological scale of analysis.

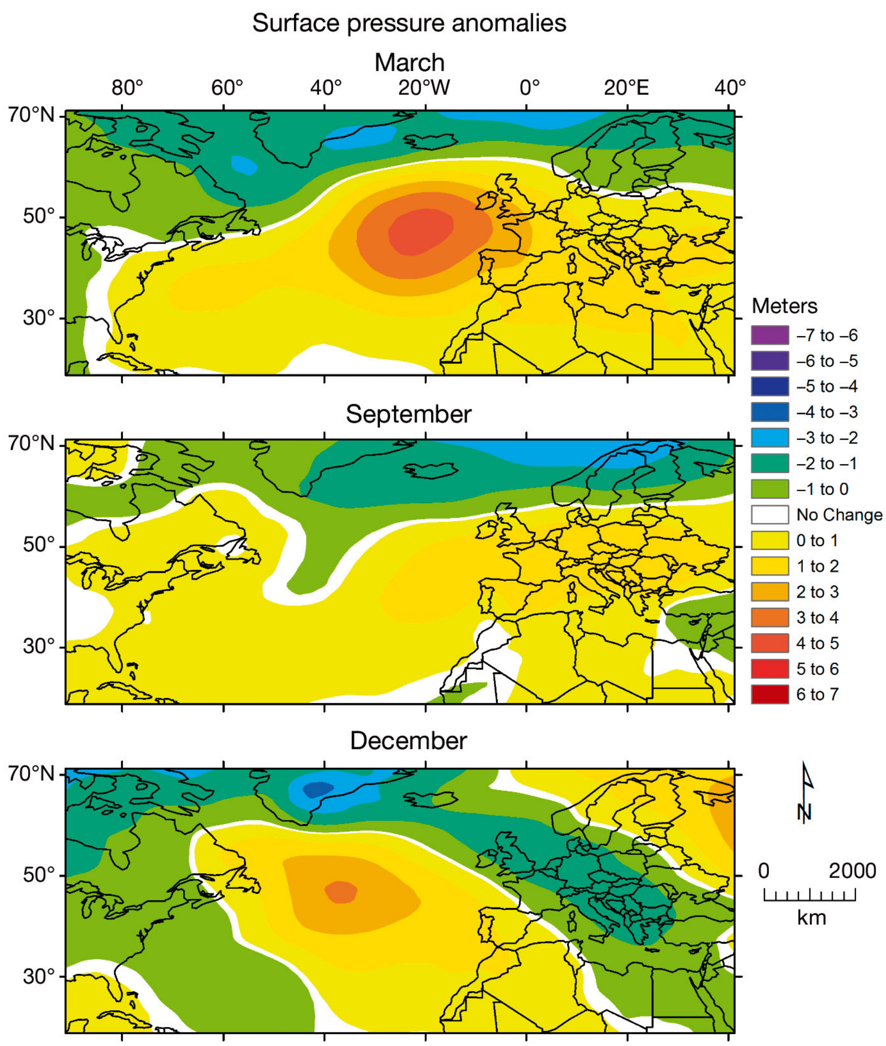

Fig. 5. Differences in mean sea level pressure for March, September, and December (vintage years minus non-vintage years), 1901–2012

4. SUMMARY AND CONCLUSIONS

This research identifies surface variables and the major flow patterns that are associated with higher-quality (vintage), and lower-quality (non-vintage) years for Port wine production in Portugal. The surface results

