Analysis of Italian Wine Quality Using Freely Available Meteorological Information

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Abstract: Meteorological conditions strongly affect viticultural activity, modifying grapevine (*Vitis vinifera*) responses and determining the quality and quantity of production. The analysis of meteorological information can provide viticulturists with operational and forecasting tools for improving the management of vineyards. Meteorological information is presently available on Internet sites with different spatial and temporal scales, allowing easy access and overcoming the necessity of installing costly weather station networks. The present research was performed for the purpose of analyzing the relationship between meteorological information freely available on Internet and the average quality (defined by vintage ratings) of Italian wine. Temperature and precipitation data were analyzed. The presence of teleconnections and their effect on quality was investigated by considering 500 hPa geopotential height, sea surface temperature, and meteorological indices such as North Atlantic Oscillation and Southern Oscillation. Results highlight strong relationships between meteorological conditions and wine quality. Higher-quality wines were obtained in the years characterized by a reduction in rainfall and high temperature patterns. Teleconnections were also detected in different periods of the growing season, thus allowing for the development of wine-quality forecasting tools. Results could aid in the evaluation of operations concerning the analysis and forecasting of wine quality.

Key words: temperature, rainfall, sea surface temperature, North Atlantic Oscillation, geopotential height, teleconnection

Wine composition is determined by various conditions: grape variety, rootstock, soil type, cultivation techniques, and climatic characteristics (Gladstones 1992, Wilson 1998, van Leeuwen et al. 2004). The first three conditions are generally constant, particularly variety and rootstock because of the control exercised by regulating councils (Rodo and Comin 2000). Cultivation techniques, at times labeled "human factors," are most often responsible for long-term variability since modification in production methods may require a long period for adoption by grapegrowers. Regulating councils may also be responsible for a limited and controlled introduction of innovation techniques (Rodo and Comin 2000). Climatic variables are the main influence on year-to-year variability. Although improvement in cultivation techniques allows for obtaining acceptable quality levels each year, climatic or meteorological conditions are largely responsible for interannual variations in production and the quality of wines obtained in specific years (Jones and Davis 2000a,b, Giaccio and Del Signore 2004). This topic is particularly important given the present period, which is characterized by accentuated climatic variability, and the forecast of drastic climatic changes in the future (Nemani et al. 2001).

Meteorological conditions can influence the main processes responsible for grapevine growth and development, plant disease infections, and some chemical and sensory characteristics of wines (Moncur et al. 1989, Huber and Gillespie 1992, Mullins et al. 1992, Esteves and Manso Orgaz 2001). Mathematical descriptions of these effects have been formulated in order to provide users (such as growers, extension services, and researchers) with operational tools for processing information to improve management and planning (Grifoni et al. 2003). Simple bioclimatic indices, more complex statistical relationships, and empirical and mechanistic simulation models (Bindi et al. 1997a,b) can be applied using climatic data, weather monitoring, and forecasting as driving variables for obtaining a generally accurate definition of vine responses to meteorological conditions (Huglin 1986).

The quality of agrometeorological variables is the basis for precise description of these effects and consequently for processing of end-user information. However, ground

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weather stations may not meet standards of accuracy and precision of measured data and of spatial and temporal representativeness (WMO 1981). Development of weather station networks could partly address these problems, but would involve high installation and maintenance costs (Vose and Menne 2004). The Internet has increasingly been used to disseminate climate and meteorological data, given its rapid manipulation and display of information, interaction and feedback with the users, and reduction of costs. The Internet allows for finding suitable applications providing free access to meteorological information with different spatial domains and temporal resolutions. Information provided by ground weather station data, satellite, radar, soundings, and weather forecast models can be integrated to derive a complete description of meteorological and climatological variables and indices, such as air temperature, rainfall, North Atlantic Oscillation (NAO) index, sea surface temperature (SST), and geopotential height.

Wine quality can be evaluated via chemical grape or wine analysis using recent techniques (such as gas chromatography together with artificial sensors such as the olfactometer), allowing for quantitative objective evaluation of the components involved in final wine composition determination (Bertrand et al. 2000). An alternative method for assessing wine quality is sensory analysis based on evaluation of color, aroma, and taste to determine annual vintage ratings. Data series are available of wine quality rankings, making it possible to determine the relationships between wine composition and climate variability (Rodo and Comin 2000, Esteves and Manso Orgaz 2001).

