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ORIGINAL ARTICLE

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The influence of climatic variability on the quality of wine

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Abstract In this paper, the quality of the wine from the Dão (Viseu) region of Portugal is examined and relationships between wine quality and climatic variability are obtained using spectral and correlation analysis to determine the structure of the temporal variations. The spectra of the series of quality of wine values show statistically significant oscillations coherent with those found in the series of teleconnection indices. The series cover a period of 33 years. A significant correlation was obtained between wine quality and minimum air temperature in May, December and total precipitation in April. The teleconnection circulation indices are used to provide some physical insight into the most significant oscillating components of the climatic and the wine quality series. We found significant and positive correlations between the quality of the wine and the Southern Oscillation Index (SOI) of August and negative with the SOI of January and with the North Atlantic Oscillation of April. Wine quality and climatic series can be predicted using statistical models depending on significant oscillations.

Introduction

The variability of the weather and of the climate plays a crucial role in determining the productivity of the agricultural crops, cattle raising and forestry. Fernandez and Parejo (1984) reported that the yields of the crops vary with the quantity and periodicity of precipitation and other meteorological conditions.

In the FAO conference in 1977 in Rome (session 19) Fernandez and Parejo (1984) stated explicitly the importance of the variability of the weather and of the climate on agricultural production and planning. At the time, all of the member states were urged to make complete use of all of the available information and meteorological services in their planning and operations.

Fuentes (1983) has stated that the meteorological information relating to agriculture should be translated into terms that will allow the farmer to make the most convenient decisions about work that depends heavily on atmospheric conditions. It would be helpful if the forecaster had, besides general meteorological knowledge, a range of information on the most important crops of the different regions to which the forecast refers.

Long-term climate variability in the past is important for predicting both the future climate and any human impact on climate, and teleconnections help to reveal the interactions between the components of the climate system (Benner 1999).

The most important predictions affecting agriculture relate to the sowing or planting season, treatment against pest and illnesses in plants, forecasting of freezes, and harvesting and storing crops. Such predictions allow farmers to take the right measures during harvest.

The objectives of this work were the following:

1. To investigate the temporary variability of climatic series in the Dão region in order to find what are the causes of this variability and the regional characteristics.
2. To find a relationship between these climatic series and the quality of the wine in order to explain what makes productivity and quality different from other areas of Portugal.
3. To obtain a model forecasting the climatic series and the effects on the quality of the wine, enabling predictions to be made that will help the farmers prepare for possible events. The model is made up of two parts, a deterministic part (associated with significant oscillations), which takes account of most of the variance of the series, and a probabilistic part since the series are already stochastic. It is an autoregressive model. We have attempted to justify the results of these temporal studies in the light of the different oscillations and patterns of circulation that affect the region and influence the behaviour of these series and are characterized by the teleconnective indices.

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Background to Viniculture in the Dão Region

The Beira region extends over a large area where there are 129 090 wine growers cultivating approximately 60 888 ha of vines, i.e, about 22% of Portugal's vineyards. Within the Beiras region, given the diversity of soils, climate and wine, the division is as follows: Beiras (Norte, Nordeste and Interior), Beira Alta and Beira Litoral. Beira Alta is located in north-central Portugal in a mountainous recess surrounded by Serras do Caramulo and Buçaco in the west and south-west and the imposing Serras das Nave and Estrela in the east and south-east, forming an important barrier to the humid air masses from the coastal and the continental winds. The delimited area is Dão. Vines grow here at an altitude of 400–500 m in otherwise poor granite soils, and schistose land towards the south. Vines from Dão, cover 2×10^4 ha (200 km^2), and produce a wine of international renown.

The Dão wine is considered one of the best in Portugal and these edapho-climatic conditions in the region do not occur in other parts of the country. This wine is the product of the vine, the environment and man's perseverance. The relationship between wine and man adapting to circumstances, through the selection of varieties of grape and the development of growing techniques, helped to create this famous wine region.

Of the total wine production for 1 year, around 80% is red wine and the rest white. The red wines are full with a ruby colour, delicate flavours and a fine bouquet; they soften and gain complexity with age. The white wines are light and fresh with soft fruity aromas and flavours.

