AJEV Papers in Press. Published online May 24, 2011.

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2011.10108
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Grapevine Phenology and Climate Change: Relationships and Trends in the Veneto Region of Italy for 1964-2009

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Acknowledgements: The authors acknowledge the Istituto Enologico di Conegliano G.B. Cerletti for providing the meteorological data set information.

Manuscript submitted Sept 2010, revised Feb 2011, accepted Apr 2011

Abstract: A long-term (1964-2009), multiple *Vitis vinifera* L. cultivar dataset has provided a comprehensive assessment of cultivar similarities/differences in phenological timing and growth phases and relationships with climate and climate change in the Veneto region of Italy. The budbreak to harvest period for the cultivars studied covered mid-April to late September, averaging 156 days but varying 55 days across cultivars. The main phenological events and intervals between events exhibited a 25 to 45 day variation between the earliest and latest years, with the bloom to veraison growth interval showing the lowest vintage-to-vintage variation. During 1964-2009, trends of 13 to 19 days earlier were found for bloom, veraison, and harvest dates, while budbreak exhibited high inter-annual variation and no trend. Similar characteristics and trends for the main phenological events were found for early, middle, and late maturing cultivars, although early maturing cultivars changed at a higher rate. Due to changes in climate in the region, significant breakpoints in the phenology time series were found, averaging 1990-91 across all cultivars, with early and middle cultivars shifting sooner than late cultivars. Growing season average temperatures warmed 2.3°C from 1964 to 2009, while annual and seasonal precipitation amounts did not change significantly. During 1964-2009, the growing period climate differences were 2.0°C between the years with the shortest and those with the longest budbreak to harvest intervals. The combined trends in phenology and climate resulted in an average shift of eight days per 1.0°C of warming. The extremely warm summer of 2003 (compressed growth intervals) and warm spring of 2007 (shifts in phenological timing) provide analog conditions to those projected for later this century.

Key words: phenology, growing season, climate, grapevines, wine, Italy

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Introduction

Phenology is the study of the relationships between climate and the timing of periodic natural phenomena such as the migration of birds, insect growth stages, and the flowering of plants. Knowledge of a plant's phenological characteristics is never more important than for *Vitis vinifera* L. grapevines where the optimum development of quality fruit for wine production is tied to phenological occurrence and timing (Jones and Davis 2000, Keller 2010). In addition, because grapevine phenology is strongly tied to climate, and has been observed in many regions over many years, its study has received considerable attention as a tool to understand how climate variability and change impacts viticulture and wine production (Chuine et al. 2004, Spanik et al. 2004, Jones et al. 2005a, Webb et al. 2008, and others).

Numerous studies have provided evidence for systematic changes in climate (Kutiel and Maheras 1998, Klein Tank and Konnen 2003, Braganza et al. 2004) showing increasing temperature trends of 0.6-0.7 °C since the start of the 20th century (IPCC 2007). Furthermore, the global climate record shows that last few decades have been some of the warmest on record (Salinger 2005) and that the rate of increase in the last 25 years has been over three times the century-scale trend (IPCC 2007). The observed changes in temperatures have also been shown to occur in both higher maximum and minimum temperatures and a greater frequency of extremes (Klein Tank and Können 2003, Kostopoulu and Jones 2005). Future climate scenarios also project that globally averaged surface temperatures will increase further by 1.4 to 5.8°C by 2100 (IPCC 2007).

While changes in average temperatures are important for agriculture in general, increasing temperatures have been shown to be accompanied by alterations of other climatic parameters such as precipitation, evapotranspiration, and the diurnal temperature range (DTR) (Weber et al. 1994, Dessens and Bücher 1995). In addition, recent studies have shown significant changes in extreme events, such as heat waves, drought events, or a higher percentage of the annual precipitation coming in heavy, more frequent events (Easterling et al. 2000, Klein Tank and Können 2003, Bartolini et al. 2008).

For the Mediterranean basin and Italy specifically, studies have indicated a similar general increase in temperature as compared to other global or hemispheric studies (Brunetti et al. 2000a and 2000b). Moonen et al. (2002) found that agrometeorological extreme risk indices had not changed tremendously in Italy during 1878-2000, with some benefit seen in a reduction of crop damage risk from frost. More recently, Kostopoulou and Jones (2005) studying Mediterranean basin climate extremes during 1958-2000 found evidence of significant warming trends in both minimum and maximum summer extremes over the region and a decline in the frequency of cold nights. As a result,

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changes in the DTR have also been observed in the region where Brunetti (2000b) found that the DTR in Italy has shown a tendency towards negative trends in the north and positive trends in the south. For precipitation there is some evidence of a reduction in overall amounts in Italy (Brunetti et al. 2002), while for extremes Kostopoulou and Jones (2005) also found positive trends in heavy precipitation events and significant increases in the number of consecutive dry days over the Mediterranean basin.

Research examining the relationships between climate and grapevine phenology have shown moderate to strong correlations (Calò et al. 1994, Jones and Davis 2000). Budbreak timing and its consistency has been tied with adequate winter chilling requirement followed by warm springs (Moncur et al. 1989, Keller 2010). Bloom events appear to be most strongly correlated with maximum temperature levels in the preceding month (Calò et al. 1994) while average temperatures or heat accumulation indices are more important for veraison and harvest (Jones et al. 2005a). Grapevine phenological timing in Europe has shown strong relationships with the observed warming with trends ranging 6–25 days earlier over numerous cultivars and locations (Jones et al. 2005a). Changes have been greatest for bloom and consequently veraison and harvest dates which typically show a stronger, integrated effect of a warmer growing season than do early growth events. In Alsace, France research has found strong ties between climate and earlier phenology with the period between budbreak and harvest becoming both earlier and shorter (15-23 days), and resulting in changes in fruit composition and increases in potential alcohol (Duchêne and Schneider 2005). Averaged over all locations and cultivars, grapevine phenology has shown an average 5-10 day response per 1°C of warming over the last 30–50 years (Jones et al. 2005a, Ramos et al. 2008). Given that wine region specific research has shown growing season average temperature warming of 1.3°C from 1950-1999 and projections of 2.0°C by 2050 (Jones et al. 2005b) further changes in grapevine phenology are likely. Webb et al. (2008) have modelled these impacts in Australia, predicting that budbreak will be 6-11 days earlier by 2050, harvest dates up to 45 days earlier, and that the growing season compresses to the point that ripening occurs in a hotter period of the season.

Given the strong influence of climate on grapevine growth behaviour, along with the potential for continued changes in climate over the next century (IPCC 2007), the main goals of the present study were to evaluate climate and phenological characteristics, variability and structural changes in the Veneto region of Italy (Supplemental Figure 1). This research examines these issues through the use of a long-term data set on grapevine phenology (18 cultivars and 46 years) and climate in the region. The length of the time period studied and number of cultivars observed allows us to better capture the underlying responses of numerous different grapevine cultivars to climate and better understand how future climates might influence vine growth in the region and throughout the world.

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Data and Methods

The phenology data used in this research are from a comprehensive, long-term collection of the Research Center for Viticulture (CRA-VIT) in Conegliano, Veneto region, Italy (Supplemental Figure 1). The collection is from single vineyard comprising five hectares with over 1000 cultivars of both Italian and globally recognized types. In the collection there are 8 plants per cultivar planted to 3 m x 1.5 m spacing on a sylvoz trellis system. The collection was initially planted in the 1950s, with cultivars being added year-by-year, and during 1986-1987 the collection was completely replanted in a block next to the original vineyard (same soils), and after four years the yearly phenological observations came from the new collection. To insure reliability between the initial planting and the new planting, the new block was planted with vine material from the old collection ensuring similar genetic responses, and was planted to the same rootstock (SO4), at the same vine density and with the same trellis system as the initial plantings. An analysis of overlapping phenological observations from the old and new blocks shows no significant differences between the two.

The phenology observations were recorded by viticultural technicians with CRA-VIT according to the Baggiolini phenological scale for budbreak (stage D), bloom (stage I), and veraison (no stage letter designation) (Baggiolini 1952). Harvest dates were determined by visual monitoring of the fruit development and health, but giving priority to the berry sugar content (Brix), and recorded when the sugar content remained the same after two consecutive measurements. The four main phenological events are also used to derive the intervals between each event (e.g., budbreak to bloom, veraison to harvest, etc.) resulting in ten phenological parameters (Table 1 and 2). The observations used in this research come from eighteen cultivars that represent early, middle and late maturing cultivars (Table 1). The data cover the 1964 to 2009 time period with complete observations except for Chardonnay, which was missing 1964-1968 for budbreak, bloom, and veraison and 1980-1983 for harvest dates.

