Tirano (1624-1930): a long time series of harvest dates for grapevine

Tirano (1624-1930): una lunga serie storica di date di vendemmia

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Abstract

Since Middle Ages, the rulers of many territories of Europe defined grape harvest dates for a lot of motivations, sometimes producing quite long archives of dates. These data are useful for paleoclimatic reconstruction because the date of harvest is influenced by a set of climatic variables like temperature, precipitation, solar radiation and so on. More specifically, the main determinant of grape harvest date is the maximum air temperature of Spring – Summer period.

In this work, time series of grape harvest dates (1624-1930) for the Alpine area of Tirano - Valtellina (North Italy) were analyzed by means of a linear model approach to reconstruct maximum temperatures of Sondrio for the bimester May - June. Unavaible data were rebuilt by means of a correlation analysis between harvest dates of Burgundy and Tirano. The final product was represented by a time series of May - June temperatures for the whole period 1624-2003.

Some climatological evaluations were carried out; in particular homogeneous periods were defined and characterized adopting a statistical approach founded on a change point analysis.

Keywords: Proxy data, Climatology, Phenology, Temperature reconstruction

Riassunto

I governatori di molti territori europei, ad iniziare dal Medioevo, definirono le date di vendemmia per svariati motivi, producendo occasionalmente serie storiche di date piuttosto lunghe. Questi dati sono utili per la ricostruzione paleoclimatica in quanto la data di raccolta è influenzata da un insieme di variabili climatiche come temperatura, precipitazione, radiazione solare e così via. Più precisamente , il principale determinante delle date di vendemmia è la temperatura massima dell'aria nel periodo primavera-estate. In questo lavoro è stata analizzata la serie storica di date di vendemmia (1624-1930) per l'area Alpina di Tirano – Valtellina (Nord Italia) attraverso l'approccio con modello lineare al fine di ricostruire le temperature massime di Sondrio nel bimestre Maggio-Giugno. I dati di vendemmia non disponibili sono stati ricostruiti con l'utilizzo dell'analisi di correlazione tra le date di vendemmia della Borgogna e Tirano. Il prodotto finale è rappresentato da una serie storica delle temperature del bimestre Maggio-Giugno per l'intero periodo (1624-2003). Sono state effettuate anche delle valutazioni di tipo climatico; in particolare, sono stati individuati ed analizzati periodi omogenei adottando un approccio statistico fondato sull'analisi di discontinuità.

Parole chiave*: Proxy data, Climatologia, Fenologia, ricostruzione delle temperature*

Introduction

By a thermodynamic point of view, the climatic system can be seen as an almost intransitive turbulent system (Peixoto and Oort 1992) with many points of equilibrium (metastable phases) subject to abrupt transitions among them (Charney and De Vore 1979). Hence the climatic system resembles economic and social systems discussed by René Thom (1975) in his catastrophe theory which studies and classifies phenomena characterized by sudden shifts in behavior arising from small changes in circumstances.

Abrupt transitions, sometimes called "climatic changes" (Palmieri *et al.* 1992), are characterized by the following causal chain of abrupt changes: (i) a change in general circulation causing (ii) a change of frequency and persistence of weather types (e.g.: anticyclonic types, troughs, foehn, etc.) affecting the selected territory causing (iii) a change in meteorological variables (temperature, cloud coverage, precipitation, etc.) into the boundary layer. This latter can act on larger scales affecting meso and macroscale phenomena. The consequence of this circular causal chain is that the research of signatures of climatic change can be carried out at different scales and on different phenomena/variables.

The above-mentioned assumptions justify the need of methods to recognize abrupt transitions in time series of climatic data obtained from direct measurements or proxy data which are useful to describe climatic behavior during periods / places without quantitative meteorological measurements; a possible approach to change point detection is based on statistical methods for change point analysis, like the FT test (Todaro 1991), the Pettitt test

(Sneyers *et al.* 1993), EP and L methods (Lanzante 1996).

Italy is one of the first areas of the World monitored by meteorological instruments but, until the first half of the 19th century, observations were limited to some historical observatories like Milano-Brera and Padova, where data collection began in the half of the 18th century (Lamb 1972). This fact justify the relevance of biological and geophysical proxy data (tree rings, pollens, stalagmites, dates of the beginning of the spring grazing in Alpine pastures, phenological observations and so on) which can partially substitute the data gauged by meteorological instruments (Pfister 2003).

The use of proxy data is nowadays a popular way to reconstruct the climate of hundred or thousand of years ago. The most important problem given by this kind of information is the accuracy and resolution of data derived from proxies. For example, tree rings offer the possibility to jump into hundreds of years in the past and coral fossils to thousands of years ago, but with an often poor quality of temporal resolution in the final temperature data (NRC 2007).

Proxy data of phenological phases (beginning of harvest, in particular) were collected for European vineyards from the Middle Ages and are adopted since many years for the reconstruction of climate data of air temperature (Le Roy Ladurie 1967).

The use of the date of appearance of phenological phases as proxy of air temperature is founded on the evidence that each plant shows a sequence of phenological phases which is genetically pre-determined; moreover the relationship between temperature and phenological proxies is founded on the assumption that the speed of appearance of the different phenological phases ("biological time") can be properly approximated by the amount of thermal resources, the so called "thermal time".