The white varieties are Barcelo, Bical, Encruzado, Malvasia Fina, Rabo de Ovelha, Terrantez, Uva Cão and Verdelho; the red are Alfrocheiro Preto, Alvarelhão, Aragonês, Bastardo, Jaen, Tinto Cão, Touriga Nacional and Trincadeira Preta.

The most important component in the wine, besides water, is alcohol, which results from the fermentation of the sugars in the grape. Not all of the sugars are broken down, fructose and glucose remaining as a residue. The most important alcohol is glycerol, which reaches a concentration of 10–12 g/l and gives the Dão wine its smoothness.

Factors in wine production are natural (soil, climate, grape varieties) and technical, which depend on the farmer's decisions.

Climate plays an important role in the quality of wine. Esteves (1997) states that the colour of wine is very sensitive to temperature, so that very high or low temperatures hinder the formation of pigments in the grape. Furthermore, if the air temperature decreases there is an increase in the amount of malic acid in the grape.

The effect of temperature is significant throughout the lifetime of the vineyard and is responsible for fluctuations in the dormancy and budding stages (Esteves 1997). Owing to the influence of solar radiation and air temperature, the growth of the vine is faster during the budding stage. A good harvest and high quality require certain conditions, namely, regular latent heat and solar radiation throughout the active lifetime of the plant, a good water reserve, good drainage, and reasonable water retention in the soil.

Each grape variety has its own characteristics that manifest themselves differently according to the climate, the soil and the techniques of viticulture used. The wine is classified on the basis of laboratory tests and tasting by the Wine Tasters Chamber.

There is special committee to credit and promote the Dão wines – the Regional Federation of the Viticulturists of the Dão Region (CVRD–FVD), and they assign one of four different grades to the wine: average = 1; good = 2; very good = 3; excellent = 4, through the Tasters Chamber and the Wine and Vineyard Institute.

In recent years the production of Dão wine has been: 1994/1995 25.4 Ml, 1995/1996 18.0 Ml, 1996/1997 50.9 Ml, 1997/1998 26.1 Ml.

The climate of the Dão Region

Viseu (Portugal) is situated at an altitude of 443.0 m, 40° 40' N and 7° 51'W. In a study carried out by Gonçalves (1985), 7940 daily weather bulletins were analysed and the various types of predominant air masses were identified. Disturbances due to the passage of the polar front in a location near Viseu were also analysed.

The identification of the air mass was based on thermal characteristics, the trajectory travelled to the region, the type of weather that was associated with it and the values of potential pseudo-temperature values of the wet thermometer (85 kPa in the 12.00 a.m. survey in Lisbon). The upper limit of the potential pseudo-temperature of the wet thermometer for identifying of the cold mass of polar air was 8°C. As a result it was found that the warm marine mass of polar air occurs all year, but is more frequent in spring (42.8%) and in the winter (37.0%). Rainfall occurs under the influence of the cold section of the depressions, and more continuous rain when it approaches the front. The presence of this mass of air is usually associated with a high zonal index. The Figure 1 shows the geographic location of the Dão area in the interior of Portugal.

The average wind speed is 5 km h^{-1}, recorded at the boundaries of the submaritime region defined by Font (1983) where the main characteristics are, for example, heterogeneity, specially of relief, and the continental rise from West to East.

According to Köppen's classification, the region belongs to group Csb (temperate, with dry summer, which is not very hot but extensive), while Thornthwaite's rational classification describes it as B_3B_2' sa', humid, mesothermic with hot summers and moderate shortage of water; thermopluviometric level: 1.1% – humid area; humidity: 93.2% – humid area; aridity: 25% – moderate shortage of water in summer (s); hydric index: 78% – humid (B_3); thermal efficiency index: 718 mm evapotranspiration (EP) – mesothermic B'_2; thermal efficiency summer concentration index: 17% (above 20% = typically continental).

The analysis of the precipitation levels is of utmost importance for climatology and its applications. Along

Fig. 1 The location of the Dão region on the Iberian Peninsula and the sub-regions

with air, water is the most essential requirement of mankind. It is indeed the fuel of life. The lack of water can affect prosperity, cause a drop in civilization and even bring about the disappearance of entire cultures (Peixoto 1972; Peixoto and Oort 1992).

