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ORIGINAL PAPER

Seasonal differences in climate in the Chianti region of Tuscany and the relationship to vintage wine quality

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Abstract Climatic factors and weather type frequencies affecting Tuscany are examined to discriminate between vintages ranked into the upper- and lower-quartile years as a consensus from six rating sources of Chianti wine during the period 1980 to 2011. These rankings represent a considerable improvement on any individual publisher ranking, displaying an overall good consensus for the best and worst vintage years. Climate variables are calculated and weather type frequencies are matched between the eight highest and the eight lowest ranked vintages in the main phenological phases of Sangiovese grapevine. Results show that higher heat units; mean, maximum and minimum temperature; and more days with temperature above 35 °C were the most important discriminators between good- and poor-quality vintages in the spring and summer growth phases, with heat units important during ripening. Precipitation influences on vintage quality are significant only during veraison where low precipitation amounts and precipitation days are important for better quality vintages. In agreement with these findings, weather type analysis shows good vintages are favoured by weather type 4 (more anticyclones over central Mediterranean Europe (CME)), giving warm dry growing season conditions. Poor vintages all relate to higher frequencies of either weather type 3, which, by producing perturbation crossing CME, favours cooler and wetter conditions, and/or weather type 7 which favours cold dry continental air masses from the east and north east over CME. This approach shows there are important weather type frequency differences between good- and poor-quality vintages. Trend analysis shows that changes in weather type frequencies are more important than any due to global warming.

Keywords Climate · Climate variability · Consensus rankings · Grape phenology · Viticulture · Weather types

Introduction

Chianti area, known as “Valle del Chianti”, is a valley in central-western Italy between Florence and Siena, at about latitude 43.5° N and 10–12° E. The first notarial document in which the Chianti refers to the wine produced in this area dates back to 1398. In this valley, the Chianti Classico area (wine also known as Gallo Nero or Black Rooster) is a subset of the broader Chianti region.

Attention to Chianti vintage quality has grown since the area was completely redrawn in 1932 in order to confine it to its ancient original area. From the 1970s onward, producers reduced the quantity of white grapes, and the production of Sangiovese grapes became dominant, till when in 1995 it became mandatory to use from a minimum 80 % up to 100 % Sangiovese grapes for producing Chianti Classico (Ewing-Mulligan and McCarthy 2001). Vintages have been assessed by a grower consortium since the 1970s, demarking the growing importance of high-quality red wines of the region. The pace of crop development depends on fixed factors such as soil and topography and on variable factors such as vineyard

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management practices and weather. Since weather and climate are largely aleatory, with their impact on the different phenological phases, they can be determinant for good or bad vintages. Sangiovese cultivar requirements are generally fulfilled by the climate in Tuscany where, in the absence of adverse weather events, this vine completes its annual growth cycle and typically produces fine wines.

The main phenological phases of grapevine (*Vitis vinifera* L.) are as follows: bud break, flowering, veraison and ripening (Jones and Davis 2000). Temperature affects the pace of development from budburst to ripening, and temperature extremes have an impact on both production and quality (Coombe 1987). Extremely low temperatures in late winter and early spring are not an issue in the Chianti region. But high temperatures during berry growth can cause premature veraison, with poorer quality grapes (Mullins et al. 1992). In addition, hot spells during ripening may cause a faster breakdown of acids, with an increase in sugar content leading to higher alcohol and lower acid levels in the resulting wine (Duchene and Schneider 2005). Cool nights during ripening along with a large diurnal temperature range stimulate the synthesis of anthocyanins and other phenolic compounds (Kliewer and Torres 1972; Mori et al. 2007). Precipitation days and precipitation amounts—especially lack of precipitation prior to harvest—are known to concentrate flavours in the latter part of the development cycle prior to harvest (Jones and Storchmann 2001; van Leeuwen et al. 2009).

Interannual climate variability is operating on a background of regional warming which has been observed in many southern European viticulture areas in the last few decades (Jones et al. 2005; Laget et al. 2008; Ramos et al. 2008; Vrsic and Vodovnik 2012; Mozell and Thach 2014), which has caused a shifting in grapevine phenology (Jones 2006; Dalla Marta et al. 2010; Daux et al. 2011; Tomasi et al. 2011; Koufos et al. 2013). Despite the regional warming, the emphasis on this research is isolating interannual climate factors that influence vintage quality variations helping to define the characteristics that make for the best and worst vintages in Chianti.

In examining wine quality for northern and central Italy over the period 1970–2002, Grifoni et al. (2006) presented strong relationships between meteorological conditions and wine quality, finding that higher quality years are related to above-average temperature and below-average precipitation, and lower quality years with the opposite. Dalu et al. (2013) using five high-quality Italian wines (Barolo and Barbaresco, Amarone, Brunello di Montalcino, Chianti Classico and Vino Nobile di Montepulciano) matched wine quality data from the respective consortia (unions of wine producers notarized in law) with Mediterranean climate patterns for the period 1970–2008.

For this wine quality, rated with a single-blind tasting of the individual varietals by a panel of experts (Corsi and Ashenfelter 2001), Grifoni et al. (2006) and Dalu et al. (2013) found that in high-ranking years, air temperatures are higher over the entire growing season with anomalies of the North Atlantic Oscillation (NAO) that are negative in late spring, close to zero in summer and positive in early fall. Examination of composite 500-hPa geopotential height maps for these seasons showed that the spring jet stream over the Atlantic diverts most of the weather perturbations towards North Europe, while still providing a sufficient amount of precipitation to central Mediterranean Europe (CME). In good years, summer warming produced by southerly winds is balanced by the cooling brought by westerly winds. Low-ranking seasons occur with a positive geopotential anomaly over western continental Mediterranean Europe (WME) which shelters CME from autumn Atlantic storms. In years of poor wine quality, temperatures are cooler, with a positive NAO in late spring and summer, and negative in early fall; in these conditions, the composite seasonal maps show the jet stream favours the intrusion of the Atlantic weather perturbations into CME in fall.

This study is a natural follow-up of the work by Grifoni et al. (2006) and Dalu et al. (2013) and an expansion of the work done by Dalla Marta et al. (2010) on phenological phases and climate parameters. Specifically, the aim of this work is the definition of good and poor vintages based on consensus for identifying key climatic factors and weather types over the entire annual development cycle, focusing on critical phenological stages.

Material and methods

Vintage quality is commonly measured through tasting assessments that provide a metric for comparing one vintage to another. These assessments, commonly called vintage ratings, are carried out by numerous regional industry organizations, wine magazines, wine writers and other agencies that monitor and value wines (Jones and Storchmann 2001; Borges et al. 2012). These metrics are often reported in different ranges (e.g. scales from 0 to 5, from 0 to 10, from 0 to 20 and from 0 to 100) where the values are not often comparable (e.g. a 95 on one rating might not be equivalent on another). Furthermore, while much agreement between the different ratings can be found, there is often enough variation such that consensus is difficult to obtain by simple comparisons. Borges et al. (2012) approached this problem by developing a consensus ranking that takes into account multiple sources of ratings that are reported on different scales. The process utilizes the Codorcet method of ranking sets of alternatives, and while there are other competing methods (e.g. the Borda method (Hulkower 2012)), Borges et al. (2012, 2013) and others (Young 1988; Balinski and Laraki 2011) conclude that the Borda approach makes sense only for designating the top ranks, and the Condorcet method (Condorcet 1785) is best for designating a ranking such as top and bottom vintages from numerous ratings alternatives.