The climate data used in this study comes from a site next to CRA-VIT cultivar collection in Conegliano, Veneto region, Italy (60 m asl, 45.85°N and 12.26°E). The station records observations of maximum, minimum, and average temperatures and precipitation at daily timescales. The time period is 1964-2009 with complete daily data during this period. The daily data were summarized for the growing season for winegrapes (Apr-Oct) based on the fact that simple growing season averages explain much of the phenological development of grapevines, production, and quality (Jones et al. 2005a). Furthermore, two commonly used heat accumulation indices were computed from the daily data: standard growing degree-days (GDD) as classified into the Winkler Index (WI; Amerine and Winkler 1944) and the Huglin Index (HI; Huglin 1978). GDD was calculated based upon the standard simple degree-day formulation using average temperatures above a 10°C base for the months of April

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through October. The HI represents a similar degree-day formulation as the WI with an adjustment that gives more weight to maximum temperatures and is multiplied by a coefficient of correction (k) which takes into account the average daylight period for the latitude studied (Huglin 1978). The HI is commonly summed over the April to September growth period when used in Europe (Jones et al. 2005a) and, while this represents one less month than the normal GDD formulation, both formulations were maintained for the ease of comparison with published data in Europe and elsewhere.

The phenology and climate data were then analyzed separately for their statistical characteristics, inter-annual variability, and trends. To examine the relationships between phenology and climate we utilized Pearson's correlation along with general stepwise linear regression to assess the climate parameter(s) that most influenced the phenological events or intervals. Given that large-scale atmospheric teleconnections had been used to describe inter-annual variability in climate and viticulture parameters in Bordeaux (Jones and Davis 2000), and Europe in general (Hurrell et al. 2003), we also examined the effect that the North Atlantic Oscillation (NAO) has on the local climate variations and the phenology of the grapevines in the region. In addition, given that many time series of data can have at least one breakpoint where the linear regression coefficient can shift over a range of years from one stable regression relationship to a different one (Chu 1996), we applied the R-package "strucchange" version 1.3-7 (Zeileis 2009), to analyse the phenological data series for significant breakpoints (a confidence range of 90% for the change point).

Furthermore, to examine the nature and relationships for extreme years the analysis compares the 2003 and 2007 vintage weather and phenological timing with the remaining years. Both of these vintages were two or more standard deviations outside the period normals due to extreme heat and dry conditions, providing a glimpse of potential grapevine responses from warmer conditions in the future.

Results

General Climate Characteristics

During 1964-2009 the annual average temperature was 13.1°C with summer months where the maximum average temperatures were near 29°C and winter months with average minimum temperatures near or slightly below 0°C (Supplemental Figure 1). The growing season (Apr-Oct) average temperature (GST) was 18.5°C placing it as a warm climate maturity group as defined by Jones et al. (2005b). In terms of heat accumulation the growing degree-days for 1964-2009 time period averaged 1813, a Region III on the Winkler index (Amerine and Winkler 1944). The Huglin index for the same time period averaged 2457 which fell in the warm index class as defined by Huglin (1978). Annual precipitation was1216 mm with growing season precipitation representing 65% of the

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annual amount (Supplemental Figure 1) and precipitation during September through November showed the highest monthly coefficient of variation.

Phenological Characteristics

The phenological characteristics for the eighteen cultivars in the collection for 1964-2009 revealed an overall average budbreak date of 17 April (Table 1). Over the time period the overall budbreak average has ranged over 28 days, occurring as early as 3 April in 1972 and as late as 30 April in 1987. Between early, middle, and late maturing cultivars there was a five day variation in average budbreak. The earliest cultivar for budbreak was Prosecco with an average of 11 April while the latest cultivars to budbreak on average were Garganega and Trebbiano Toscano on 25 April (Table 1). In terms of year-to-year variability in budbreak, Cabernet Sauvignon exhibited the lowest variability (SD +/- 5.7 days) while Marzemino and Albana has the greatest variability (SD +/- 7.8 days). Albana also has exhibited the greatest range in budbreak over the time period with 39 days between its earliest and latest budbreak (Table 1).

Bloom averaged 8 June for all cultivars during 1964-2009 with an overall average range of 37 days between the earliest (17 May in 2007) and latest years (23 June in 1965 and 1980) (Table 1). Early maturing cultivars tended to bloom 4-5 days earlier than middle or late maturing cultivars on average. The earliest flowering cultivar on average in the collection was Chardonnay (3 June) while the latest on average was Albana (13 June). Corvinone exhibited the least year-to-year variation (SD +/- 7.4 days) while Pinot noir had the highest year-to-year variation (SD +/- 9.1 days) and greatest range of 42 days between its earliest and latest bloom years (Table 1).

The average date for veraison was 13 August over all cultivars and years in the record (Table 1). Average veraison dates showed a 39 day variation between the earliest and latest years with the earliest occurring on 24 July in 2007 and the latest 1 September in 1980 and 1983. Differences between early, middle, and late maturing cultivars were more pronounced with veraison than budbreak or bloom. Early maturing cultivars averaged 9 and 14 days earlier veraison events compared to middle and late cultivars, respectively. The earliest veraison on average was seen with Müller Thurgau (30 July) and the latest was observed in Molinara (24 August), resulting in a range of over three weeks between the two cultivars (Table 1). Müller Thurgau and Corvinone had the lowest year-to-year variation in veraison of +/- 7.6 days while Corvina and Molinara varied by +/- 10.8 days during 1964-2009. The Albana cultivar exhibited the greatest range of 52 days between the earliest and latest years for veraison.

Harvest dates of cultivars in this collection averaged on 22 September during the time period (Table 1). The earliest average harvest dates occurred on 30 August in 2007 and 5 September in 2003,

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however during these years harvest dates did occur as early as the middle of August for some cultivars. The latest average harvest dates occurred on 13 October in both 1974 and 1980, resulting in a range of 43 days between the earliest and latest years. Harvest dates for early maturing cultivars occurred on average 12 days ahead of middle maturing cultivars and 20 days before late maturing cultivars. The earliest average harvest dates were seen in Müller Thurgau (6 September) while the latest average harvest dates were observed in Molinara (3 October). Pinot noir exhibited the highest year-to-year (SD +/- 13.9 days) variability while Corvinone showed the lowest variability (SD +/- 9.2 days) and the greatest range between earliest and latest years was 66 days for Marzemino.

Average intervals between the main phenological events are an important measure of vine and berry development timing due to climate. The eighteen cultivars in Veneto during 1964-2009 revealed an average budbreak to flowering interval of 52 days (Supplemental Table 1). The time period range was 35 days with the shortest average interval between budbreak and bloom 36 days in 1986 (with an April/May average temperature of 16.0°C) and the longest 71 days in 1984 (with an April/May average temperature of 13.4°C). Trebbiano Toscano, Cabernet Sauvignon and Garganega showed the shortest interval (48 days) and Trebbiano Toscano also the lowest variability from year-to-year (SD +/- 8.2 days), while Prosecco and Marzemino had the longest interval of 56 days (Supplemental Table 1). The cultivar Albana exhibited both the highest variability (SD +/- 11.7 days) and the greatest range (49 days) of the collection.

The budbreak to veraison interval was 118 days on average, with a range of 34 days from the shortest average interval of 104 days in 2000 to 138 days in 1984. Müller Thurgau exhibited both the shortest average budbreak to veraison interval (108 days) and the low year-to-year variability (SD +/- 9.0 days). Albana showed the highest variability in the interval (SD +/- 12.5 days) and the greatest range between its earliest and latest occurrence (57 days) while Molinara had the longest average interval (128 days).

The period from bloom to veraison averaged 66 days (Supplemental Table 1) with a range of 36 days from the earliest to latest average years. The shortest interval on average occurred in 1966 and 1970 (51 days) while the longest interval occurred in 1983 (87 days). The bloom to veraison period had the lowest standard deviation (SD +/- 6.8 days) of any of the event intervals indicating that it was the most consistent growth period. By cultivar Chardonnay exhibited the least year-to-year variability while Pinot noir showed the highest. In addition, a 21 day range was found between the shortest average interval (Müller Thurgau, 56 days) and the longest average interval (Molinara, 77 days).

The bloom to harvest interval for the eighteen cultivars averaged 106 days during 1964-2009 with the shortest interval occurring in 1995 (86 days) and the longest in 1986 (130 days). Müller Thurgau

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experienced the shortest average interval at 94 days while Molinara and Corvina showed an average 116 day interval (Supplemental Table 1). Similar to the bloom to veraison interval, Chardonnay and Pinot noir exhibited the least and most year-to-year variability for the bloom to harvest interval, respectively. Corvinone showed the greatest range in this interval, varying by 58 days over the time period.

The ripening stage from veraison to harvest showed an average of 39 days during the time period (Supplemental Table 1) with a range of 44 days from the shortest interval of 19 days in 1983 to 62 days in 1986 (similar to the bloom to harvest interval above). By cultivar, the veraison to harvest interval varied from the shortest for Chardonnay (34 days) to the longest for Garganega and Cabernet sauvignon (43 days). Similar to the previous event intervals, Chardonnay showed the lowest year-to-year variability in the veraison to harvest interval while Pinot noir had both the highest variability (SD +/- 12.1 days) and greatest range for the shortest to longest interval (43 days).