One important factor is the variabilityof the climate over distance structure in both space and time. An understanding of this is an important tool for analysis and its application to agriculture, and research focuses on the climatic effects that make a certain farming product particular to a certain region and how they can contribute towards greater quality and abundance. Spectral analysis is based on the technique of Fourier analysis, Mass and Schneider (1977) have applied these techniques to meteorology.

Recently many authors have related time series to the teleconnection indices. Ulbrich et al (1999) found a significant relationship between the precipitation in Portugal and the North Atlantic Oscillation the (NAO) index. Rodriguez-Puebla et al. (1998) found a significant correlation between annual precipitation in the Iberian Peninsula and several indices. Here propose statistical and empirical models, based on the oscillating components, for precipitation, for minimum temperatures, and for the quality of the wine. The model reflects the main causes for variation in precipitation over time, taking account of the highly random character of this variable.

Dates and methods

We sought to use climate series of the period between 1949 and 1994 for this study. In order to align the study with the characteristics of the wine, the farming year was used, i.e. from September to October of the following year, covering both the vegetative and reproductive cycles of the vine. The vegetative cycle comprises the hibernation and growth of the vine and the reproductive cycle refers to the development of reproductive organs and maturation.

The climatic series analysed were the following: the minimum and maximum air temperatures, measured monthly; the numbers of hours of sun in each month; the monthly mean relative humidity; the monthly accumulated precipitation; and the mean wind speed from January 1949 to December 1994. This study was carried out to investigate variability overtime and to find the causes of these variations in order to analyse the influences that these series could have on the wine of the region. In order to find a relationship between the climatic series and the quality of the wine, we had to reduce the number of the years of the climatic series to the period 1960–1992.

Whenever there were missing data in the series we proceeded in the following way: First, the corresponding monthly mean was substituted for the missing values; second, a correlation matrix was computed among the time series in order to select four surrounding series with characteristics that most closely resembled those of the station with missing data; third, a linear spatial regression was derived to interpolate the missing values. This method is similar to the one used by Rodriguez-Puebla et al. (1998).

When analysed the correlation between the climatic monthly series and the seasonal series and the quality of the wine, we found little significance for some of the individual series. Regression showed a greater correlation with the quality of the wine (r=0.60) for the following climatic series:

The monthly accumulated precipitation in April
Minimum, maximum and mean air temperatures
The wine quality.

From among these we found a relationship between the quality of the wine and the minimum air temperatures of May and December and the precipitation in April. So only these three series have been taken into account in this paper.

Figure 2 shows that the moderate temperatures in the Viseau region are due to the Atlantic influence and abundant precipitation in relation to the rest of Portugal.

The minimum air temperature increases progressively from 1.8°C in January to 13.1°C in July, when it starts decreasing again. However, it is in February that the lowest absolute temperatures are registered. There is less deviation in minimum temperature in May than in December.

The highest precipitation occurs in February reduces progressively until July and reaches a second high peak in November. Throughout the year, precipitation varies from 83 mm in summer to 467 mm in winter, with two very similar transition periods, in spring and in autumn, of 310 mm and 336 mm respectively. There is a tendency towards less precipitation in springtime, while during the other seasons, it remains steady.

Missing observations were replaced with the values obtained from the data for the same date, from observatories close to the given one specified.

Several correlation tests were carried out to find the climatic series that were related to the quality of the wine, and we found that these were the minimum temperatures in December and May and the precipitation in April (correlation coefficient, r=0.656).

There is a significant correlation between the quality of the wine and each of the following series:

Minimum temperature in December
Minimum temperature in May
Precipitation in April.