Baciocco et al. (2014), ranking Bordeaux vintages with methods by Borges et al. (2012), combined eight different sources to determine the consensus rankings for both red and sweet white wines. Baciocco et al.'s (2014) results show strong discrimination between seasonal climate characteristics between the 10 highest and the 10 lowest ranked vintages for the period 1961–2009 for red and sweet white Bordeaux wines. Increased heat accumulation during the growing season and higher maximum temperatures discriminate good- from poor-quality vintages, all this accompanied by a generally lack of precipitation, especially at veraison for the Bordeaux region.

Following this research in Bordeaux, our goal here is to examine Chianti wines from Tuscany for the period 1980–2011 using the Borges et al. (2012) method. For determining the group of top- and bottom-ranked vintages, we use five different sources, namely Wine Spectator, Decanter, Cellar Notes, Addy Bassin and Vintage Tuscany, along with assessments from the Chianti Classico Consortium, producer of Gallo Nero or Black Rooster wine and other fine DOC wines (DOC stands for "Denominazione di Origine Controllata", i.e. *Denomination of Controlled Origin*). Using the consensus rankings, our analysis includes a combination of station observations and weather type (WT) analyses. The examination was carried out by dividing the year into phenological phases and probing weather characteristics and types during the periods that produce the eight top-ranked and eight bottom-ranked years (matching the upper and lower quartiles) in terms of quality. These periods occur from dormancy to ripening and over the entire growing season; these periods were selected for the development phases of Sangiovese grapevines in Tuscany (Dalla Marta et al. 2010; Grifoni pers. com. 2014): dormancy: 1 November of the previous year to 15 March of the year in question; growing season: 1 April–30 September (Sangiovese grapes are all harvested by 30 September); spring growth: 1 April–31 May (bud break to flower); bloom: 1–15 June; summer growth: 1 June–10 August; veraison: 10–20 August; and ripening: 21 August–30 September. To examine weather effects on vintages, Siena meteorological station was chosen for the surface analysis as it is located in the heart of Tuscany at 43° 19′ N, 11° 20′ E. This meteorological station was managed by the Centro Funzionale Regione Toscana (CFR: http://www.cfr.toscana.it/) until 2007 and then by the Centro Interdipartimentale di Bioclimatologia of the University of Florence (CIBIC: http://www.cibic.unifi.it/mdswitch.html).

Following van Leeuwen et al. (2004), Jones et al. (2010) and Baciocco et al. (2014), we use the standard growing degree days (GDD) and the Huglin Index (HI; Huglin 1978) to evaluate heat accumulation; these indices are computed using daily climate data for Siena. GDD and HI are summed over the time period from April through September using the following equations:

$$\mathrm{GDD} = \mathrm{Sum}_n \max\left(T_{\mathrm{avg}} - 10^{\circ}\mathrm{C},\ 0\right);\ n = (1\ \ \mathrm{Apr},\ 30\ \ \mathrm{Sep}) \quad (1)$$

$$\mathrm{HI} = \mathrm{Sum}_n \max\left[\frac{\left(T_{\mathrm{avg}} - 10^{\circ}\mathrm{C}\right)}{2} + \frac{\left(T_{\max} - 10^{\circ}\mathrm{C}\right)}{2,\ 0}\right] \times d \quad (2)$$

GDD and HI are both set to zero when the value is negative. In these equations, we assume that the vine active phase is between April and September and that harvests are completed by 30 September. In the above equations, T_{avg}, $T_{\max}$ and $T_{\min}$ are the average, maximum and minimum temperatures in °C, respectively. The latitude correction, d, for the HI takes into account the changes in daylight, ranging from 34° to 65° latitude, with a value of 1.0 at 34° and increasing as latitude. As Huglin (1978) varied d between 1.02 and 1.06 between the latitudes of 40° and 50°, a value of 1.03 was selected for Chianti at Tuscany (latitude 43° N). Temperature is also averaged over the growth periods for maximum, minimum and average conditions as well as the number of days over 35 °C. Furthermore, daily precipitation is accumulated over the various development periods, and the number of days with precipitation of 1 mm or more is summed over the entire growing season and for all the developmental phases, apart from dormancy.

The daily temperature range (DTR) is yielded by

$$\mathrm{DTR} = T_{\max} - T_{\min} \quad (3)$$

The Mann-Whitney U test is used to compare each climate variable between the top 8 and bottom 8 consensus-ranked vintages for each of the development stages previously defined. This is a non-parametric form of the t test, especially good for smaller sample sizes where an independent group design has been used and the type of data collected is ordinal or interval. The two-tailed test using the level of significance $p \leq 0.05$ was used.

The use of techniques to characterize and quantify climatic variations is well established (e.g. Berry and Perry 1973; Smithson 1986; Harman and Winkler 1991; Yamal 1993; Kidson 2000). Typically, such techniques involve an assessment of daily conditions through the classification of surface and/or upper air circulation patterns or through the characterization of the behaviour of a variety of weather elements (NAO, AO, etc.). When the former approach is adopted, daily estimates of climate variables are specified in relation to circulation elements, while monthly or seasonal anomalies may be inferred from relative frequency of individual WTs. Classifications adopted throughout Europe widely differ in the methodology, geographical domain and meteorological parameters adopted for characterization of the weather types.

Traditionally, weather types were derived on the basis of personal expertise. This type of approach can introduce spurious inhomogeneities in the WT classification. Therefore, the task of COST Action 733 “Harmonization and Applications of Weather Type Classifications for European Regions” was a coordinated effort aimed to the development and to the application of numerical methods for an objective classification of weather situations. The weather types adopted in this work are those developed by the LaMMa Consortium using COST 733 methodology (Philipp et al. 2014) (http://www.lamma.rete.toscana.it/clima-e-energia/climatologia/tipi-di-tempo). The classification is done applying the principal component analysis of the 500-hPa geopotential height which is well correlated with the surface air temperature in the warm season (Dalla Marta et al. 2010). The application is of direct value here, since changes in frequency of extreme events associated with vintage quality could be less closely related to the mean circulation.

The WT analysis is conducted on frequencies of each type during the phenological phases. The eight WTs are developed over a spatial domain of the Mediterranean, Europe and the eastern North Atlantic that influences weather conditions over the Tuscan region (Fig. 1). The WT analysis is restricted to three decades, because time series of vintage assessment before 1980 were few, and lengthier periods would incorporate larger warming trends and important crop management changes.