The length of the budbreak to harvest period for the region averaged 156 days over all cultivars during 1964-2009 (Supplemental Table 1). This interval characterized the time needed for each cultivar to ripen and ranged 55 days from the earliest years with 144 days in 2003 to the latest year with 189 days in 1980. Chardonnay, Pinot Grigio, and Müller Thurgau exhibited the shortest average budbreak to harvest dates of 145 days, while Molinara had the longest average interval of 169 days. Müller Thurgau and Pinot Grigo had the lowest year-to-year variability from budbreak to harvest while Albana had the greatest variability (Supplemental Table 1). Albana and Chardonnay had the greatest range from their shortest to longest intervals.

Temporal correlations between the phenology averaged over all cultivars shows that budbreak timing is not significantly correlated with the later growth stages. On the other hand, bloom dates are strongly correlated with both veraison (r = 0.85, $p \leq 0.001$) and harvest (r = 0.74, $p \leq 0.001$) dates. Furthermore, the timing of veraison and harvest dates are highly correlated (r = 0.79, $p \leq 0.001$). These indicate that budbreak and bloom timing are largely independent phenological events driven by the more variable weather influences early in the season, but that as the vine continues its annual growth cycles each successive event is significantly correlated to the previous event. Also the veraison to harvest interval is sometimes driven by picking decisions, which tends to drive the variability in the length of time needed, more so than previous growth intervals.

Relationships between Climate and Phenology

Climate and the phenology of winegrapes have been shown to be strongly coupled (Calò et al. 1994, Jones and Davis 2000) and the results for this analysis also revealed significant relationships (Figure 1). The average budbreak for the eighteen cultivars in the collection showed the most significant

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response to the average temperature during February and March (R^2=0.45) where budbreak was on average 2.9 days earlier per 1°C (Figure 1A). Average bloom dates were most significantly related to maximum temperatures during 10 April to 10 June (R^2=0.77) with 4.1 days earlier per 1°C (Figure 1B). Maximum temperatures during 10 June to 20 August showed the most significant relationship with veraison dates (R^2=0.29) with 3.2 days earlier per 1°C (Figure 1C). The most significant relationship with harvest dates and climate was with the average growing season temperatures from April through October where an 8.0 day earlier harvest was achieved with a 1°C warmer vintage (R^2=0.39; Figure 1D). It is important to note that measures of heat accumulation, such as growing degree-days and the Huglin index, did not explain more of the variation in the main phenological events than did simple measures of average or maximum temperatures as shown in Figure 1.

Trends, Variability and Breakpoints in Phenology

During 1964-2009 the collection's average phenological events showed higher inter-annual variability early in the record with lower inter-annual variability since approximately 1990 (Figure 2). Furthermore, the year-to-year coefficient of variation for the average budbreak dates was nearly double those observed for the three other events, revealing the higher spring time variability in temperatures and growth (not shown). An examination of the most prominent large-scale atmospheric forcing mechanism in the region (NAO) found no significant correlations between the dominant period of the NAO index (winter - DJFM), or seasonal NAO index values (MAM or JJA) compared with the main phenological events or the intervals between the events.

While no long-term trend was found for budbreak (Figure 2 and Table 2), each of the three other main phenological events trended earlier over the time period. The trend in average bloom dates was 16 days earlier during 1964-2009 (R^2=0.36), while the trend in average veraison (R^2=0.21) and harvest (R^2=0.37) dates were 13 and 19 days earlier, respectively (Figure 2 and Table 2). Similar trends for the main phenological events were found for early, middle, and late maturing cultivars, although early maturing cultivars were changing at a slightly higher rate compared to middle and late maturing cultivars.

The intervals between the main phenological growth events showed higher inter-annual variation compared to the individual growth events themselves, hinting at a strong vintage weather conditions connection driving plant development rates between events. The bloom to veraison interval exhibited the lowest inter-annual variation of all the intervals at four days, while the coefficient of variation for budbreak to bloom (19 days) and veraison to harvest (15 days) were significantly higher than for the other intervals (not shown). The intervals also displayed trends during the time period with the budbreak to bloom interval changing the most at 18 days shorter (R^2=0.30) during 1964-2009 (Table

2). Other intervals trending shorter were budbreak to veraison (15 days, R^2=0.22), budbreak to harvest (15 days, R^2=0.14), and veraison to harvest (6 days, R^2=0.11) (Table 2). The growth intervals from bloom to veraison and bloom to harvest did not change significantly over the time period. For early maturing cultivars differences from the average values included a slight lengthening trend in the bloom to veraison period (6 days, R^2=0.13) and a greater shortening of the budbreak to harvest interval (21 days, R^2=0.35). For middle maturing cultivars a similar greater shortening of the budbreak to harvest interval (22 days, R^2=0.35) was observed and the veraison to harvest period was not trending shorter. Late maturing cultivars showed similar trends differences from the average as the early maturing cultivars (not shown).

While the general trends described above show changes over the entire time period it is important to examine if there were significant breakpoints in the time series. For budbreak no breakpoints were found in the overall average, early, middle, or late maturing cultivars, however there was a slight change to later budbreak (2-3 days) in the middle of the 1970s (Figure 3A, only for the overall average for the cultivars; early, middle, and late cultivar figures not shown). For bloom a significant breakpoint in 1991 was found for average, early, and middle cultivars showing a step change of 10 days earlier (Figure 3B). Early and middle maturing cultivars exhibited a similar breakpoint to the average, however, late maturing cultivars showed a significant breakpoint that was six years later in 1997 but with the same 10 day earlier change (not shown). Similar results were found for veraison where the overall average (Figure 3C) and early and middle maturing cultivars showed significant breakpoints in 1991-92 with a 10-11 day earlier step change while the late maturing cultivar's breakpoint occurred in 1996 and now was 12 days earlier (not shown). For harvest each of the four groupings of cultivars showed similar results with significant breakpoints during 1990-1992 with step changes from 12 to 15 days earlier (Figure 3D). Overall, the breakpoint analysis showed that was a significant advance in the vine phenology, which occurred over ten year period during the late 1980s through the late 1990s, that is in accordance with the temperature increases shown in Figure 4.

Variability and Trends in Climate

From 1964 to 2009 temperature showed moderate inter-annual variability and inter-decadal fluctuations (Figure 4). Trends were found for average, average maximum and average minimum temperatures for both the entire annual period and the growing season (Apr-Oct) (Table 3). Maximum temperatures increased the most, warming 2.5°C over the entire year (R^2=0.51) and 2.4°C during the growing season (R^2=0.38). Minimum temperatures increased by 2.0°C over the entire year (R^2=0.48) and 2.3°C during the growing season (R^2=0.46), while average temperatures increased 1.6°C and 2.3 °C for annual (R^2=0.42) and growing season (R^2 = 0.46) periods, respectively. However, it should be

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noted that annual and growing season (Apr-Oct) average maximum temperatures declined from 1964 to the mid-1980s then increased markedly through to 2009 while minimum temperatures have declined slightly in the last decade (Figure 4).

Given the differences in the underlying time series for maximum and minimum temperatures, a gradual decline in the diurnal temperature range (DTR) was seen from 1964 to 1999 followed by a noted increase in DTR through 2009 (Figure 5). As is common in mid-latitude regions, precipitation in the Veneto region showed much greater inter-annual variability and inter-decadal fluctuations than temperature (Figure 6) and no trends were found for annual or growing season precipitation (Table 3). Annual precipitation averaged 1238 mm with a 216 mm standard deviation and ranged from a low of 777 mm in 2003 to a high of 1552 mm in 1979. Overall annual precipitation showed high inter-annual variation, but has exhibited a moderate decline through 2009 (Figure 6). Similar to the phenology, we examined the climate time series for relationships with the North Atlantic Oscillation and found that the winter and seasonal NAO index values had significant, albeit minor relationships with growing season temperatures but not precipitation (not shown). The overall effect is that when the NAO is in its positive phase, the growing season is slightly warmer than normal.

Examining the climate data by the two periods defined by the phenological breakpoints, 1964-1990 and 1991-2009, revealed significant differences in temperature. The later period was 1.0-1.5°C warmer than the earlier period for average, maximum, and minimum temperatures, while no differences in precipitation were found. Furthermore, both the range and inter-annual variability in temperature were higher during 1964-1990 than the later time period (not shown) and this matched well with the lower inter-annual phenological variability since 1990 mentioned above (see Trends, Variability and Breakpoints in Phenology).

Before and After the Breakpoint and Extreme Years

A comparison of the phenology before and after the breakpoint (1964-1990 and 1991-2009) revealed significant differences in timing and interval lengths (Figure 7). Averaged over all cultivars, budbreak was not significantly different in timing between the two periods however bloom, veraison and harvest dates were all significantly earlier. Overall, the length of time from budbreak to harvest length was 13 days longer during the earlier period, driven by mostly longer budbreak to bloom and veraison to harvest intervals (Figure 7A). Similar results are seen for early, middle, and late ripening cultivars (Figure 7B,C,D).