In particular, the work of temperature reconstruction can be subdivided in three following steps (NRC 2007): (i) calibration, consisting in placing a temperature scale on the proxy data for a sufficiently long time period, which often involves the use of a linear regression technique (ii) validation, consisting in testing for an independent time period whether the empirical relationship derived in the preceding step has measurable skill, and quantitatively assessing its performance (e.g.: the linear regression coefficients derived from calibration are used to reconstruct the time series from the proxy data during this validation period, and the reconstructed temperatures are

compared with the corresponding instrumental temperature record), (iii) reconstruction of the whole time series of temperature from phenological time series by means of the validated model.

To correctly evaluate the meaning of proxy data for vineyards, physiology of grapevine can be considered; in particular the following reference thresholds describe the answer of grapevine to temperature:

- minimum (7 ÷ 10°C) and maximum cardinal (33 ÷ 36°C), defining the limits outside which the plant activity temporarily ceases, until temperatures come back into favorable boundaries;
- optimal cardinal (between 22 and 28°C) defining the upper and lower limits of optimality for plant activity;
- minimum (from -15 ÷ -18°C for plants well hardened until –2°C for plants during vegetative activity), and maximum critical thresholds (about +40°C, highly influenced by the presence of water stress) indicate the upper and lower temperature limits outside which plants experience permanent damages until death.

In many territories of Europe, grape harvest dates were defined by local rulers for a lot of motivations: to obtain wines of sufficient quality, to combat robberies etc. (Bonardi 2006). This produced the availability of quite long archives (Chuine *et al.* 2004; Le Roy Ladurie 1967; Defila 2001) of dates that are generally close to the full maturity of grapes (code 89 in phenological scale BBCH and 38 in the Eichorn and Lorenz one) (Lorenz *et al.* 1994) .

These data are useful for paleoclimatic reconstruction because the date of harvest is influenced by a set of climatic variables like temperature, precipitation, solar radiation and so on. In a general way it is possible to say that when water needs are satisfied, the main determinant of the date of harvest (harvest date) is the air tempera-

Fig. 1 – Map of vineyards adopted areas with main administrative limits and locations used in this analysis (see table 1).

Fig. 1 – Mappa delle aree viticole adottate comprensive di limiti amministrativi e sito di riferimento. (vedere tabella 1).

Tab. 1 – Meteorological and phenological data adopted for this work.
Tab. 1 – Dati meteorologici e fenologici adottati in questo lavoro.

Station	Viticultural area	Height (a.s.l.)	data	Period	notes
Tirano	Valtellina	449 m	Harvest date	1624 – 1930 (201/307 yr) 75%	Vine varieties: Nebbiolo Various discontinuities are present on this series. In particular the period 1901-1918 isn't available. Zoia, 2004
Sondrio	Valtellina	307 m	Air temperature	1901 – 1928 and 1951-2000	Ufficio Centrale Ecologia Agraria and Fondazione Fojanini
Bordeaux – Merignac	Haut Medoc	61 m	Air temperature	1951 - 2000	European Climate Assessment & Dataset (ECA&D) project.
Haut Medoc – Bordeaux	Haut Medoc	50 – 350 m	Harvest date	1752 - 2005	Vine varieties: Cabernet sauvignon and franc, Merlot (Chevet *et al.*, 2004)
Besancon	About 40 Km far from Burgundy	246 m	Air temperature	1951 - 2000	European Climate Assessment & Dataset (ECA&D) project.Climate Explorer
Burgundy	Burgundy	150 - 450 m	Harvest date	1624 - 2003	Vine varieties: Pinot noir Chuine *et al.*2005. NOAA/NGDC
Lugano	Swiss	273 m	Air Temperature	1864 - 2007	Meteoswiss

ture. If critical events (e.g. extreme frost or hail) are ignored, vineyard shows a "memory" of the past meteorological conditions that is usually limited to the ruling vegetative seasons (spring and summer that precede the harvest) and the effects of the previous year are generally limited to fruitfulness (number of bunches per shoot and number of flowers per bunch) and hence to the final production quantity (Bindi *et al.* 1996). So the grape harvesting dates were often adopted to estimate temperature of spring-summer season. For example Chuine *et al.* (2004) used this approach to reconstruct the climate of Bourgogne since 1370 with a good reliability and Chevet *et al.* (2006) carried out the same work for the vineyards of Haut-Médoc and for the period 1800-2005.

Data and methods

In this work, Nebbiolo grape harvesting dates in Tirano (Valtellina) were adopted. Valtellina has a long tradition of grape harvest dates defined by local rulers; these data are stored in public archives in Italy (e.g.: Archivio di Stato di Sondrio, Archivio Storico Municipale di Tirano and other Valtellina archives) or also in Switzerland (Chur archives) due to the fact that Valtellina was ruled by Grisons (Swiss) from 1512 to 1797. In these documents were published rules about grape harvesting and disposition on harvesting dates used for this work.

Table 1 shows Meteorological and phenological data adopted for this work; 1919-1928 is the only period with contemporaneous presence of grape harvest dates for Tirano, of air temperatures for a station close to it (Sondrio).

The grape harvest dates for Tirano used for this work were gathered and published by Zoia (2004) and are available from 1624 till 1930. Discontinuities present in this data-set are shown in table 1.

The following statistical analysis were applied to the abovementioned time series:

1. Regression analysis with least squared method to detect best linear models (LM) interpolating data, following a widely adopted framework of analysis of correlation between air temperatures and phenological data (Nordli *et al.* 2003)

2. Strucchange, a library of the R statistical software (R Development Core Team 2004) that implements methods for testing structural change in linear regression relationships, providing a unified framework for displaying information about structural changes and for assessing their significance according to various tests (Zeileis *et al.* 2002; Zeileis and Kleiber 2005). Strucchange library was created for economic purposes whereas some examples of adoption of this method for agroclimatic analysis are also available (Mariani 2006). In Strucchange library the recognition of homogeneous climatic phases is based on the analysis of mean and standard deviation. In particular each climatic phase is characterized by the steadiness of mean and standard deviation (Bai 1997).