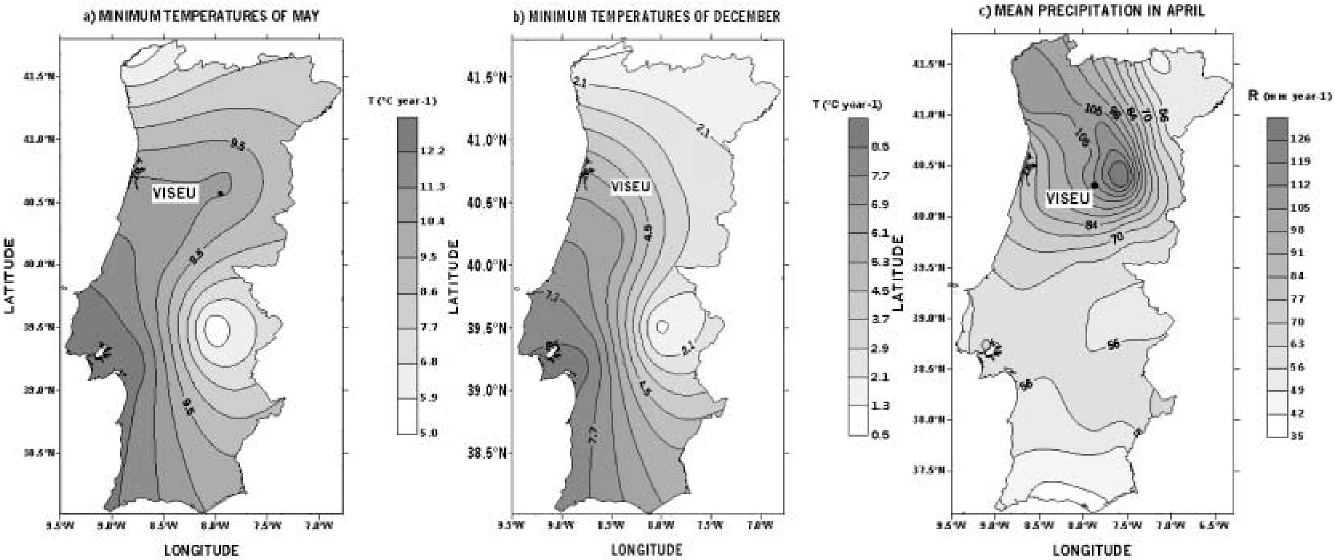


Fig. 2. a Thermal gradient of the minimum temperatures in Portugal in May; **b** thermal gradient of the minimum temperatures in Portugal in December; **c** regional variation of the precipitation during the month of April in Portugal

We therefore carried out a multiple regression of the wine quality against these three series, obtainig a linear multiple regression coefficient of 0.62.

This value was studied and its statistical analysis is presented in Table 1. From this table we can conclude that the coefficient of variation for the minimum temperatures in May is not very high; i.e. the temperatures in May do not change drastically from one year to the next. However, this does not happen with the minimum temperatures in December or the precipitation in April since the coefficient changes much more.

The values for skewness and kurtosis show that, for the temperatures, these are both random, neither value being very significant. However, this is far from the case with precipitation, since it has significant values for asymmetry and kurtosis. Most of the time series can be considered as mesokurtic because the kurtosis results (almost everything) fall between the corresponding critical values (–1.081 and 1.549) (Ardanuy and Soldevilla (1997).

The persistence values are meaningful only for the minimum temperatures in May, which means that these series probably have a meaningful autoregressive component as can be seen in Table 2.

Only the trends of the minimum air temperatures in December are significant, and these temperatures are increasing. Positive tendencies in the minimum temperatures have been found recently by authors such as Jáuregui and Luyanddo (1999) in México. The methodology used to establish the bases of the statistical pattern may be summarized as follows:

First, we did a statistical study of the series to investigate the normal behaviour of the data. Second, we analysed the tendency and persistence of each of the series to observe whether they showed any significance, using the Mann-Kendall test to interpret the variations. Third we carried out a spectral analysis, using the Fourier transformation, and fourth, we performed multiple linear-regression analysis.

Finally, with all the information, we obtain the pattern for detecting a probable situation for the following years.

Results

Spectral variability

The series variability was obtained by spectral analysis of the minimum air temperatures in December and May, the precipitation in April and the wine quality, so that the factors influencing wine quality could be detected. All of

Table 1 Statistical series studied. *CV* coefficient of variation, *Sk* skewness, *KT* kurtosis, r_1 autocorrelation coefficient, τ Mann – Kendall statistical coefficient

Parameter	M	CV	Sk	KT	r_1	τ
Minimum temperature May	8.3°C	14	–0.06	–0.87	0.43	–0.03
Minimum temperature December	3.1°C	71	0.22	–0.38	0.09	0.29
Precipitation April	99.3mm	78	1.34	1.95	–0.23	0.11