To examine the grapevine phenology response to extreme climatic years, we compared the temperature and phenology after the breakpoint (1991-2009) with the two warmest vintages during this period (2003 and 2007). The 2003 vintage was extremely warm and dry during the middle of the

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summer throughout most of Europe (Seguin et al. 2004), while the 2007 vintage was extremely warm during the early spring (April average temperature + 4°C over the long term average), slightly above average the rest of the vintage, and with near normal precipitation. For the 2003 vintage budbreak was a few days later than average (Figure 7A), but was followed by warm conditions that hastened bloom, reducing the budbreak to bloom interval 8-10 days for early, middle, and late cultivars. Even with the warmest summer on record, the bloom to veraison interval remained near the period average, potentially indicating greater overall growth stability during this stage. However, the veraison to harvest interval during 2003 compressed to 31 days, over a week shorter than the average during 1991-2009 (Figure 7A). The overall length of the budbreak to harvest period was 127 (early varieties) to 144 days (late varieties) in 2003, 10 to 16 days shorter than the 1991-2009 period average (the warmest and shortest in the record). For 2007 budbreak and bloom occurred nearly two weeks ahead of the 1991-2009 average with no differences between the early to late ripening cultivars (Figure 7). However, even with the exceptionally early budbreak and bloom in 2007 the remaining growth intervals where almost the same as those during the 1991-2000 period. Commonalities between the two years are that they both experienced the shortest budbreak to bloom intervals in the data record (38-39 days across all cultivars), however in 2007 the remaining growth periods were earlier but not shorter.

Discussion

Using a long term dataset of multiple cultivars and site specific climate data, this research examined the characteristics, relationships and trends for grapevine phenology and climate in Conegliano, Italy. The results have shown that climate in the region has clearly changed; temperatures increased appreciably since 1980, the diurnal temperature range decreased due to more rapid changes in minimum temperatures, and precipitation decreased after 1995. Similar results have been seen elsewhere in Europe (Duchêne and Schneider 2005, Jones et al. 2005a, Ramos et al. 2008, Orlandini et al. 2009). The results also showed trends in winegrape phenology, differences between phenological timing of different cultivars and moderate to strong relationships between phenology and climate. During 1964 to 2009 the 18 cultivars studied showed a cultivar range of 14 days for budbreak, while the range between cultivars dropped to 10 days for bloom, but increased to 25 and 27 days for veraison and harvest respectively. The overall average for bloom, veraison and harvest showed high interannual variability of 37, 39 and 43 days between years respectively, while the budbreak date exhibited 28 days between years. Across all varieties, budbreak and harvest dates showed a larger coefficient of variability from year-to-year while bloom dates were the most consistent.

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Examining the phenological timing across the growing season, the results from this research have shown that there are not always strong relationships between growth events. For example the data showed that an early budbreak was not always followed by an early bloom and that an early bloom did not always correspond to an early ripening. The observations of the length of the intervals between stages supported this observation and confirm other work by Calò and Costacurta (1974) and Moncur et al. (1989). Evidence of this characteristic comes from two of the warmest vintages in the region, 2003 and 2007. The 2003 vintage, the hottest on record in much of Europe (Seguin et al. 2004), experienced a normal spring and budbreak, but a very warm summer that resulted in 127, 135 and 144 day growing intervals for early, middle, and late cultivars respectively (on average 14 days shorter compared with the 1991-2009 period). While the 2007 vintage budbreak started 2-3 weeks early with spring temperatures 3.5°C warmer than average, the vintage ended up with a near normal budbreak to harvest period (only 6 days shorter than the 1991-2009 period).

Extreme years also provide further insight into the relationships between vintage weather and grapevine growth. For example, the very short budbreak to harvest period of 1993, 2003, 2005, and 2007 (155 days or less) were driven by nearly 2°C higher average temperatures while the very long budbreak to harvest period of 1967, 1973, 1980, and 1983 (185 days or more) experienced nearly 2°C lower growing season temperatures on average. This research found that the interval between budbreak and harvest, averaged across cultivars and vintages, was shortened by 8 days per 1°C warmer growing season. However, budbreak and bloom appeared to be the more climatically sensitive stages. Veraison and harvest dates exhibited lower correlations with climate, but stronger relationships with the timing of prior phenological events (mostly for veraison versus bloom), which is similar to observations in Bordeaux (Jones and Davis 2000). The low correlations between the veraison to harvest events and climate indicate the importance of the influence of grower subjectivity on maturity and picking decisions.

This research found evidence of a changing climate in Conegliano, Italy with warming rates of 1.6-2.5°C in annual and growing season average, maximum and minimum temperatures during 1964-2009, with maximum temperatures trending at a higher rate than minimum temperatures. These warming rates are similar to those found elsewhere in Alsace (Duchêne and Schneider 2005), Catalonia (Ramos et al. 2008), Tuscany (Orlandini et al. 2009), and for many other locations in Europe (Jones et al. 2005a) and worldwide (Jones et al 2005b). While other research has found significant changes in seasonal precipitation and potential evapotranspiration demand (Brunetti et al. 2002, Duchêne and Schneider 2005, Ramos et al. 2008), there was no evidence of changes in rainfall regimes in this study.

The observed warming in the region has influenced grapevine phenology resulting in 16, 13 and 19 days earlier bloom, veraison, and harvest dates during 1964-2009. Similar trends in phenology have been found across many cultivars and locations in Europe (Jones et al. 2005a). However, budbreak did not trend earlier which is likely related to numerous previous vintage, post harvest, and dormant period factors such as starch levels in the roots, chilling requirements being met, and soil temperature and moisture levels (Lombard and Richardson 1979) along with higher temperature variability that occurs during the spring time. The breakpoint analysis showed significant changes in the late 1980s through the early 1990s for bloom, veraison, and harvest while budbreak did not exhibit a significant shift. In addition, after 1990-91 the phenological events exhibited less variability, potentially indicating that the higher temperatures resulted in more consistent growth cycles on average. Furthermore, the early and medium maturing cultivars appeared to react sooner to the climate warming with breakpoints occurring during 1987/88, compared to late maturing cultivars which showed breakpoints during 1996/97 (not shown). Webb et al. (2008) found similar results for Chardonnay (early) compared with Cabernet Sauvignon (late) in Australia. Moreover, the earlier veraison and harvest dates combined with a shortened interval between the two, results in a ripening phase that is now occurring in a warmer period of the year with potential issues of lowered acidity, higher sugar content, lower anthocyanin levels, and changes in aromatic compound development (Haselgrove et al. 2000, Seguin et al. 2004, Webb et al. 2008, Keller 2010).

Conclusions

Grapevines yield high quality fruit at economically sustainable production levels when grown in suitable climates. This research has provided an examination of the growth habits and phenological timing of a range of early, middle, and late maturating cultivars and their relationships to the prevailing climate in the Veneto region of Italy. In addition, this research has detailed the trends in phenology and the influence of a warming climate, which has the potential to significantly affect cultivar suitability and wine production in this region and elsewhere worldwide.

If climates continue to change as projected (1.5 to 2.5°C by 2050), then further changes in vine growth will likely continue. However, as the 2003 and 2007 vintages in the Veneto region have shown in this research, vine growth intervals as short as 127 to 144 days for early and late cultivars, respectively, are extreme and not likely to be any shorter in the near future. This will likely mean significant changes in cultivar suitability to the climate in the region and/or further separation between the timing of sugar/acid balance, phenolic maturation and fruit character. Future research using this large cultivar collection will examine how fruit composition from these cultivars is influenced by

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phenological timing and climate, giving greater insights into the complex interactions that result in wine.