Climatic features

Climate of viticultural areas considered for this work (Bordeaux, Burgundy, and Valtellina) is characterized by the mitigating effect of the Atlantic Ocean (Oceanic influence) that determines on the given areas a precipitation regime with winter minimum and summer maximum. Obviously the influence of Atlantic Ocean is progressively decreasing from Bordeaux (close to the Ocean) to Burgundy (showing a remarkable subcontinental influence due to the distance from the Ocean) until Valtellina (located in the core of the Alpine massif and strongly affected by the shield effect of the external ranges of the Alps).

The climate of Valtellina can be classified as an endoalpine climate, which most characteristic element is the relative scarcity of precipitations. Mean yearly temperature of the bottom of the valley is about 11-12°C,

Tab. 2 – Period 1919-1928 - analysis of correlation of harvest dates vs. maximum temperatures for specific months (the Pearson's parametric coefficient test was adopted).
***Tab. 2** – Periodo 1919-1928 – analisi di correlazione tra le date di vendemmia e le temperature massime per mesi specifici (E' stato adottato il coefficiente del test parametrico di Pearson).*

	Reference period				
	month	Bimester		quarter	
Apr	0.15	-0.761 **		-0.766 ***	
May	-0.749 **				
Jun	-0.653 *		-0.775 ***		-0.713 **
Jul	-0.181	-0.613			
Aug	0.333		0.177	0.120	
Sep	0.172	0.249			

*** sign 99% ** sign 95% * sign 90%

Tab. 3 – Period 1919-1928 - analysis of correlation of harvest dates vs. minimum temperatures for specific months (the Pearson's parametric coefficient test was adopted).
***Tab. 3** – Periodo 1919-1928 – analisi di correlazione tra le date di vendemmia e le temperature minime per mesi specifici (E' stato adottato il coefficiente del test parametrico di Pearson).*

	Reference period				
	month	Bimester		quarter	
Apr	0.017	0.000		0.000	
May	0.030				
Jun	0.022		0.055		0.001
Jul	0.011	0.000			
Aug	0.053		0.071	0.024	
Sep	0.001	0.021			

but this relative mildness is frustrated by the nighttime accumulation of cold air masses sliding downslopes. This phenomenon (cold lake effect) is typical of the cold period, from autumn to spring (Barry 1972) and gives a significant increase of the risk of frost in the bottom of the valley. In these conditions, cultivation of vineyard is carried out on the most thermally favored slopes, characterized by a southern exposition that guarantees a thermal gain of 1 / 2°C on the mean yearly temperature with respect to the bottom of the valley.
The Oceanic influence on the Alpine climate is highlighted by the immediate thermal answer of air temperature and crop phenology to the forcing effect given by the change of phase in North Atlantic Oscillation (NAO) observed during the '80s (Frei and Schar 1998; Chmielewski *et al.* 2004; Linderholm 2006).

Results and discussion
The steps followed for the reconstruction of summer temperatures of Sondrio (Valtellina) on the base of the dataset of Grape Harvest Dates for Tirano (GHDT) 1624-1930 are hereafter listed:
1. Reconstruction of Sondrio monthly averaged maximum temperature by multiple correlation with Lugano monthly averaged maximum temperature and sunshine duration for the period 1865 - 1900
2. Calibration by means of the analysis of linear correlation between GHDT and meteorological data of Sondrio and reconstructed from Lugano for the period (1865-1928) ..
3. Adoption of a suitable linear model (LM1) for the period 1866-1887.
4. Validation of LM1 on the reconstruction of Sondrio maximum temperature from GHDT for the period 1916-1926
5. Further validation of LM1 based on (i) the reconstruction of air temperatures of Bordeaux Merignac (Haut Medoc) applying LM1 to grape harvest dates collected by Chevet *et al.* (2006), (ii) the reconstruction of air temperatures of Besancon applying LM1 to grape harvest dates collected by Chuine *et al.* (2004).
6. Final run of LM1 on GHDT to reconstruct Sondrio temperatures
7. Discontinuity analysis on Burgundy data with recognition of homogeneous phases by means of Strucchange statistical library (R Development Core Team, 2004)
8. Reconstruction of grape harvest dates at Tirano for years without data, obtained analyzing the linear correlation between GHDT and Burgundy grape harvest date (Chuine *et al.* 2004) for the different homogeneous phases previously recognized, with definition of specific linear models ($LM_2 \dots LM_n$).
9. Production of the Final time series of temperatures for Valtellina (1624-2003) applying LM1 to GHDT.
10. Statistical analysis on final series carried out by means of Strucchange statistical library (R Development Core Team, 2004) to detect discontinuities.

Reconstruction of Sondrio temperatures
A multi-correlation model written in R language was adopted to reconstruct monthly average maximum temperature of Sondrio (May-June-July) 1865-1900 on the base of Lugano ones, provided by Meteoswiss.
The multi correlation takes into consideration the average maximum temperature and the mean daytime length of the month (in this situation the mean of May-June-July daytime length) .
The final equation adopted was the following:

$$x = y * 0.942916 + z * 0.007981 - 5.070801$$

where x is the average monthly maximum temperature of Sondrio, y is the average monthly maximum temperature of of Lugano, and z is the average monthly daytime length of Valtellina.