This research was performed with the aim of analyzing the relationship between the quality of Italian wine and the meteorological data available on the Internet. Different temporal scales were compared in order to propose a wine-quality forecasting method based on meteorological conditions observed several months before harvest. Results are discussed with the goal of assessing wine quality with the freely available data and resolving concerns related to the use of ground weather stations.

Materials and Methods

Wine quality data series. The quality data series of six wines produced in central and northern Italy were used. Brunello di Montalcino, Nobile di Montepulciano, and Chianti Classico were produced in the Tuscany region (central Italy), in vineyards of 1300, 850, and 7000 ha, respectively. Barolo and Barbaresco were produced in the Piedmont region (northwestern Italy) and Amarone in the Veneto region (northeastern Italy) in vineyards of 1250 and 740 ha, respectively. All vineyards were located between 43°05'N and 45°32'N in latitude on a hilly territory with an elevation between 200 and 600 m a.s.l. The area is characterized by a typically Mediterranean climate, mainly affected by Azores and Russian anticyclones and by Mediterranean depressions. Precipitation is concentrated in spring and autumn with a dry period in summer (annual rainfall between 690 and 820 mm). The growing season is characterized by a hot summer (annual average temperature between 12.7 and 13.7°C).

Vintage ratings were used to define wine-quality ranking (Table 1), which is based on the collection of estimates from 1 to 5 classes (from insufficient to excellent) (Riou 1994). The rating of a given vintage was conducted in a single blind tasting of the individual varietals by a panel of experts. Although this rating does not consider variations in quality among the individual vineyards, it is the most comprehensive overall rating compiled for high-quality Italian wines (Corsi and Ashenfelter 2001).

All were deemed superior quality wines by the panel and potentially suited to aging. The quality data rankings

Table 1 Wine-quality series for Italian wines and their average values: Brunello di Montalcino (BM), Chianti Classico (CC), Nobile di Montepulciano (NM), Barolo-Barbaresco (B-B), Amarone (AM) (1 = insufficient; 2 = fair; 3 = good; 4 = optimum; 5 = excellent).

Year	BM	CC	NM	B-B	AM	Avg quality
1970	5	5	4	4	3	4.2
1971	3	5	4	5	3	4.0
1972	1	2	1	1	2	1.4
1973	3	2	3	2	3	2.6
1974	2	3	3	4	4	3.2
1975	5	4	4	3	3	3.8
1976	1	2	2	2	4	2.2
1977	4	4	4	1	4	3.4
1978	4	5	5	4	3	4.2
1979	4	4	4	4	4	4.0
1980	4	4	2	3	3	3.2
1981	3	4	3	2	3	3.0
1982	4	4	4	4	3	3.8
1983	4	5	4	3	5	4.2
1984	1	2	1	2	3	1.8
1985	5	5	5	5	4	4.8
1986	3	4	4	4	3	3.6
1987	3	3	2	3	2	2.6
1988	5	5	5	5	5	5.0
1989	2	3	1	5	2	2.6
1990	5	5	5	5	5	5.0
1991	4	3	3	3	3	3.2
1992	2	2	1	2	2	1.8
1993	4	4	5	4	3	4.0
1994	4	4	2	2	2	2.8
1995	5	5	5	4	5	4.8
1996	3	4	4	5	2	3.6
1997	5	5	5	5	5	5.0
1998	5	4	5	5	5	4.8
1999	5	5	5	5	4	4.8
2000	3	3	3	4	4	3.4
2001	4	4	4	5	5	4.4
2002	2	2	2	2	2	2.0

cover a period of 33 years (1970 to 2002). In this work all analysis was performed using the average of the six quality rankings (Barolo and Barbaresco have the same level) (Table 1). The average was used because of the existence of similar quality responses to weather conditions for all wines. Consequently, the annual quality ranking variability among different wines, observed in some years of the studied series, may be due to meteorological events in the local area (such as hail and spring frost).