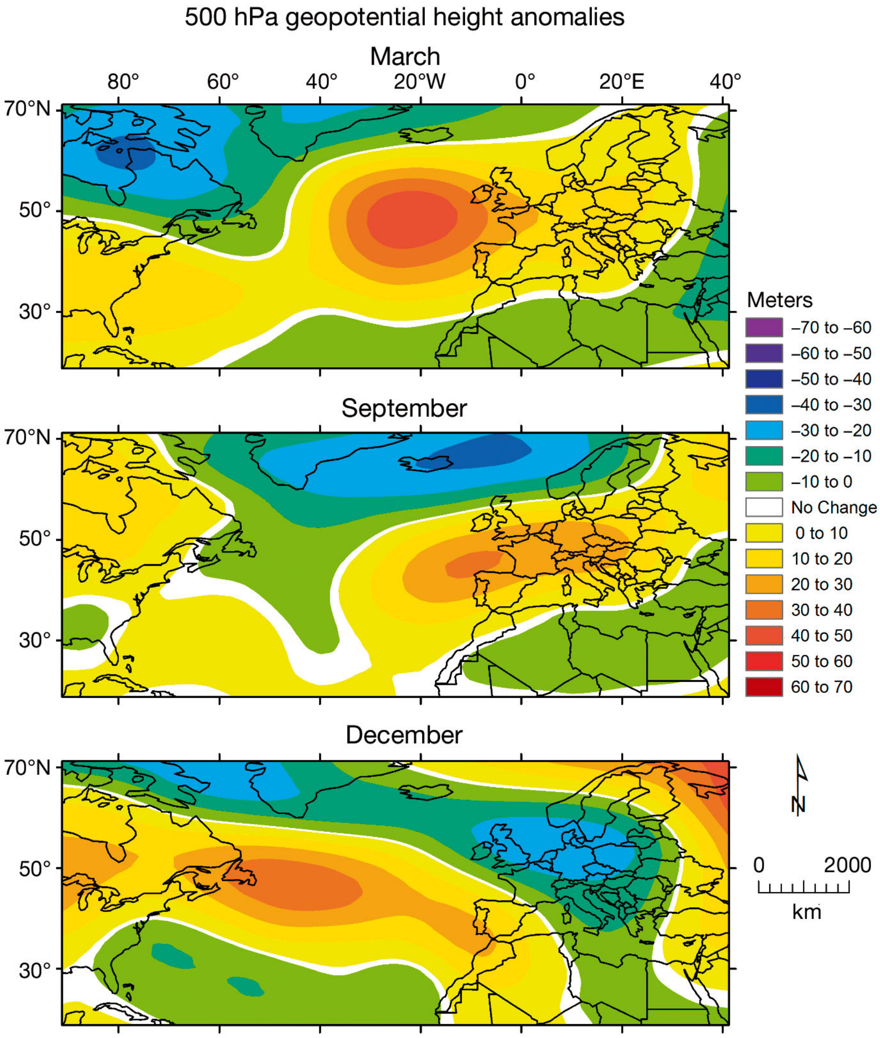

Fig. 6. Differences in mean 500 hPa geopotential height for March, September, and December (vintage years minus non-vintage years), 1901–2012

indicate an increase in maximum air temperatures, average temperatures, and the temperature-related PET data for all seasons for both non-vintage and vintage years over the study period. Minimum air temperatures have increased significantly through the study period during summer and autumn for non-vintage years and during summer for vintage years. Precipitation has remained relatively constant over the study period for both vintage and non-vintage years which, given recent temperature increases, has led to increased surface drying (Briffa et al. 2009) and increased wine quality (Dalu et al. 2013). Teleconnection analysis indicates that both vintage and non-vintage winters hold the same general flow relationships to precipitation in the Douro region. During zonal (meridional) flow regimes, precipitation decreases (increases) for the region. The monthly and seasonal composites of SLP and the significant height fields at 850, 700, 500, and 300 hPa reveal much more. In winter, December is a critical month that distinguishes vintage from non-vintage years. Specifically, the surface and upper-air flow regimes decrease the frequency and/or affect the intensity of frontal cyclones over the region for December during vintage years. Antivilo et al. (2017) indicate that dormant season low temperatures relate to subsequent vine health. By contrast, vintage years are characterized by troughing just west of and over the study region during January and February. Seasonal precipitation remains fairly constant between non-vintage and vintage years. However, for vintage years, higher (but statically insignificant) amounts of late-season precipitation occur compared to non-vintage years. Such a condition may increase soil moisture capacity leading into the spring during vintage years.

During spring, the teleconnections and surface responses are similar for both vintage and non-vintage years. Pressure at the surface and in the upperair is a more important influence in spring, when enhanced ridging over the eastern North Atlantic and western Europe is associated with vintage years. Such a condition is linked to reduced precipitation, and increased maximum and minimum air temperatures over the study region. The result agrees with the circulation findings of Dalu et al. (2013), who showed that drying during spring and summer leads to higher-quality Italian wines.