The eight WTs used in this work are those by the LaMMA Consortium for Tuscany, developed using a method related to COST 733 (Philipp et al. 2014) (http://www.lamma.rete.toscana.it/clima-e-energia/climatologia/tipi-di-tempo). These weather types are classified applying the principal component analysis of the 500-hPa geopotential. The resulting WTs, shown in Fig. 1, have the following characteristics:

- WT1: Marked northward expansion of the Azores anticyclone with blocked anticyclonic circulation over the North Atlantic and northerly winds over Italy.
- WT2: Moderate northward expansion of the Azores anticyclone with cyclonic circulation over south Scandinavia and northwesterly winds over Italy.
- WT3: Marked cyclonic circulation over Iceland with anticyclonic circulation over northern central Europe accompanied with increased precipitation over Italy, generated by intermittent Atlantic perturbations.
- WT4: Cyclonic circulation over the North Atlantic and cyclonic circulation over WME and CME with decreased precipitations over CME.
- WT5: Cyclonic circulation over the northwest Atlantic with marked anticyclonic circulation over WME and CME, inducing warm and dry conditions over Italy.
- WT6: Anticyclonic circulation over Iceland and cyclonic circulation over central Europe, with higher precipitation over Tuscany fuelled by intrusions of Arctic and polar continental air.
- WT7: Southwesterly flow over the North Atlantic with ridging over the British Isles towards Scandinavia, with easterly wind over CME resulting in very cold dry conditions with northeasterly winds over Italy, except in June, July and August (JJA) when above-average precipitation occurs over Tuscany.
- WT8: Cyclonic circulation over West Europe with a ridge over the eastern Mediterranean and above-average precipitations over Tuscany, except in JJA where the pattern

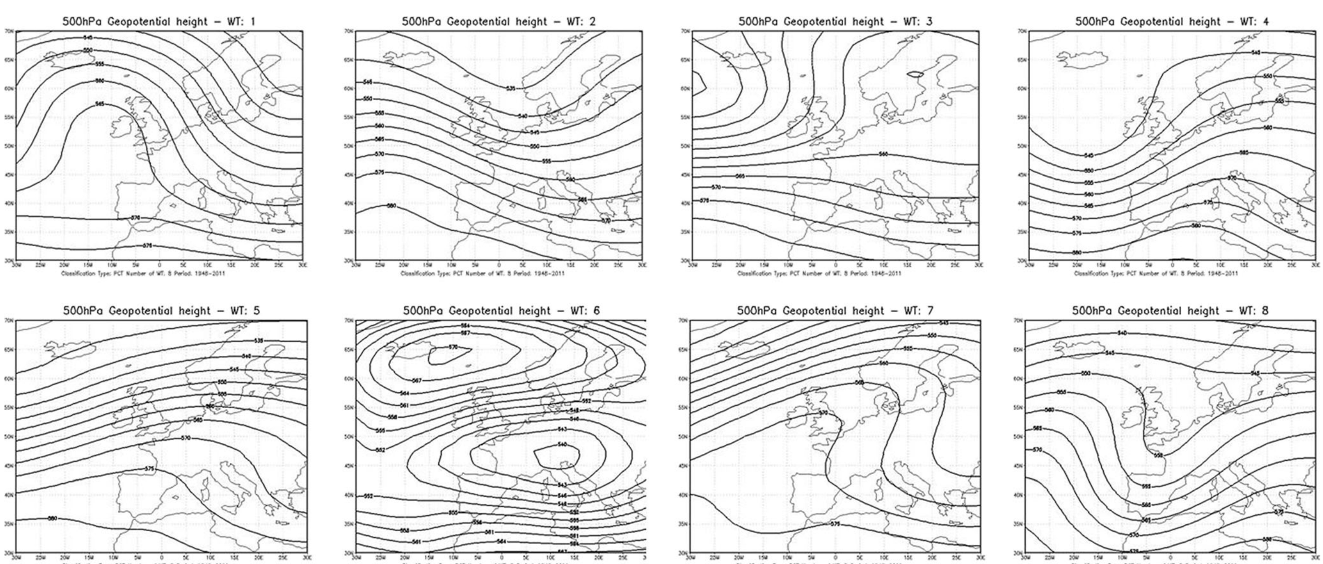

Fig. 1 Geopotential height at 500 hPa for the eight weather types (WT) classified by LaMMA-IBIMET for the period 1948–2011

is weaker and below-average precipitation occurs. This is a winter WT, generally with low frequency.

WT frequencies are calculated for each phenological phase (Fig. 2), and the Mann-Whitney *U*-test is used to compare these frequencies between the top 8 and bottom 8 (upper and lower quartile) consensus-ranked vintages.

In addition, the NAO index by the NOAA Climate Prediction Center (http://www.cpc.ncep.noaa.gov/) is used to investigate any relationships between the top 8 and bottom 8 ranked vintages, with the predominance of any weather types during the phenological phases.

Results

Vintage rankings for Chianti wine (Table 1) display a reasonably good consensus for the best and poorest vintage years. The Chianti Consortium ranked the years 1997, 1990 and 2006 as top years, as three publishers. For the worst years, 1980, 1984 and 1992, agreement among publishers is very good, apart from the Consortium not ranking 1980 at the bottom. The latter result is most likely because the producers rank vintages on a scale of 1 to 5, using scores from 2 to 5 only.

The consensus ranking computed by applying Borges et al. (2012) Condorecet method (Table 1) to six independent sources gives the three top years: 1997 as first and 1990 and 2006 as second equal; the other five used in the "good" vintage group for further analysis are 1985 (fourth) then 1988 (fifth) followed by 1999, 2001 and 2004 (sixth equal) which were generally consistent, and all ranked as "1" by the Chianti Consortium.

The worst years from the consensus method ranked 1980 (32nd) as the lowest (Table 1), followed by 1992 and 1994 (30th) as the second lowest. All the other five years selected in the "poor" vintage group, in ascending order of rank—1989, 2002, 1987, 1981 and 1991 (from 29th to 25th)—agreed well with published results, although the Consortium again did not rank 1981 especially low. The Kendall tau statistic for the solution is 0.218. The Kendall tau value is a non-parametric measure of the distance between ranked variables. The larger the distance, the more dissimilar the ranked lists are. When the value is 0, there is a total agreement, and 1, no agreement. The average Kendall tau distance for the producer consortium was 0.4, indicating that about 40 % of pairs differ in ordering between the respective lists with published rankings. With all the six rankings used for the consensus, this value was about 22 %.

Results show that 1997 is the best and 1980 the worst vintage, with the second two best and the worst being 1990 and 2006 and 1984 and 1992, respectively.