Meteorological information. A new methodology has completely changed the traditional approach to climatology in recent years, which previously was generally affected by a lack of available environmental information. Past observations (from ground, satellite, soundings), generally characterized by spatial/temporal discontinuity, were reprocessed and combined with output of weather forecast models in order to derive a more comprehensive spatial/temporal description of the environment at a global level. This method is known as "reanalysis" and makes possible the reconstruction of atmospheric analyses (and, consequently, of all meteorological variables) for the entire earth's surface with spatial/temporal continuity. All meteorological information was provided by NOAA-CIRES Climate Diagnostics Center, Boulder, CO (http://www.cdc.noaa.gov/). Data were processed by NCEP/NCAR Reanalysis Project (Kalnay et al. 1996) and were available from 1948 onward (spatial resolution: each pixel of 2.5° x 2.5°).

In particular air temperature, cumulated precipitation, 500 hPa geopotential height, and sea surface temperature (SST) were used. Air temperature was directly available as monthly average values, while cumulated precipitation was in terms of precipitation rate (mm/s); however, this was recalculated in mm/month; both variables were used in terms of average value over the wine production area of the six wines. The 500 hPa geopotential height represents the altitude in meters of the layer in the atmosphere where the air pressure is 500 hPa, and it is well correlated with weather characteristics at ground. SST represents the temperature of the surface of the sea.

The North Atlantic Oscillation (NAO) index and Southern Oscillation Index (SOI), which are derived by meteorological information and in particular by sea level pressure, were also used. The NAO index, based on the difference of normalized sea level pressure between the Azores and Iceland, is a temporal fluctuation of zonal wind strength across the Atlantic Ocean due to pressure variation in both the subtropical anticyclone belt and the subpolar low near Iceland. In the northern hemisphere the winter NAO index (December to March) shows a significant relationship with storm track, temperature, and precipitation (Hurrell and van Loon 1997). The SOI is a standardized index based on observed sea level pressure differences beween Darwin, Australia (lat: 131°; long: -12°) and Papeete, Tahiti (lat: -149°; long: -17°) and is a measurement of the large-scale fluctuations in air pressure occurring between the western and eastern tropical Pacific which quantify the ENSO (El Niño Southern Oscillation) phenomenon.

Relationships between wine quality and meteorological information. Correlations between wine quality and air temperature and precipitation data were calculated over the wine production area. The correlations were calculated on a monthly to a multimonthly basis, also accordingly with several bioclimatic indices used in evaluation of the potential suitability of a region for viticulture (Winkler et al. 1974, Huglin 1986, Fregoni et al. 2003). Correlation maps between wine quality and 500 hPa geopotential height or SST were used to verify the possible impact of large-scale phenomena on wine quality of the studied area (Nemani et al. 2001). The maps were created using the interactive plotting and analysis link from the website www.cdc.noaa.gov, which allowed the uploading of wine-quality data and the calculation of their correlation (teleconnection) with meteorological variables measured in each pixel of the European-North African area. Teleconnection is generally defined as "the phenomenon in which atmospheric interaction between widely separated regions (in space and time) can be identified through statistical correlations" (Hurrel 1996). In our study, such an approach could be justified by the potential impact of SST and 500 hPa geopotential height values, occurring in specific areas, on meteorological conditions over the wine production area during the following months of the growing season. Subsequently, in order to quantify the existing teleconnection inside the studied areas and define the regression functions during the highest correlation periods, meteorological variable data were extracted from the database (www.cdc.noaa.gov) and correlated with the wine quality series. Finally, the presence of teleconnections between wine quality and monthly large-scale meteorological circulation was also investigated by means of the NAO and SOI indices.

Results and Discussion

Wine quality and meteorological variables. In order to analyze the relationships between wine quality and air temperature (Table 2) and precipitation (Table 3), all possible monthly and multimonthly combinations during the January to October period were considered. Higher correlations were found using the average values including the last months of the season. A positive effect was observed for air temperature, confirming that wines of high-quality ranking were produced during warm years (Table 2). Moreover, the highest correlation was obtained using the May to October period (Figure 1A), which emphasizes the importance of the thermal pattern throughout the entire growing season. Rainfall was inversely correlated with wine-quality ranking (Table 3). Statistical significance of the rainfall was higher than for temperature ($p < 0.01$) in many multimonth combinations. The highest correlations were obtained using the last months of the season (-0.559 for September to October (Figure 1B) and -0.553 for September) because of the importance of weather conditions during harvest period when fungal infections and sugar accumulation can be affected by intense precipitation.