The SLP and geopotential heights analyses suggest that March is the critical month of spring season change. During vintage years, the March SLP pattern differs from those of the preceding January and February, with increases in SLP and 500 hPa heights for the study region. Such conditions favor desiccation and increased solar radiation, thereby supporting the original hypothesis of a dry spring contributing to vintage Port production. After March, a more consistent circulation pattern develops, with little detectable difference between vintage and non-vintage years.

Summer is characterized by temporally increasing temperature-related surface variables for both non-vintage and vintage years. However, a difference of means test discloses that during vintage year summers, PET is significantly lower than during non-vintage years, which lowers overall vine and water stress (Jones 2015). However, atmospheric flow, indicated by teleconnection and SLP and 500 hPa composites, exhibits little overall difference between vintage and non-vintage years.

For autumn, all temperature-related surface variables have increased significantly over time for both non-vintage and vintage years. The teleconnection analysis shows that mean daily maximum air temperatures increase during times of meridional flow in autumn. September appears to be the month of critical difference in pressure and flow patterns between non-vintage and vintage years, as pressure increases and 500 hPa ridging builds over Europe during vintage years. These changes support increased temperatures and PET and decreased precipitation during the harvest period. The results agree with Dalu et al. (2013) who found that poor-quality wine results from zonal flow across Europe in autumn.

Vintage Port production occurs in association with lower PET during summer and greater autumn T_{max} in conjunction with an anomalously high PET rate during that season. This implies that during vintage year summers, temperature extremes are minimized, leading to a lower PET rate. Such a situation likely allows more water to remain in grapes on the vine. Autumns during vintage years tend to have significantly greater T_{max} and a coincident increase in PET. Thus, during the harvest season climatic conditions that allow more balanced flavor profiles and higher-quality Port production (Jones 2015).

Although the original hypothesis that a generally wet winter followed by a dry spring and a hot and dry summer favour the production of vintage Port was supported in the analysis, some relationships were not statistically significant. This analysis instead suggests that a reduced PET during summer is important to producing vintage Port. Such a situation decreases vine and water stress on the plants which increases the presence of compounds that better balance the flavor in the grapes. The lower PET slightly offsets the increasingly high summer T_{max} (Briffa et al. 2009) that would otherwise increase vine stress. Further, anomalously high temperatures and increased PET during the autumn seem to be important for increased acid and sugar balance immediately prior to harvest. This leads to higher-quality flavor profiles and wine characteristics.

Future research should be invested in identifying relationships at finer temporal and spatial scales, especially during the critical months of December, March, and September. The purpose would be to identify more precisely the within-month variability at these critical times in the growing season, focusing on precipitation and associated soil moisture characteristics critical to higher-quality grape production and resulting Port wine. Sub-monthly changes in surface characteristics and atmospheric flow during the autumn season should also be investigated further. Improved long-lead climate outlooks makes forecasting trends in the Port wine industry promising, particularly since the world's supply is concentrated in such a confined area.

LITERATURE CITED

Agati G, Matteini P, Oliveira J, de Freitas V, Mateus N (2013) Fluroescence approach for measuring anthocyanins and derived pigments in red wine. J Agric Food Chem 61:10156–10162

Antivilo FG, Paz RC, Keller M, Borgo R, Tognetti J, Junent FR (2017) Macro- and microclimate conditions may alter grapevine deacclimation: variation in thermal amplitude in two contrasting wine regions from North and South America. Int J Biometeorol 61:2033–2045

Baciocco KA, Davis RE, Jones GV (2014) Climate and Bordeaux wine quality: identifying the key factors that differentiate vintages based on consensus rankings. J Wine Res 25:75–90

Battaglini A, Barbeau G, Bindi M, Badeck FW (2009) European winegrowers' perceptions of climate change impact and options for adaptation. Reg Environ Change 9:61–73

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

Blanco-Ward D, Garcia Queijeiro JM, Jones GV (2007) Spatial climate variability and viticulture in the Miño River Valley of Spain. Vitis 46:63–70

Briffa KR, van der Schrier G, Jones PD (2009) Wet and dry summers in Europe since 1750: evidence of increasing drought. Int J Climatol 29:1894–1905

Cunha M, Abreu I, Pinto P (2003) Airborne pollen samples for early-season estimates of wine production in a Mediterranean climate area of northern Portugal. Am J Enol Viticult 54:189–194