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Figures

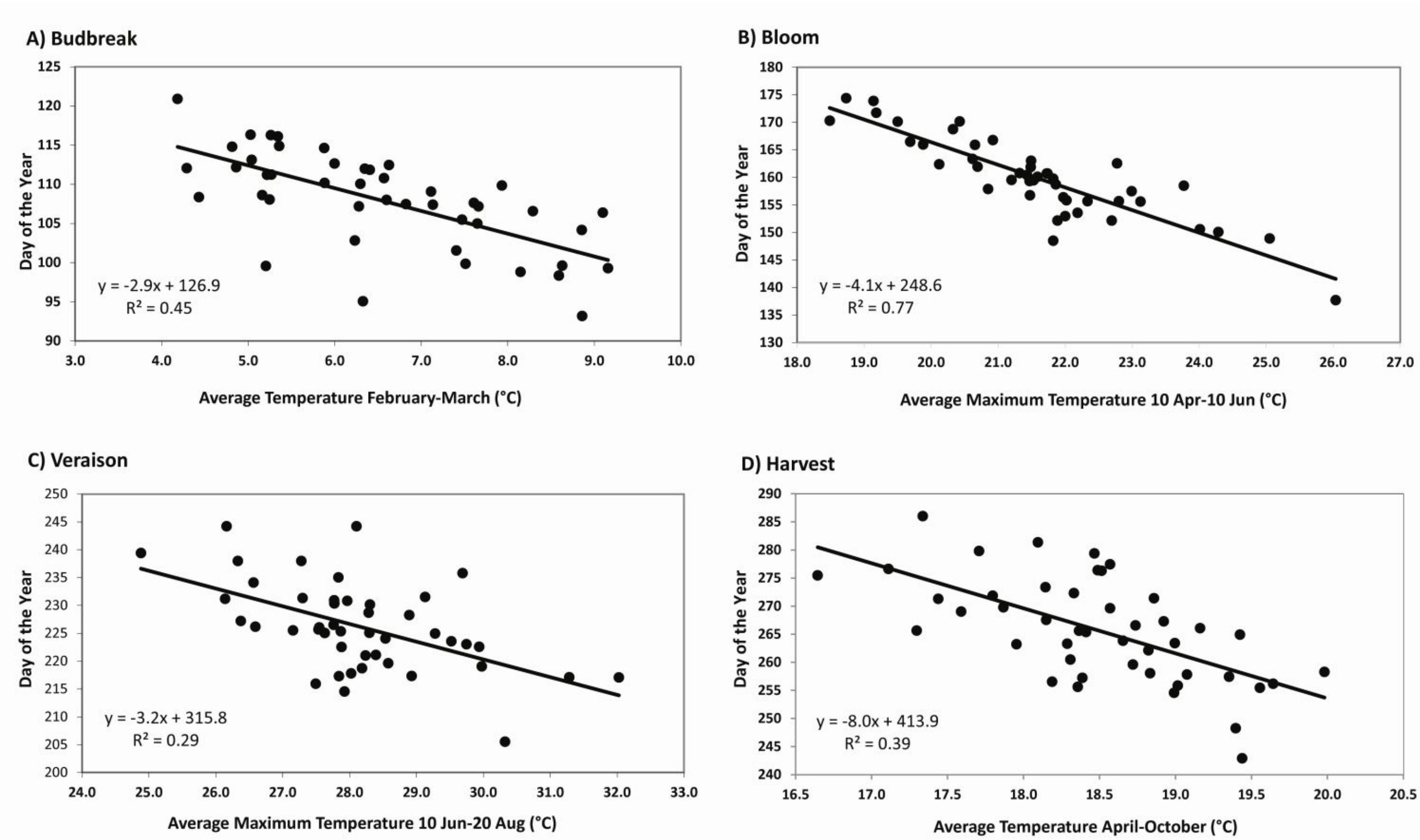

Figure 1: Relationships between the most significant climate parameter related to the average phenological dates of the 18 *V. vinifera* cultivars for A) budbreak, B) bloom, C) veraison, and D) harvest during 1964-2009 in Conegliano, Italy.

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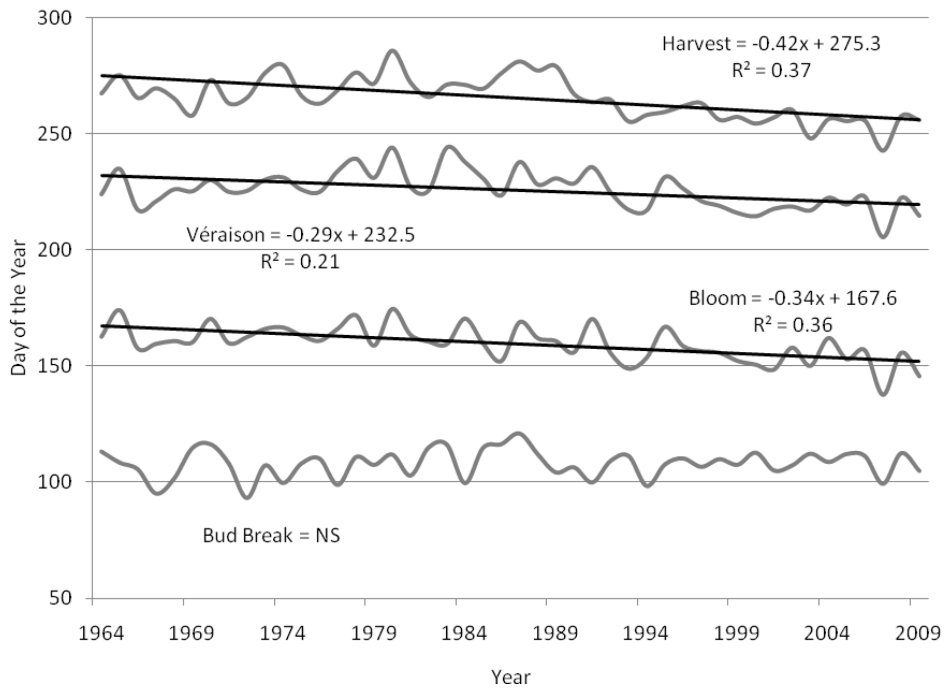

Figure 2: Time series and linear trends for the average phenological dates of the 18 *V. vinifera* cultivars for budbreak, bloom, veraison, and harvest during 1964-2009 in Conegliano, Italy.

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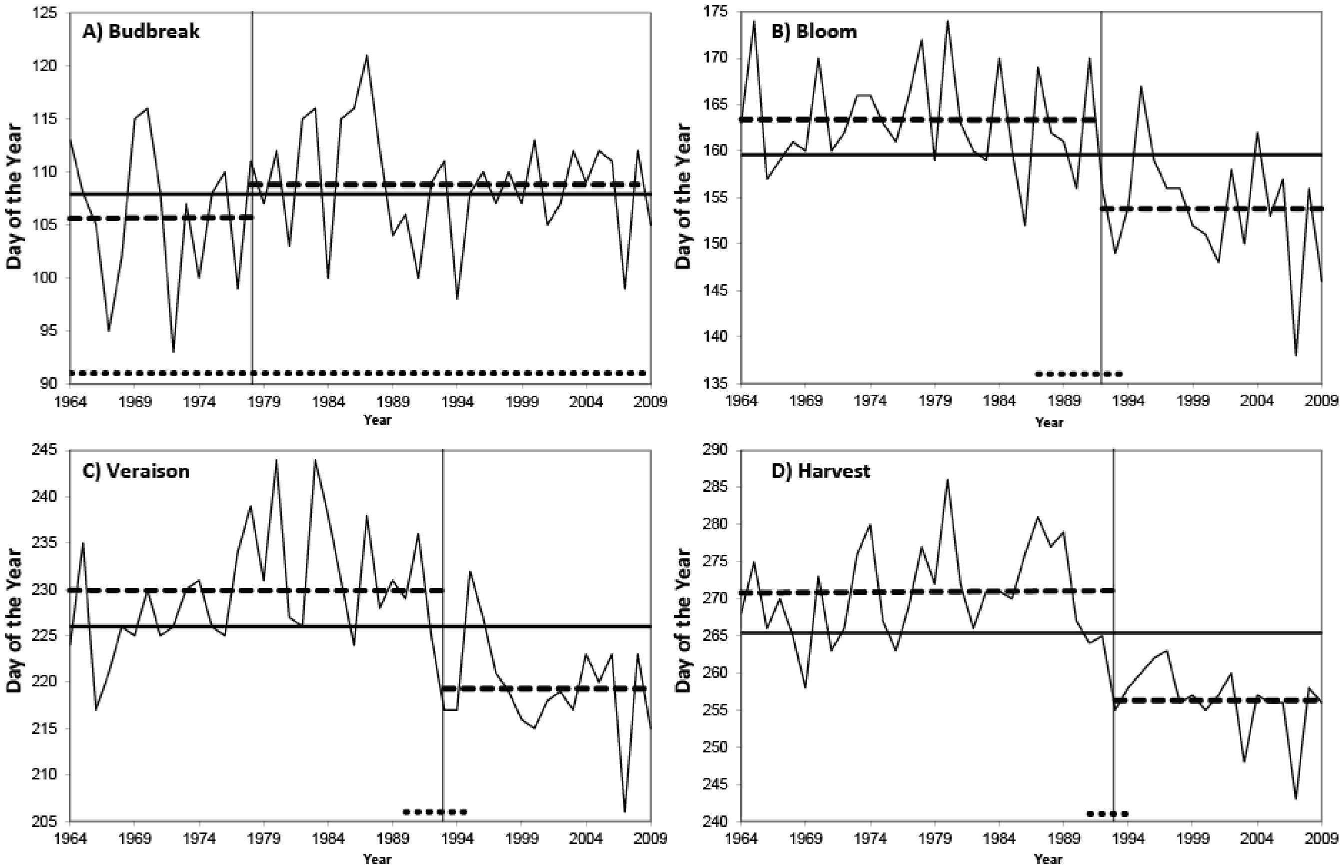

Figure 3: Time series and breakpoints for the average phenological dates of the 18 *V. vinifera* cultivars for A) budbreak (not significant), B) bloom (significant), C) veraison (significant), and D) harvest (significant) during 1964-2009 in Conegliano, Italy. Solid horizontal line represents the overall series mean, the bold dashed line represents the means of the two periods (before and after the significant breakpoint, vertical line), and the dashed line just above the x-axis is the confidence interval of the breakpoint (budbreak is not significant).