The significance level of the correlation are very high , > 0.998 , with a Multiple R^2 of: 0.9496.

Calibration and validation

The analysis of the correlation between Tirano grape harvest dates and Sondrio temperatures, partly reconstructed by multiple correlation from Lugano (period 1865-1900) and partly observed (period 1901-1930), was referred to maximum and minimum temperatures on different periods (months, bimesters and quarters). Results are resumed in table 2 and 3 and figures 2,3 and show that grape harvest dates are significantly correlated with maximum temperatures whereas the correlation is not significant with minimum ones. For maximum temperatures (table 2) the analysis referred to bimesters gives significant results for April–May and May-June (ii) analysis referred to three months periods gives better results for April – June and May-July and (iii) for single month analysis, significant results are obtained only for May and June.

Grape harvest dates are better correlated with temperatures of late spring – beginning of summer (months of May, June and July) because most of vegetation activities are subject to the Liebig minimum law, stating that each physiological process is determined only by the most limiting factor; in this specific case, the most limiting factor for phenological activities of grapevine is represented by the temperatures of May and June (Garnier 1955, Le Roy Ladurie 1967). On the contrary, during the central summer period (July, August) low temperatures aren't normally a significant limiting factor for phenological evolution, which is mainly determined by variables like solar radiation or water availability. This means that for example the earliness effect induced by a mild spring (or, vice-versa the delay induced by a cold one) is generally conserved for the whole cycle, until harvest. More precisely, the May and June thermal course affects the date of flowering. Grapevines is a species with a late flowering time, in Valtellina area, flowering ranges between the mid and the end of June. According to a recent phenological survey (Failla *et al*. 2004), the date of flowering has a direct phenological effect on the date of ripening. In fact the date of a phenological phase depends on the date of the previous phases and on the thermal course of the following period. As discussed before, in July and August generally the temperature are not a limiting factor for vine development. So the most limiting factor seems to be the May and June thermal courses and their effect on the date of flowering.

Furthermore it can be observed that grape harvest date for Valtellina is less sensitive to summer temperatures (period May-July) than France area considered in this work (Haut-Medoc, Burgundy) (Le Roy Ladurie and Baulant 1980). This phenomenon can be explained by the fact that summer in Valtellina is warmer than France

Tab. 4 – Average harvest date in Valtellina at present
Tab. 4 – Media attuale delle date di vendemmia in Valtellina

	Pinot noir	**Merlot / Cabernet**	**Nebbiolo**
Harvesting date	10 September	25 September*	15 October

(*)25 September represents the average grape harvesting date for Bordeaux bunch of red grapes (Merlot + Cabernet Sauvignon + Cabernet franc) considering that Merlot is earlier (20 September) and the two Cabernet are later (30 September)

Tab. 5 – Evaluation of statistical performance of reconstruction of average maximum temperatures of May – July for Sondrio in the period 1916-1926.
Tab. 5 – Valutazione delle performance statistiche nella ricostruzione delle temperature medie massime di Maggio-Luglio di Sondrio nel periodo 1916-1926.

Parameter	MAE	RMSE	EF	R2	Media Oss	Media Stime
Min	0.00	0.00	-inf.	-inf.		
Max	+inf.	+inf.	1.00	+inf.		
Best	0.00	0.00	1.00	1.00		
Calculated value	1.09	4.54	-0.02	0.61	26.40	25.47

Tab. 6 – Evaluation of statistical performance of reconstruction of average maximum temperatures of May – July for Bordeaux: comparison between measurements at Bordeaux Merignac airport and simulations carried out applying LM1 to harvest data collected by Chevet (2006). For the meaning of acronyms used for statistical indexes see appendix 1.
Tab. 6 – Valutazione delle performance statistiche di ricostruzione delle temperature medie massime di Maggio-Luglio di Bordeaux: comparazione tra le misurazioni all'aeroporto di Bordeaux Merignac e le simulazioni effettuate applicando LM1 alle date di vendemmia raccolte da Chevet (2006). Per il significato degli acronimi usati per gli indici statistici consultare l'appendice 1.

Parameter	MAE	RMSE	EF	R2	Media Oss	Media Stime
Min	0.00	0.00	-inf.	-inf.		
Max	+inf.	+inf.	1.00	+inf.		
Best	0.00	0.00	1.00	1.00		
Calculated value	1.28	5.98	-0.20	0.77	23.69	22.42

areas and, by consequence, limitation due to summer temperature is less relevant.

Finally the better correlation of grape harvest dates with maximum temperatures than for minimum ones is a result of the grapevine physiology and is corroborated by the particular weight to daily maximum temperatures given by some different empirical indexes (summation of maximum temperatures, index of light energy and
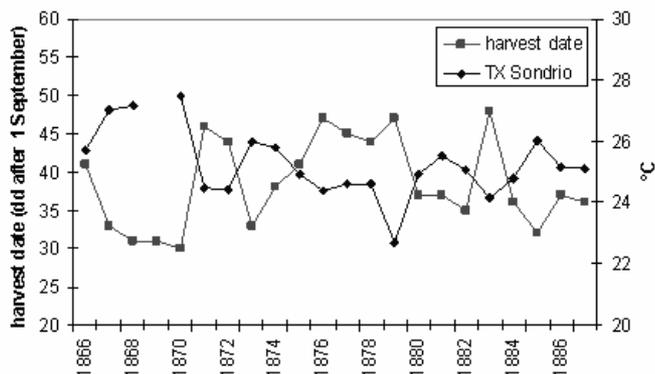
Fig. 2 – Temperatures of Sondrio and grape harvest dates of Tirano. The opposite correlation is evident.