Dalu JD, Baldi M, Marta AD, Mancini M (2013) Mediterranean climate patterns and wine quality in north and central Italy. Int J Biometeorol 57:729–742

Deser C (2000) On the teleconnectivity of the "Arctic Oscillation". Geophys Res Lett 27:779–782

Duchêne E, Schneider C (2005) Grapevine and climatic changes: a glance at the situation in Alsace. Agron Sustain Dev 25:93–99

Esteves MA, Orgaz MDMO (2001) The influence of climatic variability on the quality of wine. Int J Biometeorol 45: 13–21

Fraga H, Santos JA (2017) Daily prediction of seasonal grapevine production in the Douro wine region based on favourable meteorological conditions. Aust J Grape Wine Res 23:296–304

Fraga H, Santos JA, Malheiro AC, Moutinho-Pereira J (2012) Climate change projections for the Portuguese viticulture using a multi-model ensemble. Cienc Tec Vitivinic 27:39–48

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2013) Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. Int J Biometeorol 57:909–925

Fraga H, Malheiro AC, Moutinho-Pereira J, Cardoso RM and others (2014a) Integrated analysis of climate, soil, topography and vegetative growth in Iberian viticultural regions. PLoS ONE 9: e108078

Fraga H, Malheiro AC, Moutinho-Pereira J, Jones GV, Alves F, Pinto JG, Santos JA (2014b) Very high resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios. Reg Environ Change 14:295–306

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2014c) Climate factors driving wine projection in the Portuguese Minho region. Agric For Meteorol 185:26–36

Fraga H, García de Cortázar Atauri I, Malheiro AC, Santos JA (2016) Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. Glob Change Biol 22:3774–3788

Grifoni D, Mancini M, Maracci G, Orlandini S, Zipoli G (2006) Analysis of Italian wine quality using freely available meteorological information. Am J Enol Vitic 57: 339–346

Henderson JP, Rex D (2012) About wine. Cengage Learning, Clifton Park, NY

Jones GV (2015) Climate grapes and wine: terroir and the importance of climate to winegrape production. www.guildsomm.com/stay_current/features/b/gregory_jones/posts/climate-grapes-and-wine

Jones GV, Alves F (2012) Impact of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal. Int J Glob Warm 4:383–406

Jones GV, Davis RE (2000a) Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am J Enol Vitic 51: 249–261

Jones GV, Davis RE (2000b) Using a synoptic climatological approach to understand climate–viticulture relationships. Int J Climatol 20:813–837

Jones GV, White MA, Cooper OR, Storchmann K (2005) Climate change and global wine quality. Clim Change 73: 319–343

Kalnay E, Kanamitsu M, Kistler R, Collins W and others (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteor Soc 77:437–472

Karnauskas KB, Smerdon JE, Seager R, González-Rouco JF (2012) A Pacific centennial oscillation predicted by coupled GCMs. J Clim 25:5943–5961

Kenny GJ, Harrison PA (1992) The effects of climate variability and change on grape suitability in Europe. J Wine Res 3:163–183

Koundouras S, van Leeuwen C, Seguin G, Glories Y (1999) Influence of water status on vine vegetative growth, berry ripening and wine characteristics in Mediterranean zone (example of Nemea, Greece, variety Saint-George, 1997). J Int Sci Vigne Vin 33:149–160

Kürbis K, Mudelsee M, Tetzlaff G, Brázdil R (2009) Trends in extremes of temperature, dew point, and precipitation from long instrumental series from central Europe. Theor Appl Climatol 98:187–195

Luterbacher J, Dietrich D, Xoplaki E, Arosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303: 1499–1503

Makra L, Vitanyi B, Gal A, Mika J, Matyasovszky I, Hirsch T (2009) Wine quantity and quality variations in relation to climatic factors in the Tokaj (Hungary) winegrowing region. Am J Enol Vitic 60:312–321

Malheiro AC, Santos JA, Fraga H, Pinto JG (2010) Climate change scenarios applied to viticultural zoning in Europe. Clim Res 43:163–177

Malheiro AC, Campos R, Fraga H, Eiras-Dias J, Silvestre J, Santos JA (2013) Winegrape phenology and temperature relationships in the Lisbon wine region, Portugal. J Int Sci Vigne Vin 47:287–299