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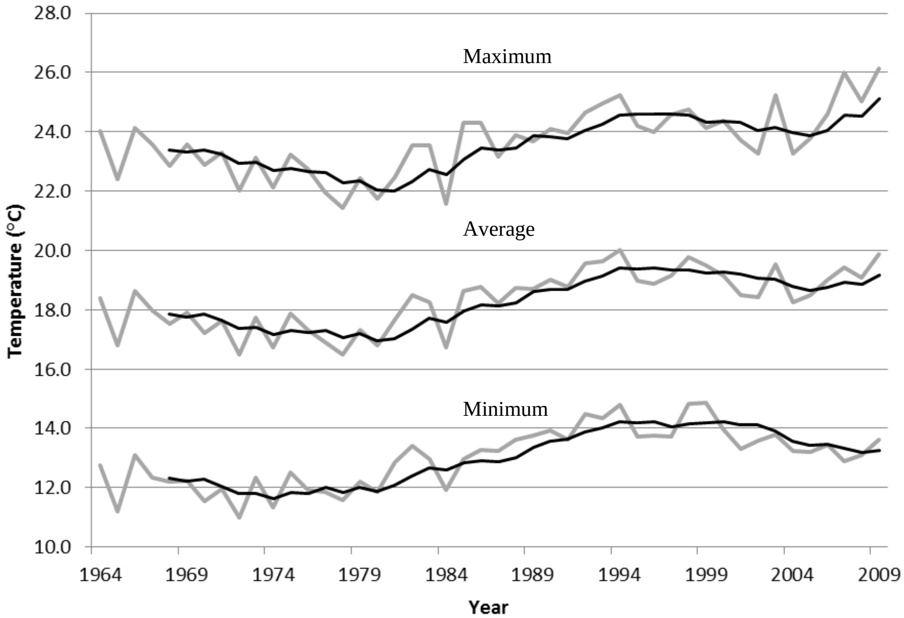

Figure 4: Time series (grey lines) and five year moving average (dark lines) for growing season (April through October) average, maximum, and minimum temperatures during 1964-2009 in Conegliano, Italy.

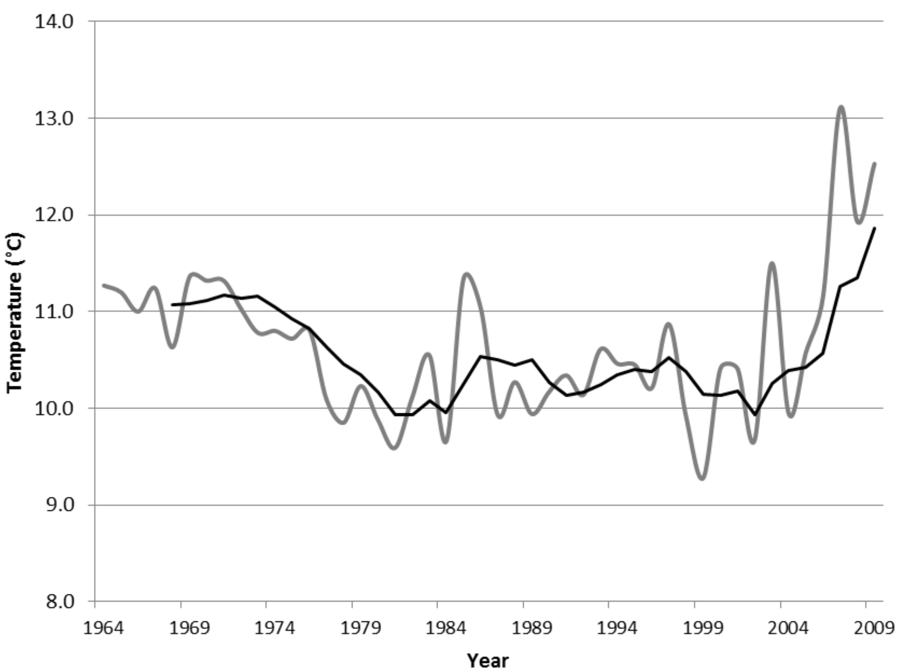

Figure 5: Time series (grey line) and five year moving average (dark line) for growing season (April through October) average daily diurnal temperature range (DTR) during 1964-2009 in Conegliano, Italy.

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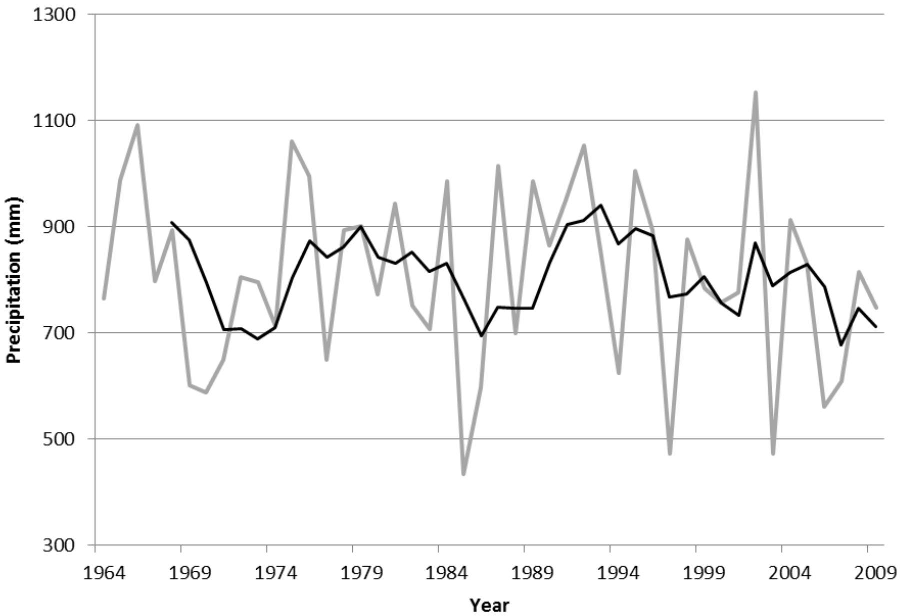

Figure 6: Time series (grey line) and five year moving average (dark line) for annual precipitation during 1964-2009 in Conegliano, Italy.

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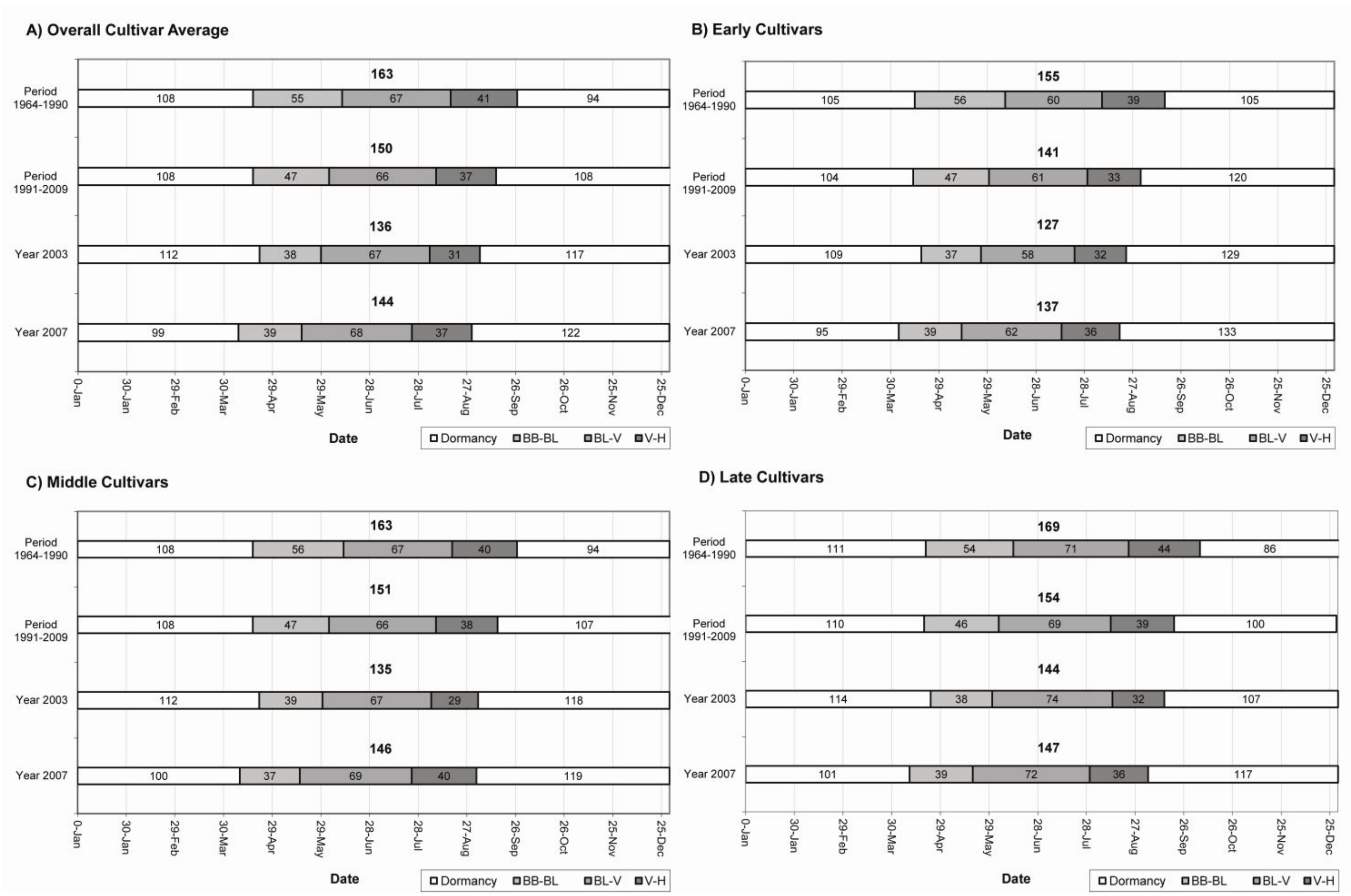

Figure 7: V. vinifera cultivar phenology before (1964-1990) and after (1991-2009) the average breakpoint and for the two extreme years 2003 and 2007 in Conegliano, Italy for A) the overall cultivar average, B) early cultivar average, C) middle cultivar average, and D) late cultivar average (see Table 1 for cultivars in each category). The first segment of each bar is from the first of the year to the average budbreak (dormancy period), the second segment of the bar from budbreak to bloom (BB-BL), the third segment of the bar from bloom to veraison (BL-V), the fourth segment of the bar from veraison to harvest (V-H) and the last bar segment from harvest to the end of the year (dormancy period). The numbers above the middle bar segments are the total number of days from budbreak to harvest for each period or year.