Fig. 2 – Temperatura di Sondrio e date di vendemmia di Tirano. Risulta evidente la correlazione inversa..
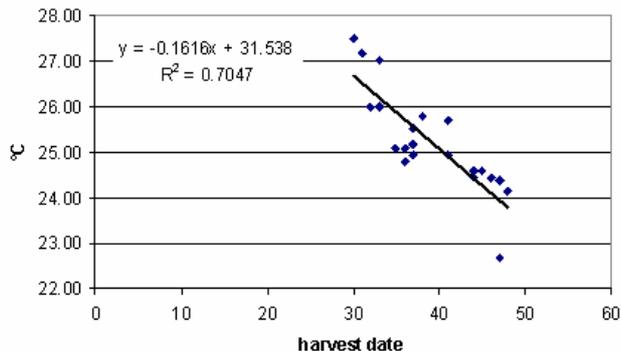

Fig. 3 - Scatterplot showing the linear model (straight line) interpolating harvest dates (x) and May-June – July mean maximum temperatures (y).

Fig. 3 – Grafico a dispersione che mostra il modello lineare (linea retta) interpolante le date di vendemmia (x) e media delle temperature massime del periodo Maggio-Giugno-Luglio.
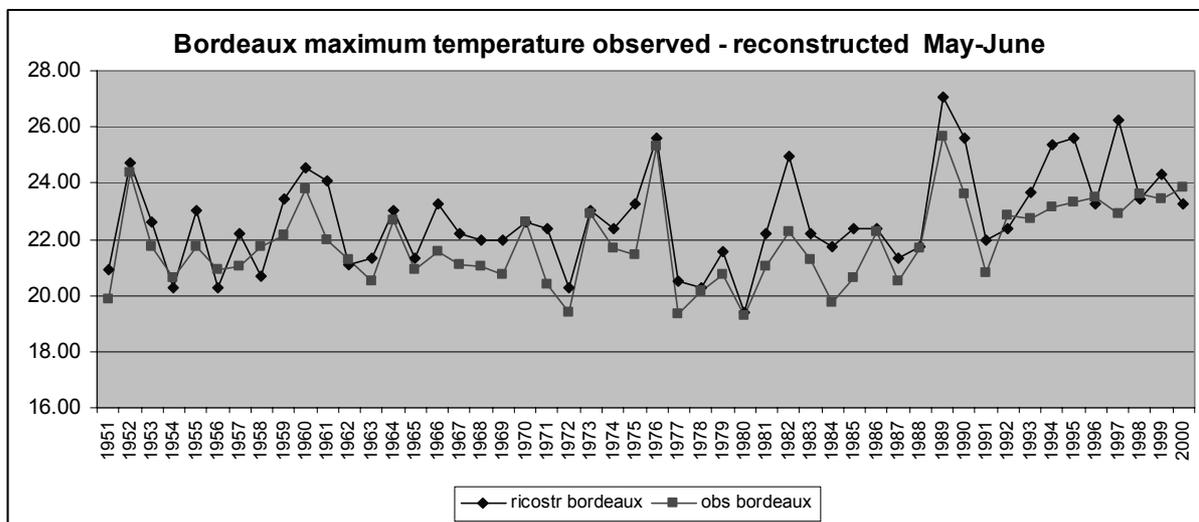

Fig. 4 – Average maximum temperatures of May – June for Bordeaux: comparison between measurements at Bordeaux Merignac airport and simulations carried out applying LM1 to harvest data collected by Chevet (2006)

Fig. 4 – Media delle temperature massime di Bordeaux periodo Maggio-Giugno; confronto tra le misure effettuate all'aeroporto di Bordeaux-Merignac e le simulazioni effettuate applicando il LM1 alle date di vendemmia raccolte da Chevet (2006).
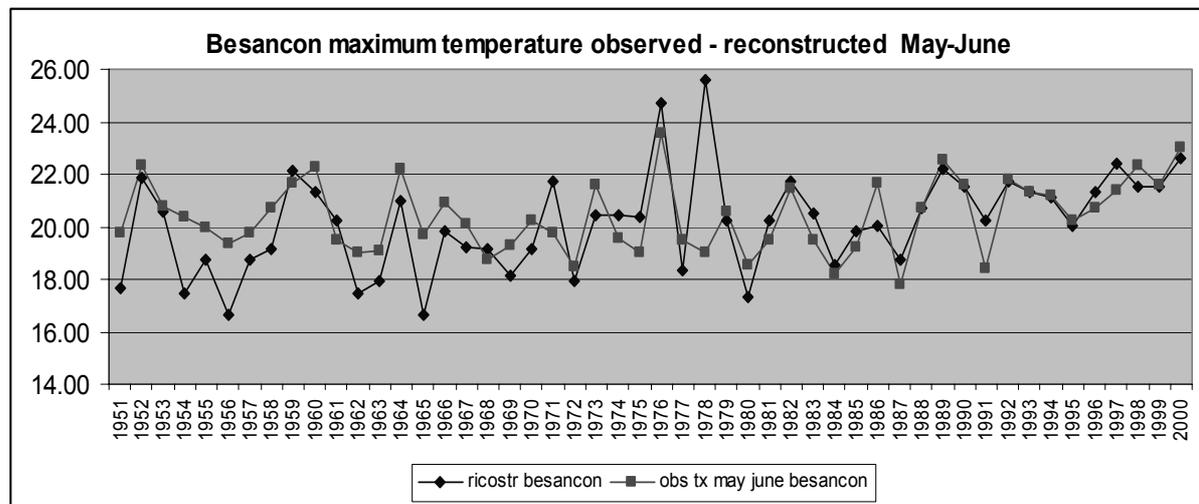

Fig. 5 – average maximum temperatures of May – June for Besancon: comparison between measurements at Besancon airport and simulations carried out applying LM1 to harvest data collected by Chuine *et al.* (2004)

Fig 5 – Media delle temperature massime di Besancon nel periodo Maggio-Giugno.; confronto tra le misure effettuate all'aeroporto di Besancon e le simulazioni effettuate applicando il LM1 alle date di vendemmia raccolte da Chuine et al. (2004).