Particularly in the case of rainfall, equivalent significance is also obtained if the first months of the year are included (Tables 2 and 3). The relationships can be used to forecast the quality of the wine to be produced (that is, July, July to August, February to July), providing useful information for planning grapevine and harvest management in order to improve the quality of final production.

Correlation maps: 500 hPa geopotential height and SST. The results obtained considering single meteorological variables have been confirmed by the analysis of 500 hPa geopotential height over the southern portion of the central Mediterranean Sea. Accordingly, higher-quality wines were obtained during the years characterized by geopotential height above the average values. In par-

Table 2 Correlation coefficient (r) between wine quality and monthly or multimonthly average air temperature. Statistical significance: $p \leq 0.05$ for $r \geq 0.344$; $p \leq 0.01$ for $r \geq 0.442$; $p \leq 0.001$ for $r \geq 0.546$.

Jan	Jan–Feb	Jan–Mar	Jan–Apr	Jan–May	Jan–Jun	Jan–Jul	Jan–Aug	Jan–Sep	Jan–Oct
0.245	0.200	0.105	0.110	0.200	0.179	0.249	0.270	0.345	0.410
Feb	Feb–Mar	Feb–Apr	Feb–May	Feb–Jun	Feb–Jul	Feb–Aug	Feb–Sep	Feb–Oct	
0.063	0.000	0.000	0.126	0.114	0.195	0.224	0.302	0.367	
Mar	Mar–Apr	Mar–May	Mar–Jun	Mar–Jul	Mar–Aug	Mar–Sep	Mar–Oct		
-0.063	-0.173	0.134	0.110	0.205	0.228	0.300	0.370		
Apr	Apr–May	Apr–Jun	Apr–Jul	Apr–Aug	Apr–Sep	Apr–Oct			
0.000	0.276	0.290	0.237	0.176	0.351	0.418			
May	May–Jun	May–Jul	May–Aug	May–Sep	May–Oct				
0.297	0.200	0.310	0.315	0.366	0.436				
Jun	Jun–Jul	Jun–Aug	Jun–Sep	Jun–Oct					
0.000	0.210	0.249	0.307	0.412					
Jul	Jul–Aug	Jul–Sep	Jul–Oct						
0.285	0.279	0.318	0.431						
Aug	Aug–Sep	Aug–Oct							
0.173	0.253	0.406							
Sep	Sep–Oct								
0.237	0.422								
Oct									
0.362									

Table 3 Correlation coefficient (r) between wine quality and monthly or multimonthly cumulated precipitation. Statistical significance: $p \leq 0.05$ for $r \geq 0.344$; $p \leq 0.01$ for $r \geq 0.442$; $p \leq 0.001$ for $r \geq 0.546$.

Jan	Jan–Feb	Jan–Mar	Jan–Apr	Jan–May	Jan–Jun	Jan–Jul	Jan–Aug	Jan–Sep	Jan–Oct
0.126	-0.114	-0.045	-0.114	-0.084	-0.122	-0.303	-0.318	-0.421	-0.477
Feb	Feb–Mar	Feb–Apr	Feb–May	Feb–Jun	Feb–Jul	Feb–Aug	Feb–Sep	Feb–Oct	
-0.321	-0.148	-0.210	-0.148	-0.184	-0.371	-0.370	-0.460	-0.513	
Mar	Mar–Apr	Mar–May	Mar–Jun	Mar–Jul	Mar–Aug	Mar–Sep	Mar–Oct		
0.100	-0.084	-0.032	-0.089	-0.324	-0.326	-0.437	-0.487		
Apr	Apr–May	Apr–Jun	Apr–Jul	Apr–Aug	Apr–Sep	Apr–Oct			
-0.207	-0.089	-0.138	-0.369	-0.359	-0.462	-0.507			
May	May–Jun	May–Jul	May–Aug	May–Sep	May–Oct				
0.045	-0.063	-0.351	-0.335	-0.447	-0.496				
Jun	Jun–Jul	Jun–Aug	Jun–Sep	Jun–Oct					
-0.126	-0.387	-0.362	-0.466	-0.509					
Jul	Jul–Aug	Jul–Sep	Jul–Oct						
-0.481	-0.411	-0.503	-0.549						
Aug	Aug–Sep	Aug–Oct							
-0.217	-0.424	-0.494							
Sep	Sep–Oct								
-0.553	-0.559								
Oct									
-0.276									