Climatic factors

Climate variables, significantly different between the top 8 and bottom 8 ranked vintages, varied between development

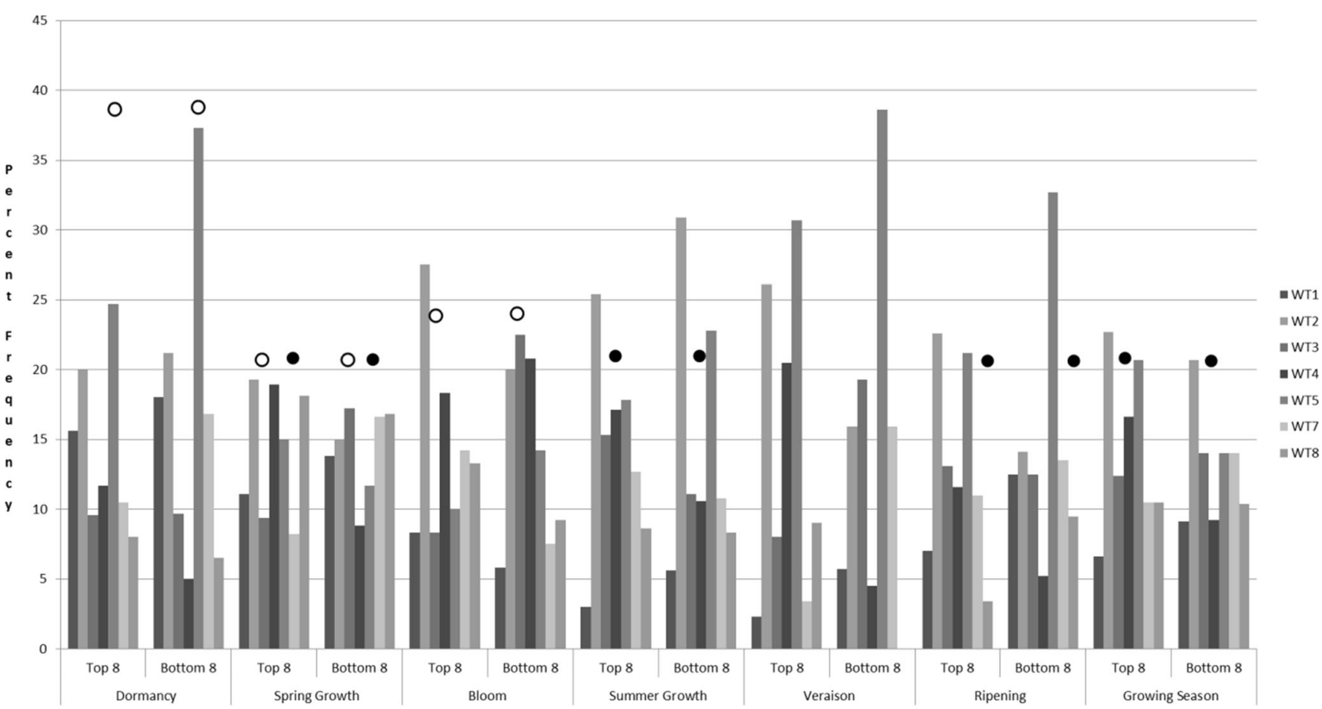

Fig. 2 Frequency of weather types (WT) between the top 8- and bottom 8-ranked Chianti vintages in Tuscany for various phenological phases. Those significant (α=0.05) are *filled circles*, and not quite significant (α=0.10) are *open circles*. WT6 is not listed as the highest frequency attained in any season was 0.2 %, and it was absent in summer and early autumn

Table 1 Ranks from assessment scores converted to Chianti wines in Tuscany for vintages during 1980–2011 and consensus rankings

Yearly ranks from publishers and consensus ranking								Sorted consensus	
Year	PRO	WS	DEC	VT	CN	AB	Consensus	Year	Rank
1980	12	29	31	32	31	29	32	1997	1
1981	12	25	21	27	22	24	26	2006	2
1982	12	20	8	20	14	19	21	1990	2
1983	1	17	8	20	27	25	21	1985	4
1984	30	32	31	27	32	27	30	1988	5
1985	1	3	1	4	4	3	4	2001	6
1986	12	22	21	13	28	22	23	2004	6
1987	27	27	21	20	28	30	27	1999	6
1988	1	3	1	1	5	13	5	2007	6
1989	27	28	28	27	25	32	29	1995	10
1990	1	1	1	1	2	9	2	2008	11
1991	27	24	8	27	25	19	25	2011	12
1992	30	31	28	27	30	30	30	1998	13
1993	12	11	8	20	19	17	16	2000	13
1994	12	25	8	20	22	22	23	2009	15
1995	1	22	1	4	11	9	10	1993	16
1996	12	20	1	13	19	27	16	1996	16
1997	1	2	1	4	1	1	1	2003	16
1998	12	13	21	4	13	21	13	2005	16
1999	1	3	8	4	7	3	6	2010	16
2000	12	17	21	4	14	7	13	1982	21
2001	1	8	8	4	7	13	6	1983	21
2002	30	29	28	20	6	26	28	1994	23
2003	12	10	21	13	22	17	16	1986	23
2004	1	13	8	4	14	6	6	1991	23
2005	12	17	21	13	19	3	16	1981	26
2006	1	7	1	1	3	1	2	1987	27
2007	12	3	8	4	7	7	6	2002	28
2008	1	13	8	13	9	9	11	1989	29
2009	12	13	14	13	14	14	15	1992	30
2010	12	11	16	20	16	16	16	1984	30
2011	12	8	11	13	11	11	12	1980	32

Consensus represents the ranked vintages as a consensus of the inputs as specified by Borges et al. (2012) (see text for details on the method). The final two columns represented the ranked vintage years in order from 1 to 32

Pro producer consortium, *WS* Wine Spectator, *DEC* Decanter, *VT* Vintage Tuscany, *CN* Cellar Notes, AB Addy Bassin

phases (Table 2). DTR did not attain significance for any phase. For the dormancy period, higher average and minimum temperatures and minimum precipitation often resulted in the upper-quartile vintages. For the spring and summer growth periods, higher average and maximum and minimum temperatures together with higher GDD and HI units were a common feature in these phases, together with more ≥35 °C days during the summer growth period. Less precipitation and rain days were important only during veraison for the top 8 vintages.

For the ripening period, more GDD units favoured top quartile-ranked vintages. Over the entire growing season, higher average temperatures as depicted by higher GDD and HI units and more ≥35 °C days were the most important climatic elements that distinguished top and bottom quartile-ranked vintages. Maximum temperatures were 1.8 °C and minimum temperatures 1.3 °C higher for the top-quartile compared to the bottom-quartile vintages. The differences in the means are shown in Table 2.

For the growing season, there is a warming trend of about 2 °C in maximum temperatures for the 1980–2011 period, with an increase in DTR, GDD and HI (not shown). Minimum temperatures show little trend. There are no trends in numbers of days below 0 °C, above 35 °C, precipitation or precipitation days of 1 mm or more.

No significant associations were exhibited between the upper or lower quartile-ranked vintages, and the NAO index, although the July to June NAO index was almost significant with the ranked vintage (positively).