Mateus N, Machado JM, de Freitas V (2002) Development changes of anthocyanins in *Vitis vinifera* grapes grown in the Douro Valley and concentration in respective wines. J Sci Food Agric 82:1689–1695

Mayson R (2012) Port and the Douro, 2nd edn. Infinite Ideas, Oxford

Neumann PA, Matzarakis A (2011) Viticulture in southwest Germany under climate change conditions. Clim Res 47: 161–169

Oliveira H, Fernandes I, de Freitas V, Mateus N (2015) Ageing impact on the antioxidant and antiproliferative properties of Port wines. Food Res Int 67:199–205

Ortiz MC, Sarabia LA, Symington C, Santamaria F, Inigueze M (1996) Analysis of ageing and typification of vintage ports by partial least squares and soft independent modelling class analogy. Analyst (Lond) 121:1009–1013

Pirra AJ, Bianchi-de-Aguiar F, Arroja L, Capela I (2010) The influence of Port wine in winery effluent production. Fresenius Environ Bull 19:3177–3184

Real AC, Borges J, Cabral JS, Jones GV (2015) Partitioning the grapevine growing season in the Douro Valley of Portugal: accumulated heat better than calendar dates. Int J Biometeorol 59:1045–1059

Real AC, Borges J, Cabral JS, Jones GV (2017) A climatology of vintage port quality. Int J Climatol 37:3798–3809

Robinson J (1986) Vines, grapes and wines. Octopus Publishing, London

Rodó X, Comín FA (2000) Links between large-scale anomalies, rainfall and wine quality in the Iberian Peninsula during the last three decades. Glob Change Biol 6: 267–273

Rodwell MJ, Rowell DP, Folland CK (1999) Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature 398:320–323

Rogers J, McHugh M (2002) On the separability of the North Atlantic Oscillation and Arctic Oscillation. Clim Dyn 19: 599–608

Rudnitskaya A, Delgadillo I, Legin A, Rocha SM, Costa AM, Simoes T (2007) Prediction of the Port wine age using an electronic tongue. Chemom Intell Lab Syst 88:125–131

Santos J, Corte-Real J, Leite S (2007) Atmospheric large-scale dynamics during the 2004/2005 winter drought in Portugal. Int J Climatol 27:571–586

Santos JA, Malheiro AC, Karremann MK, Pinto JG (2011) Statistical modelling of grapevine yield in the Port Wine region under present and future climatic conditions. Int J Biometeorol 55:119–131

Santos JA, Malheiro AC, Pinto JG, Jones GV (2012) Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Clim Res 51:89–103

Santos JA, Gratsch SD, Karremann MK, Jones GV, Pinto JG (2013) Ensemble projections for wine production in the Douro Valley of Portugal. Clim Change 117:211–225

Scaife AA, Folland CK, Alexander LV, Moberg A, Knight JR (2008) European climate extremes and the North Atlantic Oscillation. J Clim 21:72–83

Scherrer SC, Appenzeller C, Liniger MA (2006) Temperature trends in Switzerland and Europe: implications for climate normals. Int J Climatol 26:565–580

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

Song XL, Zhang GJ (2014) Role of climate feedback in El Niño-like SST response to global warming. J Clim 27: 7301–7318.

Souriau A, Yiou P (2001) Grape harvest dates for checking NAO paleoreconstructions. Geophys Res Lett 28: 3895–3898

Stevenson T (2011) Sotheby's wine encyclopedia, 5th edn. Dorling Kindersley (DK), London

van den Besselaar EJM, Sanchez-Lorenso A, Wild M, Klein Tank AMG, de Laat ATJ (2015) Relationship between sunshine duration and temperature trends across Europe since the second half of the twentieth century. J Geophys Res Atmos 120:10823–10836

Vintage Port (2016) Declared vintages. www.vintageport.biz/declared_vintages.html

Yarnal B (1993) Synoptic climatology in environmental analysis: a primer. Belhaven, London

Editorial responsibility: Gerrit Hoogenboom, Gainesville, Florida, USA

Submitted: March 28, 2017; Accepted: February 27, 2018
Proofs received from author(s): May 17, 2018