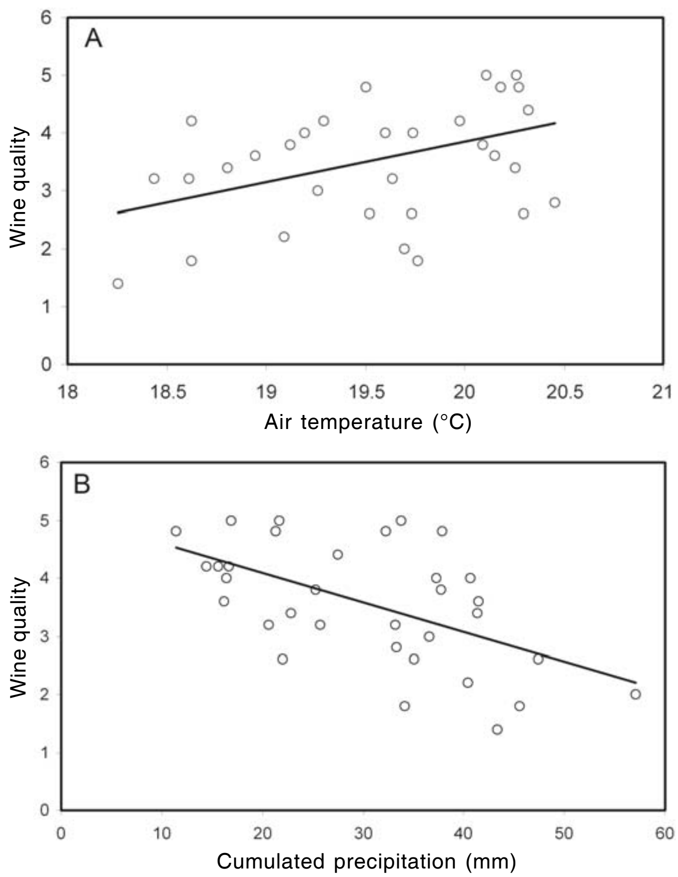

Figure 1 Rectilinear regressions between wine quality and air temperature (**A**) and cumulated precipitation (**B**) over May to October (1970–2002) and September to October (1970–2002), respectively. Data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO (http://www.cdc.noaa.gov/).

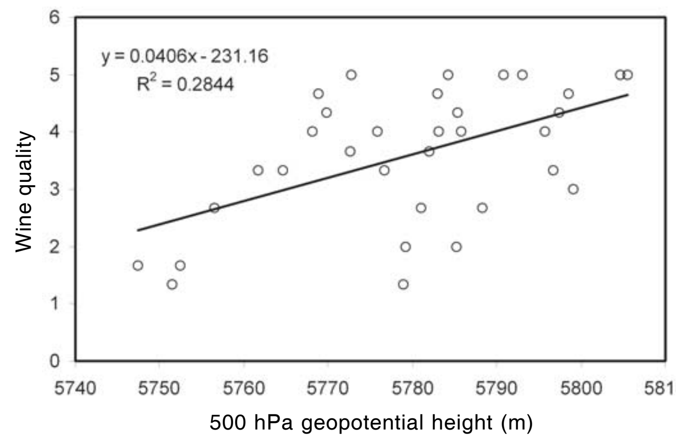

Figure 3 Rectilinear regression between wine quality and 500 hPa geopotential height over southern portion of central Mediterranean Sea for April to July (1970–2002). The determination coefficient (R^2) and regression equation are indicated in the graph.

ticular, the highest correlation value was observed for the April to July period (Figure 2). Data were extracted for this period over the central Mediterranean area (4 pixels defined by lat. 32.5 to 37.5; long. 15 to 20). The correlation obtained was highly significant ($p < 0.001$), with a determination coefficient $R^2 = 0.28$ (Figure 3). These results are in accordance with the previous correlation obtained between wine quality and May to October air temperature. The latter is positively correlated ($R^2 = 0.31$) to April to July 500 hPa geopotential height over the central Mediterranean area (data not shown). High values of this meteorological variable are generally responsible for high temperature and dry conditions during the summer months in Italy, conditions favorable for high-quality wine.