Weather types

Figure 2 shows the frequencies of the WT between the upper and lower quartile-ranked Chianti vintages, and the temperature and precipitation statistics for each weather type and phenological period are shown in Figs. 3 and 4. For the dormancy period (Fig. 2), WT5, although not quite significant (between 5 and 10 %), was more predominant for the lower-quartile vintages, contrasting with WT4 for the upper-quartile vintages, although the latter frequencies did not attain any level of significance. WT5 produced milder winters, which were dry, and WT4 produced the mildest winters, which, in contrast, were much wetter than normal (Fig. 3a).

For the spring growth period, WT7 and WT3 (Fig. 2b) were significant and not quite significant (between 5 and 10 %) respectively for the lower-quartile years, whereas WT4 was much more prevalent in the upper-quartile years, although the differences were not significant. WT3 and WT7 produced generally lower temperatures at Siena than WT4, where temperatures were above average. Precipitation amounts between these types did not differ greatly. For the 15-day bloom period, WT3 was not quite significant in the lower-quartile vintages (Fig. 2). These years (Fig. 3c) were characterized by cooler temperatures in Siena (Fig. 3c).

WT4 (Fig. 2) was significantly more frequent in the upper-quartile years for summer growth. This pattern (Fig. 3d) produced warm dry conditions in Tuscany. The 11-day veraison period was too short to establish any significance between differences in weather types, but there was a tendency towards those giving drier conditions in upper-quartile vintages, compared with wetter conditions in lower-quartile vintages (not

Table 2 Summary of statistically significant relationships (α=0.05) between consensus rankings for Chianti wines during different phenological phases of the Sangiovese grapevine in Tuscany, and mean values of these variables between the upper and lower quartile-ranked vintages

Phenological phase	Significant variables	Variable	Top 8	Bottom 8
Dormancy (1 Nov–15 Mar)	T_{avg} ↑	T_{avg} (°C)	7.5	6.5
	T_{min} ↑	T_{min} (°C)	4.4	3.3
	P ↑	P (mm)	338	270
Spring growth (1 Apr–31 May)	T_{max} ↑	T_{max} (°C)	19.7	17.6
	T_{avg} ↑	T_{avg} (°C)	15.0	13.3
	T_{min} ↑	T_{min} (°C)	10.0	8.3
	GDD ↑	GDD (°C days)	349	201
	HI ↑	HI (°C days)	525	341
Bloom	–	–	–	–
Summer growth (1 Jun–10 Aug)	T_{max} ↑	T_{max} (°C)	28.8	27.2
	T_{avg} ↑	T_{avg} (°C)	23.1	21.6
	T_{min} ↑	T_{min} (°C)	17.3	16.0
	GDD ↑	GDD (°C days)	1060	801
	HI ↑	HI (°C days)	1336	1024
	>35 °C ↑	>35 °C (days)	1.9	1.0
Veraison (10–20 Aug)	T_{min} ↑	T_{min} (°C)	19.3	17.5
	P ↓	P (mm)	2.3	18.4
	P Days ↓	P Days (days)	0.6	1.8
Ripening (21 Aug–30 Sep)	GDD ↑	GDD (°C days)	470	426
Growing season (1 Apr–30 Sep)	T_{max} ↑	T_{max} (°C)	25.4	23.6
	T_{avg} ↑	T_{avg} (°C)	20.1	18.5
	T_{min} ↑	T_{min} (°C)	14.7	13.4
	GDD ↑	GDD (°C days)	1856	1574
	HI ↑	HI (°C days)	2411	2092
	>35 °C ↑	>35 (°C days)	3.3	1.0

An upward-pointing (downward-pointing) arrow indicates a statistically significant relationship between that climate variable and high (low) rankings. For example, a high T_{min} during veraison is associated with higher ranked (better quality) Chianti wines, whereas high precipitation during the same phase is associated with poor ranked wines

T_{avg} average temperature, T_{max} maximum temperature, T_{min} minimum temperature, *P* precipitation, *P Days* number of days with precipitation of 1 mm or more, *GDD* growing degree days, *HI* Huglin Index

shown). Lower-quartile years displayed a significantly higher frequency of WT7 (Fig. 2), and again, WT4 was more predominant in the upper-quartile years and promoted cooler yet above-average precipitation (Fig. 4a) at Siena over the ripening period, while WT4 resulted in warmer, drier conditions.

For the entire growing season, WT4 (Fig. 2) was the dominant pattern producing significantly better vintages. This type produced above-average growing season temperatures at Siena (Fig. 4b) with precipitation not being abnormally above or below average.

Concerning NAO, there was a significant relationship between the current October–March NAO and WT4 and WT5: the negative phase of the NAO favoured WT4 with an r^2 of 0.50 (mild and dry dormancy periods).

Time series of WT are shown in Fig. 5. For the 183-day growing season, both WT3 and WT4 have increased over the 1908–2014 period by 10 and 9 days, respectively. WT1, WT2 and WT5 display decreases in the order of 6–8 days for this period of the year, with no trend for WT6 and WT7.

Discussion

As for Baciocco et al. (2014), the Borges et al. (2012) methodology effectively enabled a ranking of Chianti vintages using consortium assessments and published vintage rating charts. When paired with each of the six sources, only 22 % of the pairs differed, in contrast with 30–40 % when each of the individual published lists is compared; this represents a considerable improvement.

The consensus results between the top and bottom quartile-ranked vintages are somewhat consistent with Dalu et al.'s (2013) findings, but with differences as the studies are not entirely comparable with the current analysis. In assessing