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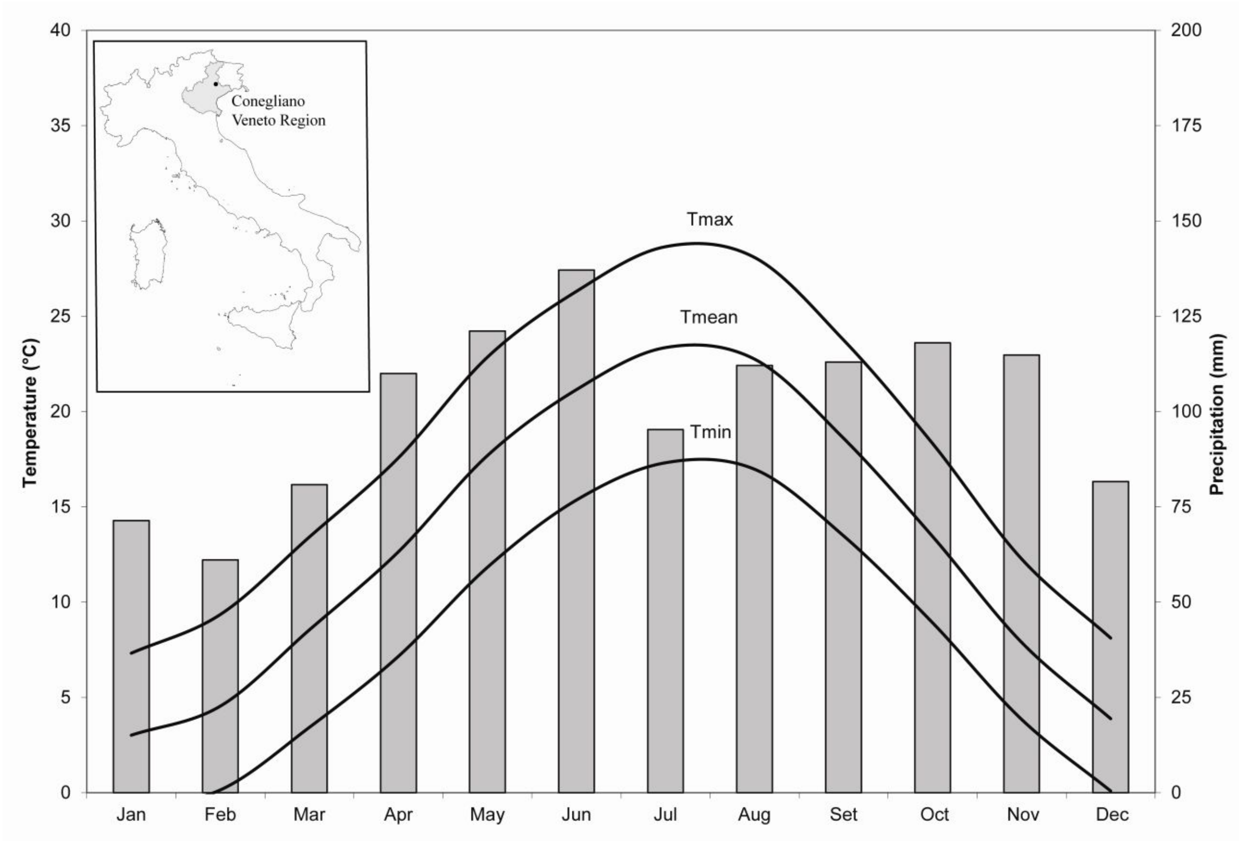

Supplemental Figure 1: Average monthly temperature and precipitation characteristics for the site of the V. vinifera cultivar collection and climate station in Conegliano in the Veneto region of Italy (inset) during 1964-2009.

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Table 1: Statistics of budbreak, bloom, veraison, and harvest dates for the eighteen V. vinifera cultivars, their overall average and averages for early (*), middle (#), and late (^) cultivars for 1964-2009 in Conegliano, Italy.

Event	Statistic (Date or Days)	Muller Thurgau*	Pinot Grigio*	Chardonnay*	Franconia*	Pinot Noir*	Merlot#	Albana#	Tocai Friulano#	Cabernet Franc#	Corvinone#	Prosecco#	Cabernet Sauvignon^	Garganega^	Marzemino^	Trebbiano di Soave^	Trebbiano Toscano^	Corvina^	Molinara^	**Overall Average**	**Early Average***	**Middle Average#**	**Late Average^**
Budbreak	Mean	14-Apr	16-Apr	13-Apr	12-Apr	15-Apr	18-Apr	22-Apr	20-Apr	17-Apr	15-Apr	11-Apr	22-Apr	25-Apr	13-Apr	20-Apr	25-Apr	16-Apr	18-Apr	17-Apr	14-Apr	17-Apr	18-Apr
	Stdev	6.2	6.5	7.3	7.3	5.9	7.1	7.8	6.6	6.6	6.9	6.2	5.7	6.2	7.7	6.8	7.0	6.7	6.5	6.0	6.4	6.2	5.9
	Maximum	27-Apr	30-Apr	27-Apr	30-Apr	28-Apr	4-May	5-May	2-May	28-Apr	4-May	24-Apr	5-May	5-May	30-Apr	5-May	8-May	28-Apr	2-May	30-Apr	28-Apr	1-May	2-May
	Minimum	1-Apr	2-Apr	28-Mar	27-Mar	1-Apr	1-Apr	27-Mar	5-Apr	1-Apr	30-Mar	28-Mar	8-Apr	10-Apr	28-Mar	6-Apr	9-Apr	1-Apr	1-Apr	3-Apr	1-Apr	2-Apr	5-Apr
	Range	26	28	30	34	27	33	39	27	27	35	27	27	25	33	29	29	27	31	28	27	29	27
Bloom	Mean	5-Jun	5-Jun	3-Jun	6-Jun	6-Jun	8-Jun	13-Jun	8-Jun	7-Jun	9-Jun	6-Jun	9-Jun	12-Jun	8-Jun	9-Jun	12-Jun	8-Jun	9-Jun	8-Jun	5-Jun	9-Jun	10-Jun
	Stdev	7.7	8.0	8.7	8.8	9.1	8.1	8.2	8.4	8.9	7.4	8.1	7.6	8.2	7.7	7.7	7.5	8.0	7.8	7.6	8.2	7.8	7.2
	Maximum	19-Jun	23-Jun	21-Jun	23-Jun	27-Jun	25-Jun	1-Jul	25-Jun	25-Jun	26-Jun	22-Jun	24-Jun	1-Jul	25-Jun	25-Jun	1-Jul	25-Jun	24-Jun	23-Jun	20-Jun	25-Jun	24-Jun
	Minimum	13-May	14-May	13-May	15-May	16-May	17-May	21-May	16-May	15-May	20-May	14-May	19-May	24-May	21-May	20-May	21-May	17-May	21-May	17-May	14-May	17-May	20-May
	Range	37	40	39	39	42	39	41	40	41	37	39	36	38	35	36	41	39	34	37	37	39	35
Veraison	Mean	30-Jul	4-Aug	5-Aug	7-Aug	8-Aug	12-Aug	14-Aug	14-Aug	14-Aug	16-Aug	16-Aug	16-Aug	16-Aug	16-Aug	18-Aug	20-Aug	21-Aug	24-Aug	13-Aug	5-Aug	14-Aug	19-Aug
	Stdev	7.6	8.5	9.2	10.5	9.7	9.2	10.1	10.1	9.0	7.6	9.8	8.4	10.3	8.5	10.5	8.8	10.8	10.8	8.1	7.9	8.4	8.6
	Maximum	16-Aug	23-Aug	23-Aug	1-Sep	31-Aug	31-Aug	7-Sep	4-Sep	7-Sep	1-Sep	7-Sep	30-Aug	7-Sep	7-Sep	7-Sep	7-Sep	17-Sep	17-Sep	1-Sep	19-Aug	4-Sep	8-Sep
	Minimum	12-Jul	16-Jul	14-Jul	17-Jul	15-Jul	22-Jul	17-Jul	23-Jul	25-Jul	24-Jul	27-Jul	24-Jul	26-Jul	2-Aug	24-Jul	26-Jul	2-Aug	20-Jul	24-Jul	14-Jul	25-Jul	30-Jul
	Range	35	38	40	46	47	40	52	43	44	39	42	37	43	36	45	43	46	59	39	35	41	39
Harvest	Mean	6-Sep	8-Sep	8-Sep	12-Sep	17-Sep	18-Sep	19-Sep	19-Sep	24-Sep	26-Sep	27-Sep	28-Sep	28-Sep	28-Sep	28-Sep	30-Sep	2-Oct	3-Oct	22-Sep	10-Sep	22-Sep	30-Sep
	Stdev	10.0	12.2	10.1	13.7	13.9	13.2	9.6	11.4	9.5	9.2	12.0	13.0	12.5	13.1	12.8	11.4	11.8	9.8	9.2	10.1	8.4	10.4
	Maximum	29-Sep	17-Oct	29-Sep	10-Oct	3-Nov	24-Oct	9-Oct	24-Oct	12-Oct	18-Oct	19-Oct	7-Nov	28-Oct	1-Nov	24-Oct	24-Oct	25-Oct	25-Oct	13-Oct	7-Oct	10-Oct	27-Oct
	Minimum	23-Aug	18-Aug	16-Aug	17-Aug	25-Aug	22-Aug	29-Aug	3-Sep	31-Aug	6-Sep	30-Aug	6-Sep	28-Aug	26-Aug	29-Aug	7-Sep	8-Sep	15-Sep	30-Aug	20-Aug	3-Sep	4-Sep
	Range	37	60	43	54	70	63	40	51	42	42	50	62	61	66	56	46	47	40	43	49	37	53