Good relationships were also found between wine quality and SST in the area of the Atlantic Ocean west of the Canary Islands and over the central and western Mediterranean (Figure 4). For the May to June period, the SST data time-series (1970 to 2002) over the Atlantic Ocean west of the Canary Islands (18 pixels defined by lat. 20 to 25 and long. -60 to -37.5) was extracted. The correlation obtained was highly significant ($p < 0.001$), with a determination coefficient $R^2 = 0.39$ (Figure 5).

Such results assume an important role for the potential development of a wine-quality forecast. The occurrence of SST and/or 500 hPa geopotential height over specific areas and at specific times could be used to estimate the wine quality of the next production with a certain level of accuracy, as demonstrated by the values of the

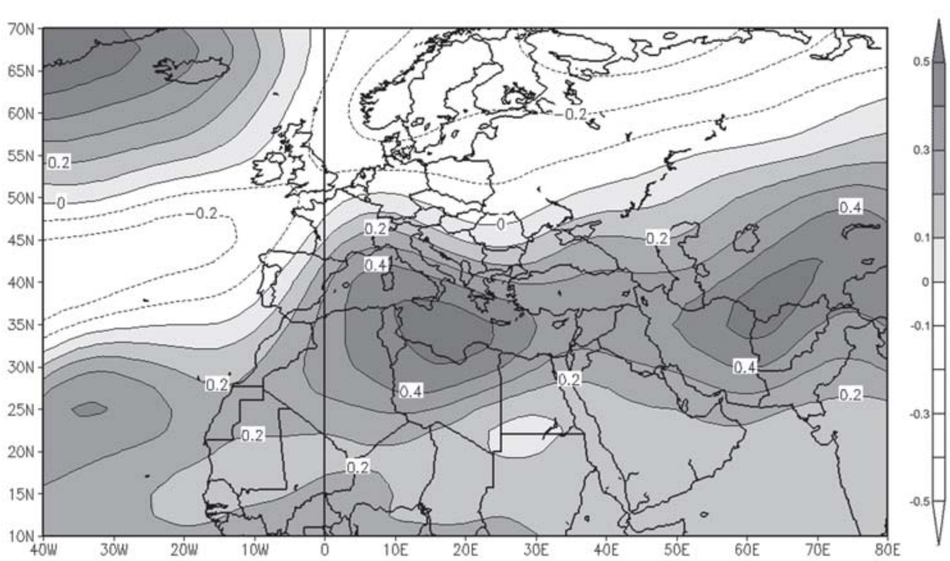

Figure 2 Correlation map between wine quality and 500 hPa geopotential height over the April to July (1970-2002). Contours represent correlation coefficient (grey tones indicate positive correlation). Map provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO (http://www.cdc.noaa.gov/).

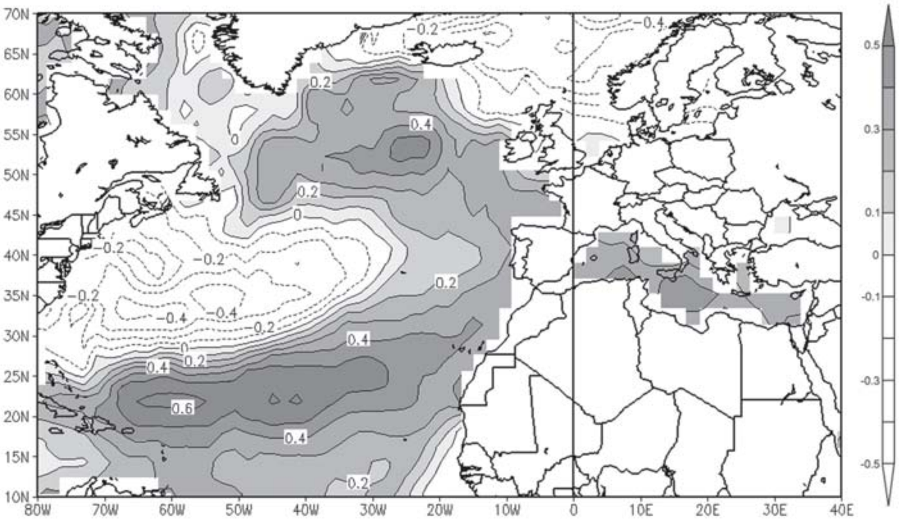

Figure 4 Correlation map between wine quality and sea surface temperature of May to June (1970–2002). Contours represent correlation coefficient (grey tones indicate positive correlation). Map provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO (http://www.cdc.noaa.gov/).