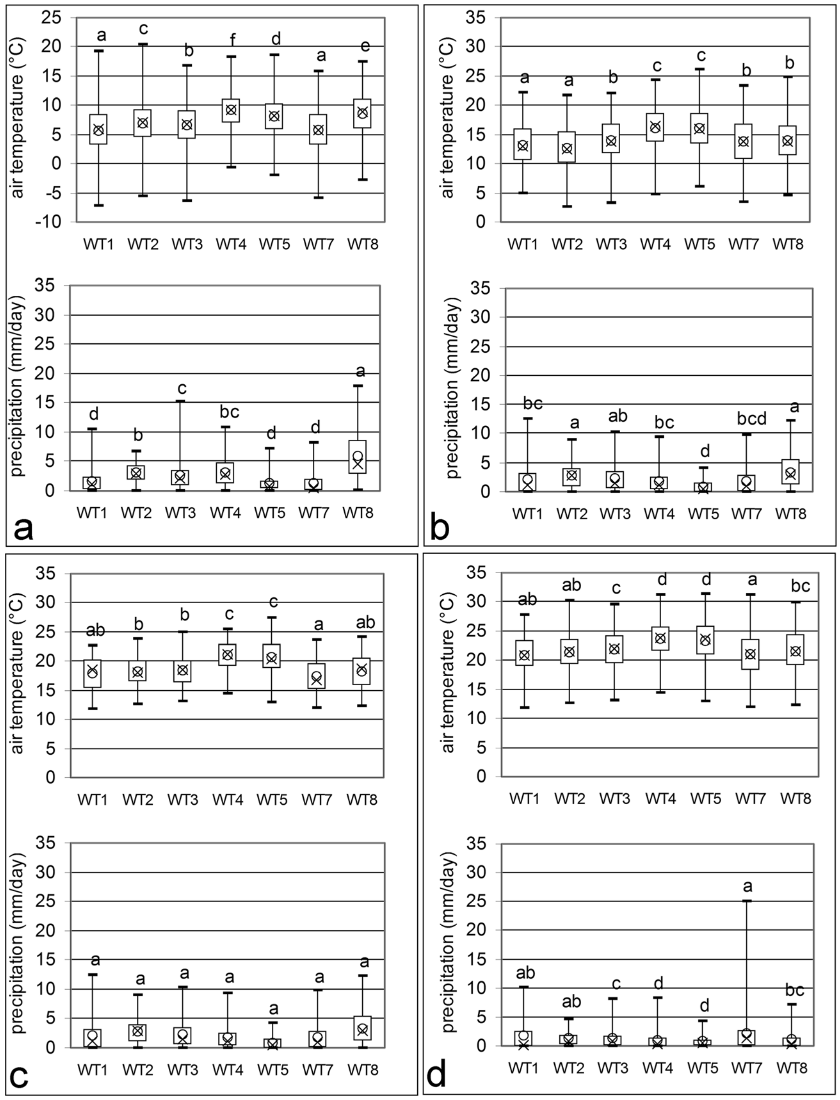

Fig. 3 Siena temperature (*top*) and precipitation (*bottom*) in °C and mm respectively for each of the seven LaMMA WT for each phenological phase attain significance or near significance; **a** dormancy, **b** spring growth, **c** bloom and **d** summer growth. The *rectangular boxes* present two quartiles (upper and lower); the lower quartile is equivalent to the 25th percentile and the upper quartile to the 75th percentile. *o* mean, *x* median (50th percentile), - upper and lower extremes

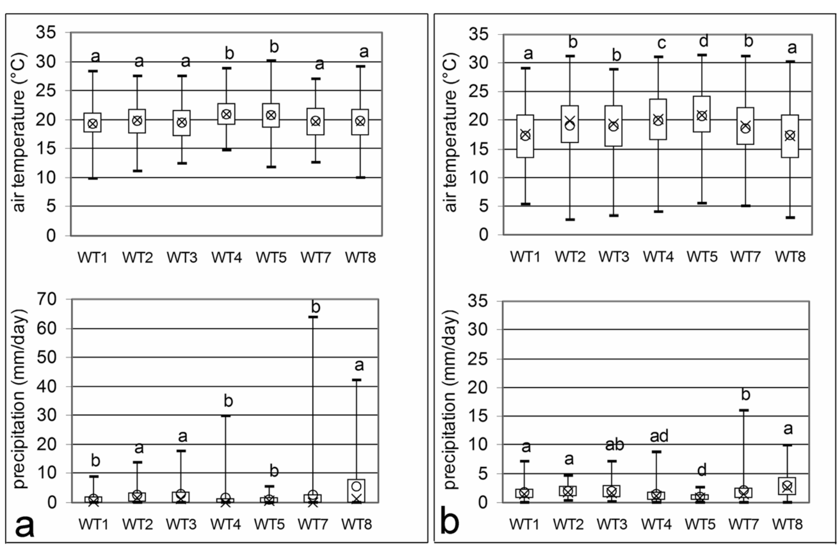

Fig. 4 As for Fig. 3, but for **a** ripening and **b** the growing season

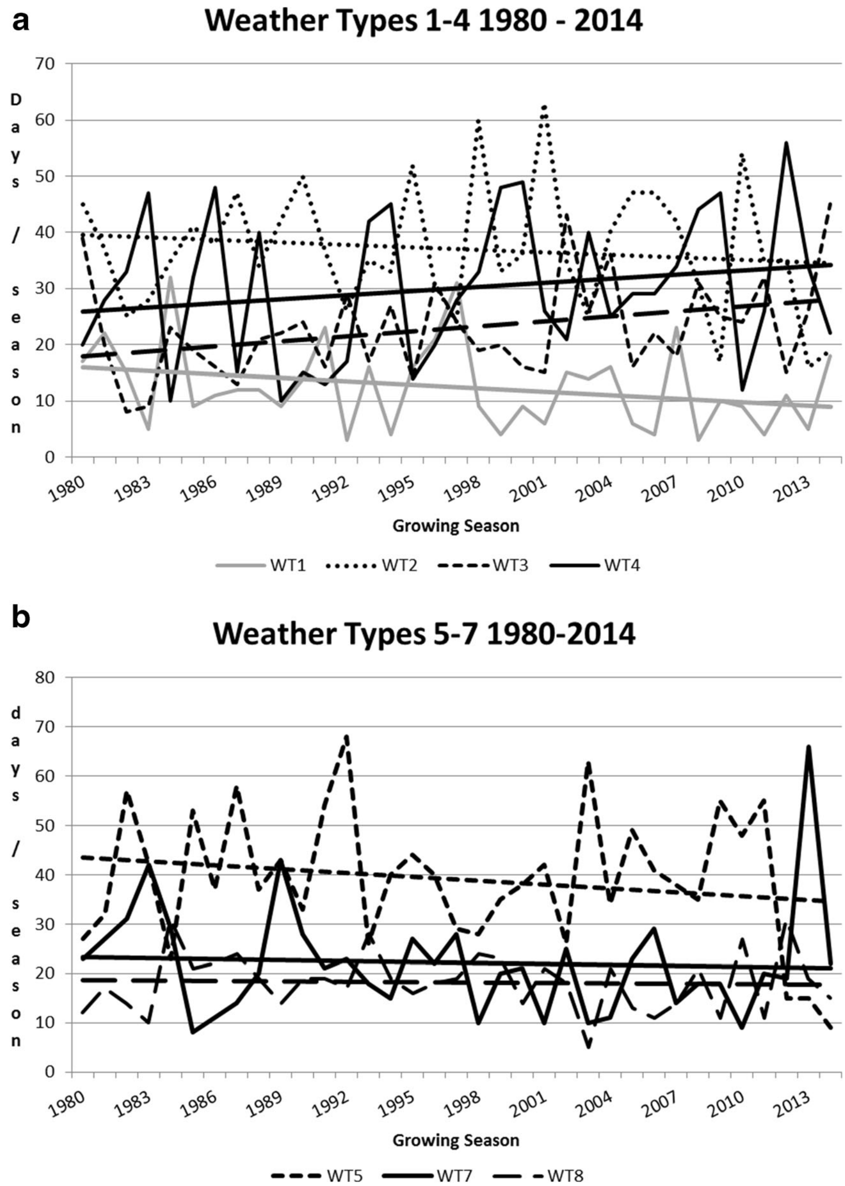

Fig. 5 Growing season (1 April–30 September) time series 1980–2014, in weather types (WT) 1–6 and 7–8. The trend is shown as a linear regression

good- and poor-quality vintages for northern and central Italy, they use wine quality data provided by the respective consortia taking the top and bottom 10 years from 1970 to 2008. Three of the low-ranked years (1980, 1981 and 1991) and seven of the top years (1985, 1988, 1990, 1997, 1999, 2004 and 2006) were similar. The analysis splits the growing season into the boreal spring (March, April and May (MAM)), summer (JJA) and early autumn (SO).