American Journal of Enology and Viticulture (AJEV). doi: 10.5344/ajev.2011.10108
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Table 2: Linear trend characteristics (R^2, p-values, slope or annual trend and the total trend over the 46 years) for each of the overall average phenological growth events and intervals between growth events (averaged over all 18 cultivars) for 1964-2009 in Conegliano, Italy. Note that NS means that that trend for that variable is not significant.

Variable	R^2	P-Value	Annual Trend	Total Trend
Budbreak	NS			
Bloom	0.36	≤0.001	-0.34 days	-16 days
Veraison	0.21	≤0.001	-0.29 days	-13 days
Harvest	0.37	≤0.001	-0.42 days	-19 days
Budbreak to Bloom	0.30	≤0.001	-0.39 days	-18 days
Budbreak to Veraison	0.22	≤0.001	-0.33 days	-15 days
Budbreak to Harvest	0.14	≤0.001	-0.32 days	-15 days
Bloom to Veraison	NS			
Bloom to Harvest	NS			
Veraison to Harvest	0.11	≤0.001	-0.14 days	-6 days

Table 3: Linear trend characteristics (R^2, p-values, slope or annual trend and the total trend over the 46 years) for annual (January-December) and growing season (April-October) climate parameters for 1964-2009 in Conegliano, Italy. Note that NS means that that trend for that variable is not significant.

Variable	R^2	P-Value	Annual Trend	Total Trend
Annual Average Temperatures	0.42	≤0.001	+0.034°C	+1.6°C
Annual Maximum Temperatures	0.51	≤0.001	+0.055°C	+2.5°C
Annual Minimum Temperatures	0.48	≤0.001	+0.044°C	+2.0°C
Annual Precipitation	NS			
Growing Season Average Temperatures	0.48	≤0.001	+0.051°C	+2.3°C
Growing Season Maximum Temperatures	0.38	≤0.001	+0.052°C	+2.4°C
Growing Season Minimum Temperatures	0.46	≤0.001	+0.051°C	+2.3°C
Growing Season Precipitation	NS			

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Supplemental Table 1: Statistics of the length of the intervals between budbreak, bloom, veraison, and harvest dates for the eighteen V. vinifera cultivars, their overall average and averages for early (*), middle (#), and late (^) cultivars for 1964-2009 in Conegliano, Italy.

Event	Statistic (Days)	Muller Thurgau*	Pinot Grigio*	Chardonnay*	Franconia*	Pinot Noir*	Merlot#	Albana#	Tocai Friulano#	Cabernet Franc#	Corvinone#	Prosecco#	Cabernet Sauvignon^	Garganega^	Marzemino^	Trebbiano di Soave^	Trebbiano Toscano^	Corvina^	Molinara^	**Overall Average**	**Early Average***	**Middle Average#**	**Late Average^**
Budbreak to Bloom	Mean	52	50	52	55	52	51	52	49	52	55	56	48	48	56	50	48	53	52	52	52	52	51
	Stdev	10.0	10.1	10.5	11.1	10.8	11.1	11.7	10.3	11.4	10.9	9.0	8.9	9.5	10.6	10.5	8.2	10.5	10.3	10.3	10.5	10.7	9.8
	Maximum	74	71	76	82	80	73	93	68	76	75	74	67	72	80	72	66	74	72	75	77	77	72
	Minimum	33	33	33	36	33	32	34	31	32	33	42	32	32	35	31	33	35	31	33	34	34	33
	Range	41	38	43	46	47	41	59	37	44	43	33	35	40	45	41	33	39	41	41	43	43	39
Budbreak to Veraison	Mean	108	110	114	117	116	116	114	116	120	123	126	116	113	125	120	117	127	127	118	113	119	121
	Stdev	9.0	9.5	10.7	12.0	10.7	11.2	12.5	11.6	11.4	9.4	10.0	9.8	10.6	10.8	11.3	9.5	11.9	12.4	10.8	10.4	11.0	10.9
	Maximum	129	132	142	143	137	144	148	137	141	142	146	135	141	153	149	148	151	151	143	137	143	147
	Minimum	91	91	90	93	99	90	91	94	98	99	102	95	99	105	97	103	103	86	96	93	96	98
	Range	38	41	52	50	38	54	57	43	43	43	44	40	43	48	52	45	48	65	47	44	47	49
Budbreak to Harvest	Mean	145	145	145	148	153	155	153	150	152	160	164	168	159	156	168	161	158	169	156	147	156	163
	Stdev	9.8	9.8	13.2	11.3	14.4	14.7	14.6	13.0	13.2	12.1	11.2	12.7	13.3	13.4	14.3	13.7	11.7	13.8	12.8	11.7	13.1	13.3
	Maximum	172	172	187	173	182	189	189	185	187	185	194	193	196	194	197	192	193	191	187	177	188	194
	Minimum	127	127	124	123	129	132	126	124	130	129	146	138	139	137	139	136	140	138	132	126	131	138
	Range	45	45	63	50	53	57	63	61	57	56	48	55	58	57	58	57	53	53	55	51	57	56
Bloom to Veraison	Mean	56	60	63	62	63	65	62	67	68	68	70	67	65	70	70	69	74	76	66	61	67	70
	Stdev	6.6	5.6	5.1	7.3	8.6	6.2	6.9	5.5	7.0	6.8	5.8	5.9	6.4	5.9	7.3	8.4	8.2	8.2	6.8	6.6	6.4	7.2
	Maximum	69	77	78	85	88	84	91	93	87	86	92	83	84	90	89	93	101	97	87	79	89	91
	Minimum	44	50	52	42	42	53	50	59	52	54	59	57	53	58	44	48	54	50	51	46	55	52
	Range	25	27	26	43	46	31	41	34	35	32	33	26	31	32	45	45	47	47	36	33	34	39
Bloom to Harvest	Mean	94	95	97	98	103	102	99	104	109	109	113	110	108	112	111	110	116	116	106	97	106	112
	Stdev	10.1	9.8	6.5	9.6	12.7	10.7	9.0	11.2	9.4	11.0	8.7	10.7	8.6	9.6	9.8	9.7	10.5	8.0	9.8	9.7	10.0	9.6
	Maximum	122	132	114	120	143	136	117	129	137	138	134	141	127	135	130	128	138	137	131	126	132	134
	Minimum	74	78	87	81	78	85	76	77	90	80	96	86	93	96	89	93	89	96	86	80	84	92
	Range	48	54	27	39	65	52	41	52	47	58	38	55	34	39	41	36	49	41	45	47	48	42
Veraison to Harvest	Mean	38	35	34	36	40	37	37	37	41	42	42	43	43	42	41	41	42	41	39	36	39	42
	Stdev	9.4	9.7	6.5	10.5	14.8	10.3	9.1	11.5	10.7	10.6	8.8	11.9	8.1	10.8	10.4	9.7	9.0	7.8	10.0	10.2	10.2	9.7
	Maximum	59	60	53	57	75	63	52	62	63	63	62	73	64	63	71	63	61	63	63	61	61	65
	Minimum	23	16	20	12	10	19	13	10	17	15	21	17	31	22	22	15	28	26	19	16	16	23
	Range	36	44	33	45	65	44	39	52	46	48	42	57	33	41	50	48	33	37	44	45	45	43