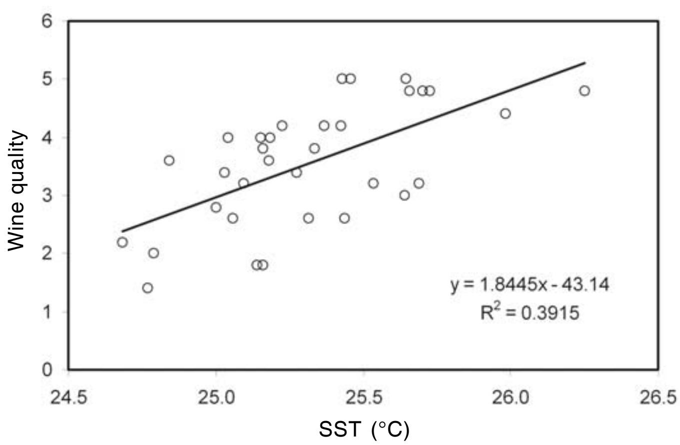

Figure 5 Rectilinear regression between wine quality and sea surface temperature over the Atlantic Ocean west of the Canary Islands for May to June (1970–2002). The determination coefficient (R^2) and regression equation are indicated in the graph.

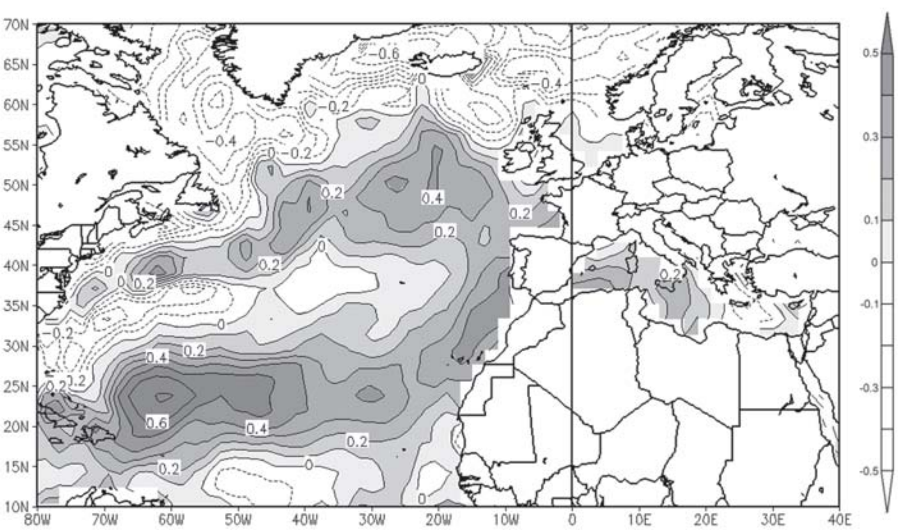

Figure 6 Correlation map between sea surface temperature for May to June and the air temperature for July to October over wine production area (1970–2002). Contours represent correlation coefficient (grey tones indicate positive correlation). Map provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, CO (http://www.cdc.noaa.gov/).

determination coefficients. A similar approach is also used in a type of seasonal weather forecast called "analogue forecast," where the state of the atmosphere and ocean at a specific location, in teleconnection with the climate of a widely separated region, is used as the starting point for forecasting the future atmospheric configuration on that region (Baldi et al. 2004). In our study the relationship between SST and wine quality can be attributed to the existence of a relationship between the SST over the Atlantic Ocean west of the Canary Islands and the climate over the wine production area (Figure 6).

Wine quality and meteorological indices: NAO and SOI. Wine-quality rankings were inversely correlated with the NAO index of several previous months (included in the growing season) and, in particular, the higher negative correlations were obtained on a monthly basis for April ($R^2 = 0.193$, $p < 0.05$) and May ($R^2 = 0.129$, $p < 0.05$) (Table 4). More significant results were obtained by developing regressions of wine quality versus NAO index aggregated on a multimonthly basis including April and May. The best result, for some selected aggregations, was obtained for the April to July period ($R^2 = 0.368$, $p = 0.0001$) (Figure 7), likely because the NAO index defines a specific atmospheric synoptical configuration over the Atlantic Ocean, affecting regional rainfall and air temperature.