Climate factors

With climate factors, previous research has found that the optimum April–September mean temperature T_{avg} for Sangiovese grapes ranges from 17.5 to 19.5 °C (Jones 2013). Our results here show that the upper-quartile vintages range between 19.2 and 20.8 °C, and the lower-quartile vintages range between 17.3 and 19.8 °C. Thus, the upper quartile showed less temperature variability than the lower quartile-ranked vintages.

During the development phases, temperature from budburst to the beginning of veraison is the key parameter, with T_{max} being more important than T_{min}; seven out of the eight upper-quartile seasons experienced a T_{max} of 25 °C and T_{avg} of 19.5 °C or more. Dormancy temperatures, prior to the growing period, are significant as well: only two out of the top 8 recorded T_{min} below 4.0 °C, whereas only two out of the bottom 8 had T_{min} above 4.0 °C. There was also a link between wetter dormant periods and higher wine quality with all but one year recording 300 mm or more compared with only two above 300 mm for the poor-quality years. This is consistent with prior research showing a linkage between wet dormant periods and higher wine quality (Ashenfelter 2008;

Jones and Davis 2000; Jones and Storchmann 2001). Warmer dormant period influences found for Tuscany are also consistent with conditions in Bordeaux (Baciocco et al. 2014).

The precipitation relationships were less critical; low precipitation and days with ≥1 mm were significant between the good- and poor-quality years for the 11-day veraison period, but not for ripening. In the good years, on only one occasion did the precipitation total more than 5 mm, compared with five in the poor-quality years, which is consistent with previous finding for red wines in Bordeaux (Ashenfelter 2008; Baciocco et al. 2014; Jones and Davis 2000; Jones and Storchmann 2001).

However, at variance with previous findings, more precipitation totals in the bottom-quartile compared with the top-quartile years were not significant for Sangiovese wine quality in Tuscany. These differences were not that pronounced during the ripening phenological phase: the top years averaged totals of 72 mm compared with 96 mm for the bottom years.

Examination of the good- and poor-ranked vintages is informative, with 1997 at the top and 1980 at the bottom. The dormancy period was consistently warmer and wet with fewer frosts. Temperature was certainly a defining factor in the first part of the growing season: T_{max} and T_{min} were 3–4 °C higher in 1997 which had over double the amount of precipitation in the spring growth period, which was also the case for the bloom period. T_{max} and T_{avg} were also warmer in 1997 by 2 °C for summer growth with 200 mm of precipitation compared with 30 mm. However, veraison was warm and dry in 1997 compared with that in 1980. Again, T_{max} was higher during the ripening period. Over the entire growing season, GDD and HI were 50 % higher with maximum temperatures almost 3 °C higher, but precipitation amounts were more than double. Precipitation, as with the top quartile, only appeared significantly during veraison. DTR was not significant at all.

Two of the bottom 8 years, 1991 and 1992, occurred during and immediately after the Mt. Pinatubo volcanic eruption on 15 June 1991. The latter was the third bottom year (Table 2). The volcanic influence on the surface temperature is highly seasonal in character (Jones et al. 2003); Fischer et al. (2007) showed that the strongest, highly significant cooling signal (about −0.5 °C averaged over Europe) is found during the summer of year 1, in this case 1992, after the eruption. This signal showed a large spatial variability, with weak negative anomalies found in central Europe and parts of the Mediterranean. With the precipitation anomalies low, statistical significance for precipitation changes following the eruption occurs; however, post-eruption summers display a tendency towards wetter conditions over parts of the Mediterranean and over northern Europe. Climate anomalies for Siena for the 1991 growing season and for the 1992 season are consistent with volcanic eruption climate signal. During the winter dormant period, minimum temperatures were about 2 °C below average, and the lowest of any of the bottom 8 years. Growing season temperatures, GDD and HI were not much below average (T_{avg} 19.2 °C compared with an average of 18.5 °C for the bottom 8 and 20.0 °C for the top 8), but precipitation days were much higher (418 mm on 47 days, compared with 475 mm on 42 days for the bottom 8, and 297 mm on 33 days for the top 8).

Weather types

The WT analysis revealed which types were favoured between the top and bottom quartile-ranked vintages. The predominant weather type common to all periods of development for the good vintages, apart from bloom, was WT4. With a 500-hPa trough over the North Atlantic and a ridge over the central Mediterranean, anticyclonic conditions accompanied by warmer and drier conditions at sea level. Specifically, at all times of the year, temperatures are above normal, and, apart from the dormant period, precipitation is below normal; during dormancy, above-average precipitation may occur. Similar results are obtained for the top-ranked year (1997) except for dormancy, summer growth and ripening period.

For the poorly ranked vintages, the weather type varied; WT3 and WT7 were important for spring growth and veraison, with WT3 for bloom. The occurrence of WT8 during ripening was a key. Over the entire growing season, a higher frequency of WT7 led the lower-ranked vintages. In 1980, the phenological stages generally followed these trends, with WT7 also important during bloom and WT3 during ripening. In contrast, WT2 and WT3 were more important over the entire growing season in 1980. During WT3, the upper anticyclonic ridge over northern Europe favours the intrusion of the Atlantic perturbations into the central Mediterranean region, with cooler and wetter conditions throughout the growing season in Tuscany.

The occurrence of a negative NAO in October–March promotes a higher frequency of WT4, with warmer wetter winters, with more storms reaching the Mediterranean region; this was a precursor of the top-quartile years. Conversely, a positive October–March NAO gave a higher frequency of WT5, the antecedent to the bottom quartile with warmer but drier winters, and the Atlantic storm track located north of the Mediterranean region (Dalu et al. 2013).

Year 1992, which was affected by the Mt. Pinatubo volcanic eruption, had the highest number of precipitation days during the bloom and summer growth periods (33), with the ripening period being much cooler and wetter. WT5 was very dominant, occurring 37 % of the time, resulting in mild but moist conditions, conducive for high plant disease pressure throughout the 1992 season.