Huglin's index) useful to define the attitude to viticulture (Fregoni 1985; Huglin 1986).

Thereafter grape harvest dates were adopted to reconstruct monthly maximum temperatures of the quarter May – June - July (Tx), adopting the correlation equation obtained for the period 1866-1887 (figure 3).

LM1: $y = -0.1616x + 31.538$ ($R^2 = 0.7047$)

Obviously, before the use of this equation on the whole time series of grapevine harvest, a validation on an independent data-set was carried out. The validation of this equation was performed evaluating the accuracy of the reconstruction on temperature of Sondrio measured in the period 1916-1926. Therefore an other validation was performed on two independent thermal time series of Besancon (1951-2000) and Bordeaux Merignac (1951-2000), respectively on the base of phenological data of Burgundy (Chuine *et al.* 2004) and Haute Medoc – Bordeaux (Chevet 2006). French phenological data were previously homogenized subtracting 35 days for Burgundy and 20 days for Bordeaux, in order to overcome the systematic error induced by the fact that Nebbiolo grape is a quite late variety, which harvest in Valtellina (table 4) happens 20 days after Cabernet sauvignon, Cabernet franc and Merlot (reference grape varieties for harvest time series of Bordeaux) and 35 days after Pinot noir (reference grape variety for harvest time series of Burgundy) (Fregoni 1985).

Residual systematic effects not considered during homogenization were probably originated by differences in training system, cultivation techniques or also by latitudinal and topoclimatic factors: French areas considered in this work have lower temperature than Sondrio during May-July and this affects the harvesting date in association with other factors as in particular solar radiation.

Results of validation test (diagrams in figures 4, 5, tables 5, 6) show that correlation and RMSE between temperatures obtained by model and temperatures measured are quite good. Moreover the performances of the empirical model during validation are better than calibration ones. This shows that the extension in space and time of the results of the empirical model is possible and that the model can be applied for areas and for time periods quite different from that for which it was produced.

Valtellina grape harvest dates reconstruction for years without data

The observation of the two series (Tirano and Burgundy) shows that the relative behavior isn't homogeneous. In particular Burgundy series show a change of phase in 1734 confirmed by the discontinuity analysis (figure 7) .

The discontinuity of 1734 is probably produced by a change of phase in Atlantic circulation and was also described by Bell that described the mildness of the climate before this discontinuity (Bell 1980) and by Pfister that note that "suddenly", from 1719 to 1729 the wine became exuberant, from which we should expect warm summers and early harvests (Pfister 1988). It's interesting to observe that, for the same period, warm summers are evident in Tirano time series too. Due to the presence of this discontinuity the correlation analysis between Ti-
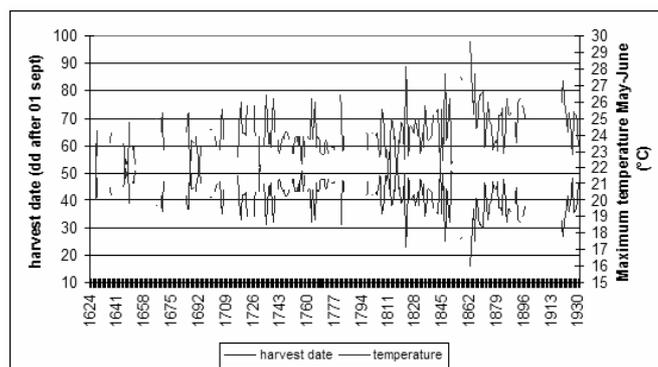
Fig. 6 - Temperature reconstruction for Valtellina (MAY- JUNE) from available harvest dates from Zoia (2004)
Fig. 6 *– Ricostruzione delle temperature (Maggio-Giugno) dalle date di vendemmia disponibili da Zoia (2004)*
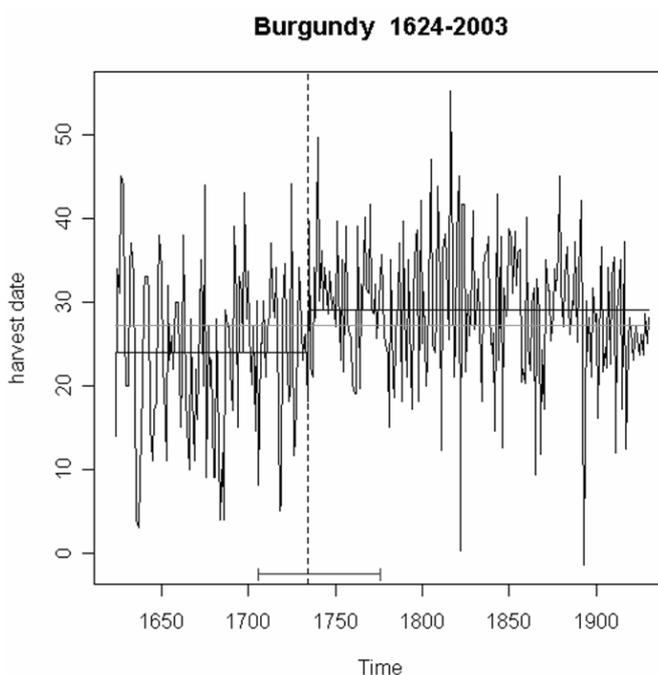
Fig. 7 - Diagram showing the result of the breakpoint analysis carried out on harvest data of Burgundy (Chuine, 2004). The most probable year of discontinuity is 1734 (vertical line) and with a confidence of 95% the discontinuity drops into the range 1706-1776 (horizontal range). The mean harvest date is 24 before the discontinuity and 29 after.
Fig. 7 – Diagramma che mostra i risultati dell'analisi di discontinuità effettuata sulle date di vendemmia della Borgogna (Chuine, 2004). L'anno più probabile in cui avviene la discontinuità è il 1734 (linea verticale)e cade con un limite di confidenza del 95% nel periodo 1706-1776 (linea orizzontale rossa). La data media di vendemmia prima della discontinuità è 24, dopo risulta 29 .