Although El Niño Southern Oscillation (ENSO) plays a significant role in determining the interannual variability of climate in the lower latitudes, its influence on European climate is weak (Mathieu et al. 2004). No significant correlation was found between the wine quality and the SOI either on a monthly or a multimonthly basis (data not shown).

Conclusions

Analysis of large-scale meteorological information available on the Internet confirmed previously known relationships between wine quality and weather conditions, determined using data measured at field level. The possibility of using freely available meteoro-

Table 4 Correlation coefficient (r) between wine quality and monthly or multimonthly average NAO index. Statistical significance: $p \leq 0.05$ for $r \geq 0.344$; $p \leq 0.01$ for $r \geq 0.442$; $p \leq 0.001$ for $r \geq 0.546$.

Jan	Jan–Feb	Jan–Mar	Jan–Apr	Jan–May	Jan–Jun	Jan–Jul	Jan–Aug	Jan–Sep	Jan–Oct
-0.032	-0.089	-0.071	-0.268	-0.375	-0.422	-0.468	-0.477	-0.443	-0.404
Feb	Feb–Mar	Feb–Apr	Feb–May	Feb–Jun	Feb–Jul	Feb–Aug	Feb–Sep	Feb–Oct	
-0.105	-0.077	-0.329	-0.440	-0.500	-0.533	-0.542	-0.488	-0.451	
Mar	Mar–Apr	Mar–May	Mar–Jun	Mar–Jul	Mar–Aug	Mar–Sep	Mar–Oct		
0.000	-0.324	-0.467	-0.535	-0.563	-0.577	-0.512	-0.451		
Apr	Apr–May	Apr–Jun	Apr–Jul	Apr–Aug	Apr–Sep	Apr–Oct			
-0.439	-0.535	-0.601	-0.608	-0.607	-0.539	-0.487			
May	May–Jun	May–Jul	May–Aug	May–Sep	May–Oct				
-0.359	-0.428	-0.474	-0.459	-0.392	-0.327				
Jun	Jun–Jul	Jun–Aug	Jun–Sep	Jun–Oct					
-0.247	-0.363	-0.355	-0.295	-0.228					
Jul	Jul–Aug	Jul–Sep	Jul–Oct						
-0.345	-0.318	-0.232	-0.152						
Aug	Aug–Sep	Aug–Oct							
-0.182	-0.095	0.000							
Sep	Sep–Oct								
0.045	0.141								
Oct									
0.164									

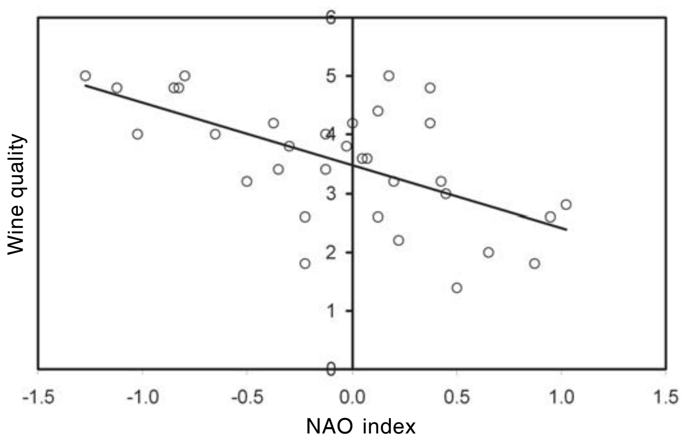

Figure 7 Rectilinear regression between wine quality and North Atlantic Oscillation index for April to July (1970–2002).

logical information may help winegrowers reduce weather-monitoring costs related to station installation and maintenance. However the low resolution of Internet meteorological information makes it difficult to create an operational system. Nevertheless, future development in the field of meteorology and information technology is likely, allowing freely available real-time information to be characterized by increased spatial and temporal resolution, which is more suitable to operational aims. In this context, our study represents a starting point to develop wine-quality forecast models for specific viticultural areas. Such information, together with seasonal forecasts, could support vine-management decisions concerning optimal wine quality.

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