Dalu et al. (2013), who examined the atmospheric circulation over the Mediterranean basin, found that the cross basin flow is controlled by the position of the two branches of the jet stream in the Euro-Atlantic region; with the landing site in the

Mediterranean basin determined by the position of the exit region of the Atlantic jet stream, this jet acts as a waveguide for the Atlantic storms (Hoskins et al. 1983; Rodwell et al. 1999; Ziv et al. 2010). For the top-ranked years, the jet stream is weaker in spring: the African jet retreats eastwards and the Atlantic jet assumes a northeasterly tilt. With this configuration, Mediterranean Europe is drier and the central Mediterranean Europe (CME) is warmer. In summer, the African jet also retreats further eastwards and the Atlantic jet assumes a more southerly position producing warmer and drier conditions over Mediterranean Europe. The September–October configuration for the African jet is similar, with a weaker Atlantic jet located more westward, again promoting warmer drier conditions over CME. These results are consistent with the top-quartile years of this study, where weather WT4 is much more prevalent.

In the bottom-ranked years, Dalu et al. (2013) found that in MAM and JJA, the two jets are stronger, with the African jet located further west and the Atlantic jet further east in MAM and further west in JJA. Under this configuration in spring, central Europe is wetter, while the Provençal region and the Piedmont region are drier and West Mediterranean Europe is slightly warmer. In summer, CME is wetter and slightly warmer. In September and October, the African jet moves further east with the Atlantic jet further south favouring wetter and cooler conditions over CME. This was in agreement with the bottom-quartile years favouring weather WT3 and WT7 from this study.

Although there has been a warming trend with increases in maximum temperatures, GDD and HI, the trends in WT balance each other out. The frequency of WT4 responsible for good vintages has increased. So too has that of WT3, which promotes poor vintages. The trend to lower frequencies of WT5 is not of significance for vintage quality. Although many of the lower-quartile years occurred in the period 1980–1992 and upper-quartile years subsequently, the trend is not significant. The role of global warming producing increases in temperature parameters is thus compensated by WT during the growing season.

Conclusions

Generally, the Mediterranean climate is favourable to wine grape cultivars. In Tuscany, Chianti wine production dates back to the thirteenth century; this century marks the beginning of the production of this excellent red wine. The Chianti area is a small part of Tuscany; this region of few hundred square kilometres is located in west-central Italy and bounded by the Tyrrhenian Sea to the west and by the Apennines to the east. Even with marked local climate differences induced by topographic features, Tuscany is sufficiently small to be affected by the same weather system at any time.

The key conclusions are as follows:

1. Consensus rankings of vintage ratings grouped vintages according to assessments for Chianti wines improving on the variation between rating agencies. The Condorcet method has successfully separated the upper- from the lower-quartile vintages, and, as it has been demonstrated for French and Italian wines (Borges et al. 2012; Baciocco et al. 2014), this method is a robust tool for an unbiased evaluation for a wine region given a collection of input vintage ratings. The benefit of such an assessment allows further research to define the climatic factors during phenological phases important in determining wine quality measures such as ratings.
2. Best-quality vintages occur in warm and dry growing seasons, and inferior-quality vintages in cooler and wetter conditions. The examination within specific phenological phases highlighted the importance of climatic factors during the different active growth periods of the grapevine. It has been found that higher GDD, HI, T_{max}, T_{avg} and T_{min} and more days with temperature above 35 °C were the most important discriminators between good- and poor-quality vintages of Chianti wines; these parameters were important in the spring and summer, with GDD as the chief factor during ripening. Only during veraison were elements of moisture important: low precipitation amounts and precipitation days giving rise to better quality vintages. During the dormancy period, warmer and wetter winters led to higher quality vintages, while warmer and drier winters led to lower quality vintages. The top-quartile vintages were characterized by seasonal T_{max} 2 °C and T_{avg} 1.5 °C higher than the lower-quartile vintages along with 350–400 more heat units over the growing season. Future research, such as utilizing principal component or factor analysis (Baciocco et al. 2014), can be used to further differentiate the more important climatic variables.
3. Variations in atmospheric circulation affecting CME are critical in determining the resultant climatic anomalies throughout the growing season. Previous work (Dalu et al. 2013) has shown that the positioning of the Atlantic and African jet streams is crucial. In winter and early spring, the intrusion of a sufficient number of Atlantic storms is important for determining the correct balance between heat and precipitation for the vegetative developmental stages of the vines. However, in summer, the right equilibrium between cooler westerly flow from the Atlantic and warmer southerly flow from Africa is very important in providing heat for the optimum acid, alcohol and sugar composition in the grape; precipitation amount becomes more critical, especially at veraison, for Chianti grapes. In early autumn, persistent precipitation increases plant disease pressures.

4. This work has extended the investigation by analysing the frequencies of WT that affect Tuscany. The analysis shows upper-quartile vintages are favoured by WT4: more anticyclones over CME giving warm dry growing season conditions. Furthermore, the WT analysis demonstrated that dormancy periods prior to such seasons had conditions where WT4 was warmer and wetter and correlated strongly with negative phases of the NAO. The lower-quartile vintages all relate to higher frequencies of either (i) WT3 producing cyclonic perturbations at sea level crossing CME favoured, with cooler and wetter conditions, and/or (ii) WT7 with cold dry continental air masses from the east and northeast over CME. Warmer but drier WT5s during dormant periods were not positive in setting the stage for a higher quality vintage. Not surprisingly, NAO positive phases were strongly associated with WT5. The only year with a volcanic circulation signature, 1992, produced the third lowest ranked vintage; WT5 was very dominant giving mild but moist conditions, especially during flowering and very likely high disease pressure.
5. The WT identification during critical periods, coupled with modern seasonal climate predictions, can allow advance anticipation of the season ahead, useful for management of climate risks with decision support systems. Once any future growing season is over, an analysis of both climate indices and WT data should provide a basis for the forward identification of high-quality vintages, as the foundation of the balance between optimum acid, alcohol and sugar composition in the grape has been established. The converse—the anticipation of poor-quality vintages—is likely to be more difficult for producers; however, vine and crop management can be used to offset adverse climate conditions.
6. The European climate has been warming over the last three decades. However, this study shows that trends in WT are important in compensating for any trends to higher quality vintages because of temperature increases. The growing season weather is an important determinant of vintage quality.
7. Future trends from the Intergovernmental Panel on Climate Change Fifth Assessment Report (Kovats et al. 2014) show significant agreement for all emission scenarios with strong warming and drying projected over CME for the growing season. Although this may be beneficial in the next decade or so for improving Chianti wine quality, once critical threshold values of key climate variables are exceeded, there is expected to be an impact on the future high-quality vintages. Then, changes in grape cultivars, elevation and aspect of the vineyard and other crop management approaches will likely be necessary (Mozell and Thach 2014).

Summarizing, on the basis of our previous and present studies, we can postulate that above-average temperatures with lower precipitation and anticyclonic weather types in the period April–September lead to higher ranked vintages, while below-average temperatures combined with higher precipitation, with a tendency towards cyclonic weather types, lead to lower ranked vintages. Warm and wet winters are beneficial, while cold and dry winters are adverse to good Chianti vintages. The weather types have been more important in determining quality than any climate trends over the 1980–2011 period.

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