rano and Burgundy series was carried out on the two homogeneous phases (1624-1734 and 1735-2003) in order to create a linear model useful to rebuild unavailable Tirano harvest dates.

Resulting linear models are:
LM 2 (period 1624-1734) :
$$y = 0.2922x + 38.207 \ (R^2 = 0.2619)$$

LM 3 (period 1735-1930) :
$$y = 0.459x + 27.725 \ (R^2 = 0.3906)$$

The Final Dataset of Harvest Dates (FDHD) for Tirano (1624-2003) (figure 8) shows that the earliest harvest happened in 1862 (16 September), corresponding to an average maximum temperature on the reference period (May-June) of 29°C; on the contrary, during 1811 (the 2nd coldest summer of time series), grapes were harvested on 27th of October, corresponding to an average maximum temperature of 20.6°C.

The discontinuity analysis, carried out on Sondrio temperature reconstructed from FDHD, shows a main breakpoint in 1821 which represents the end of the central phase of Little Ice Age (LIA), delimiting two main subperiods :

(i) 1624 – 1821, characterized by a sequence of years with low summer temperatures (maximum values often below 22°C) and moderate interannual variability (average standard deviation 0.94 – table 5). In particular summers from 1624 to 1663 were quite cold, with average maximum temperature of about 23.1°C; thereafter until 1685 summers became suddenly warmer, while a progressive cooling happened till 1716, when an increase started till 1821, signed by sometimes strong fluctuations (e.g.: cold summer of 1816) enlightened by the increased standard deviation (1.05).

(ii) 1822 – 2003: these years started with the very hot 1822; then, until 1855, summers were characterized by very strong interannual variability that marks the ending of LIA (average temperature swings from 23°C to 28 °C in very short periods and standard deviation = 1.40).

Tab. 7 – Evaluation of statistical performance of reconstruction of average maximum temperatures of May – July for Besancon: comparison between measurements at Besancon airport and simulations carried out applying LM1 to harvest data collected by Chuine *et al.* (2004). For the meaning of acronyms used for statistical indexes see appendix 1.
**Tab. 7** – *Valutazione delle performance statistiche di ricostruzione delle temperature medie massime di Maggio-Luglio di Besancon: comparazione tra le misurazioni all'aeroporto di Besancon e le simulazioni effettuate applicando LM1 alle date di vendemmia raccolte da Chuine et al. (2004). Per il significato degli acronimi usati per gli indici statistici consultare l'appendice 1.*

Parameter	MAE	RMSE	EF	R2	Media Oss	Media Stime
Min	0.00	0.00	-inf.	-inf.		
Max	+inf.	+inf.	1.00	+inf.		
Best	0.00	0.00	1.00	1.00		
Calculated value	0.81	5.33	0.34	0.40	21.77	21.74

Tab. 8 – Average maximum temperature (May-June) and relative Standard deviation on reference periods.
Tab. 8 – *Media delle temperature massime (Maggio-Giugno) e relative deviazioni standard nei periodi di riferimento.*

Periods	Temp	Dev.st
1624/1663	23.08	0.87
1664/1685	23.85	0.82
1686/1716	23.29	0.89
1717/1821	23.84	1.05
1822/1855	24.27	1.40
1856/1924	25.07	1.32
1925/1972	24.30	0.79
1973/2003	25.05	0.91
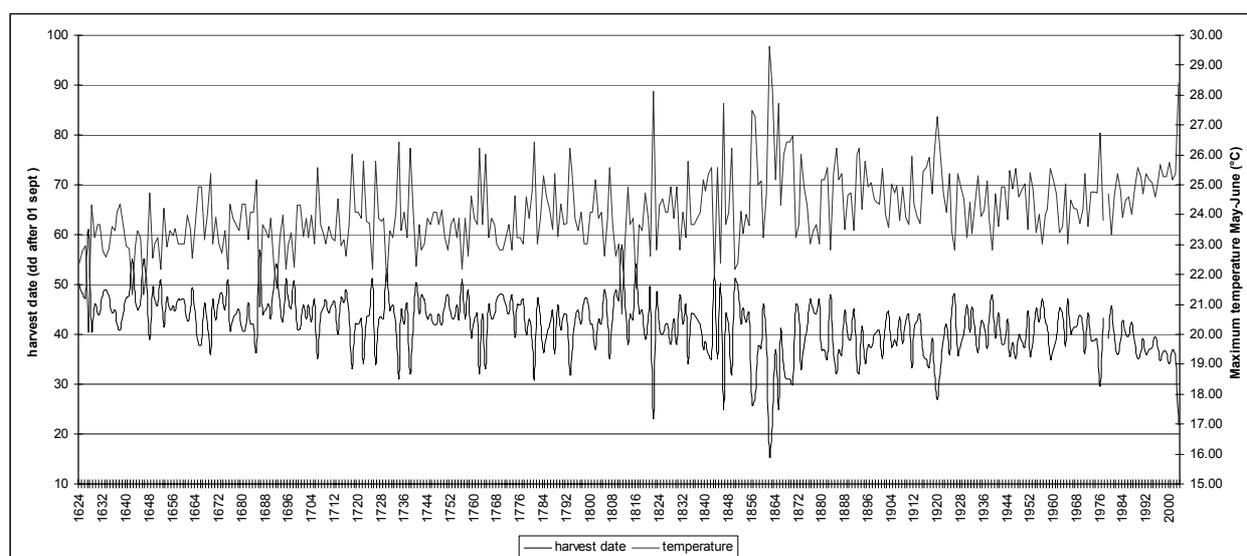
Fig. 8 - Reconstruction of harvest date of Tirano and May-June maximum temperatures for the whole period (1624 – 2003). The vertical dashed line shows the main breakpoint of the series occurred in 1822.
Fig. 8 – *Ricostruzione delle date di vendemmia di Tirano e temperature medie massime di Maggio-Giugno per l'intero periodo (1624-2003). La linea verticale tratteggiata mostra il principale punto di discontinuità avvenuto nel 1822.*

(Table 7) The quality of data for period 1855-1865 is significantly affected by the presence of a new plant disease, the powdery mildew – (Uncinula necator Schw.) – that after the appearance in France (1847) spread rapidly to the whole Europe giving severe damages to grapevine production (Angeli and Pertot 2007). Anticipated harvest dates could have been adopted in Valtellina in order to limit the damages of this phenomenon, which brought significant consequences on the climatic representativeness of harvest dates. This anomalous period was overcome by the introduction of sulfur based fungicides, representing a valid solution to the problem, restored the normal method of choice of the harvest dates.

From 1856 an abrupt increase in temperatures started, especially during 1861-1870, decade with temperatures warmer than 26°C, associated with a positive NAO phase (LeRoy Ladurie *et al.* 2006; Jones *et al.* 1997; Luterbacher 2002; Menzel 2003). This warmer phase lasted until 1924 and a successive cooler period followed until 1972, when started the present warm phase.

Conclusion

A summer temperature reconstruction time series since 1624 for Sondrio is now available thanks to grape harvest dates. This was possible also thanks to the fact that during the considered historical period, in Sondrio viticultural district, the most important cultivar remained the same, and specifically the Nebbiolo grape. So the harvest dates were for all time referred to the same cultivar. The method adopted for the correlation between harvest date and air temperature has been validated using two independent French time series relative to grape harvest and temperature of Bordeaux and Burgundy regions. From the statistical and climatological analysis of Sondrio temperature time series is evident that especially during 19th century the climate has encountered very different phases, probably associated with frequent changes of phase in atmospheric flows. The validation with French time series show also that the method here defined can be applied to European viticultural areas area with a significant oceanic influence (following Koeppen classification climates Cfb or transitionals climates between Cfb and Csa). This evaluation shows that these macroscale climate features of the abovementioned area are strictly correlated, due to the action of the same mix of macroscale climatic factors. From the phenological point of view, it was supported the recent conclusion that in the Valtellina viticultural model, which consists on a late ripening variety grown in an endoalpine climate, the date of harvest is mainly related to the flowering date, which in turn is related to the May and June maximum temperatures.

Acknowledgments

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Appendix 1 – Statistical indexes

P_i simulated value;
O_i observed value;
O observed value average;
n number of values examined.

Relative Root Mean Squared Error (RRMSE)

$$RRMSE = \sqrt{\frac{\sum_{i=1}^{n}(Pi-Oi)^2}{n}} \times \frac{100}{\overline{O}}$$

This index describe the difference between observed and simulated values. The result is divided for the average of observations. In this way an error relative measure can be retrieved. The optimal value for this index is zero.

Mean Absolute Error (MAE)

$$MAE = \frac{\sum_{i=1}^{n}|Pi-Oi|}{n}$$

The optimal value for this index is zero.

Modelling Efficiency (EF)

$$EF = \frac{\sum_{i=1}^{n}(o_i-\overline{o})^2 - \sum_{i=1}^{n}(s_i-o_i)^2}{\sum_{i=1}^{n}(o_i-\overline{o})^2}$$

If EF<0, the distance between simulated and observed

value $\sum_{i=1}^{n}(s_i-o_i)^2$ is higher than the distance between observed and simulated values and their average $\sum_{i=1}^{n}(o_i-\overline{o})^2$.
In this situation the observation average is the best estimator for the studied variable.
If EF>0, the estimated values are better than the average of observed values.

Coefficient of Residual Mass (CRM)

$$CRM = \frac{\sum_{i=1}^{n}O_i - \sum_{i=!}^{n}S_i}{\sum_{i=1}^{n}O_i}$$

A CRM value > 0 shows that the model underestimate the variable (O>S). A CRM negative value shows that the model overestimate the variable (O<S).