Table 2 Percentage of variance explained by the significant oscillations and the autoregressive function (*AR*) of teleconnections indices and climatic series. *SOI* Southern Oscillation Index, *NAO* North Atlantic Oscillation

Series	Variance explained (%)				
	2–3 years	3–4 years	4–7 years	≥16 years	AR
SOI January	36.2		25.4		
SOI August	**28.7**	15.5	16		6.2
NAO April	**32.8**		12.7	6.2	
Minima temperature of May	7.5		12.8	**16.3**	
Minimum temperature of December	11.8	9.9	17.3	**20.3**	7.2
Precipitation of April	**46.2**		11.8		3.8
Wine of quality	25.0		**31.3**		

the series were homogenized (anomaly divided by standard deviation). We have used the Blackman and Tukey procedure to find the spectrum, which is based on the Fourier transform of the serial correlation coefficients and smoothed with an appropriate bandwidth to derive a consistent estimate of the spectrum. The Markov red-noise spectrum (Mitchell et al. 1966) was used as a test of statistical significance of the peaks.

To investigate the seasonal variations and to find statistically significant and consistent periodicity, and we related them to the physical causes. We thus obtained spectra for the series, together with the levels of significance and spectral population. Figure 3a, c, e, g shows the residual spectrum, resulting from the elimination of the deterministic part from the series (note – this residual series remains under the population spectrum). In this way we obtained empirical-statistical models based on the history of the climate.

Figure 3b, d, f, h represents the observed and estimated series that are the result of data adjustment to mathematical functions representative of the variations or significant fluctuations.

Figure 3a represents the spectrum of minimum air temperatures in May, showing a low-frequency peak that indicates a strong tendency and also significant peaks for periods of 2.5 and 4.6 years; their known variance is 7.5% and 7.3% respectively.

In Fig. 3b the estimated and observed series of minimum air temperatures in May are shown with a correlation coefficient r=0.852.

In Fig. 3c the spectrum of minimum air temperatures in December shows a strong tendency and significant periods of 5.3 years and for 2.6 years with a known variance of 17.3% and 11.8%.

Figure 3d shows the observed and estimated series of minimum temperatures in December with r=0.853. This series has a significant autoregressive part with a known variance of 7.2%.

The precipitation spectrum for April (Fig. 3e) has significant peaks for 2.5, 2.7 and 5.3 years. These had previously been recorded by Corte-Real et al. (1998), and the known variance is 21.6% for the 2.5-year peak. The series has a significant autoregressive part, for which the correlation coefficient between the observed and estimated series rises to 0.786 (Fig. 3f).

The spectrum of the quality of the wine (Fig. 3g) shows significant peaks of variance for 4.6, 5.3, 2.5, and 2.7 years: 17.3%, 14%, 12.9% and 12.1% respectively. In Fig. 3h the observed and estimated series do not have a significant autoregressive part, the correlation coefficient being 0.750.

We thus obtained empirical-statistical models based on climate history.

In Table 2 shows that all of the series present significant oscillations of between 2–3 years and 4–7 years with a fair amount of variance. The precipitation in April, the minimum temperature in December and the Southern Oscillation Index (SOI) in August demonstrate autoregression, which means that these series have a stochastic part.

In Fig. 3, peaks of between 2 and 5.3 years are significant in all of the series. This means that these oscillations may be considered as signs of the wine quality and of climatic elements that affect it. The 4.6-year series depicts the quality of the wine.

On the basis of these significant peaks we built the deterministic model. The precipitation series needed an autorregressive correlation.

The correlation coefficients of the observed and modelled time series are depicted in Fig 3b, d, f, h. The series present autoregression, as indicated in Table 2, as well as the percentage of the variances explained by the autoregressive model. The correlation coefficient of the temperature series is greater as a result of the modelling of the trend component.

Corte-Real et al. (1998) and Rodriguez-Puebla et al. (1998) have also detected these oscillations of 2.5 and 2.6 years in Portugal.

The 5.3-year oscillation may correspond to half a solar cycle and is seen in the April and December spectra in Fig. 3.

Teleconnection index

We investigated the behaviour of the circulation and the variability of the planetary waves over time at high level (70–50 kPa), which is important because it is strongly coupled with short-term climatic fluctuations on the surface, which affecting them directly.

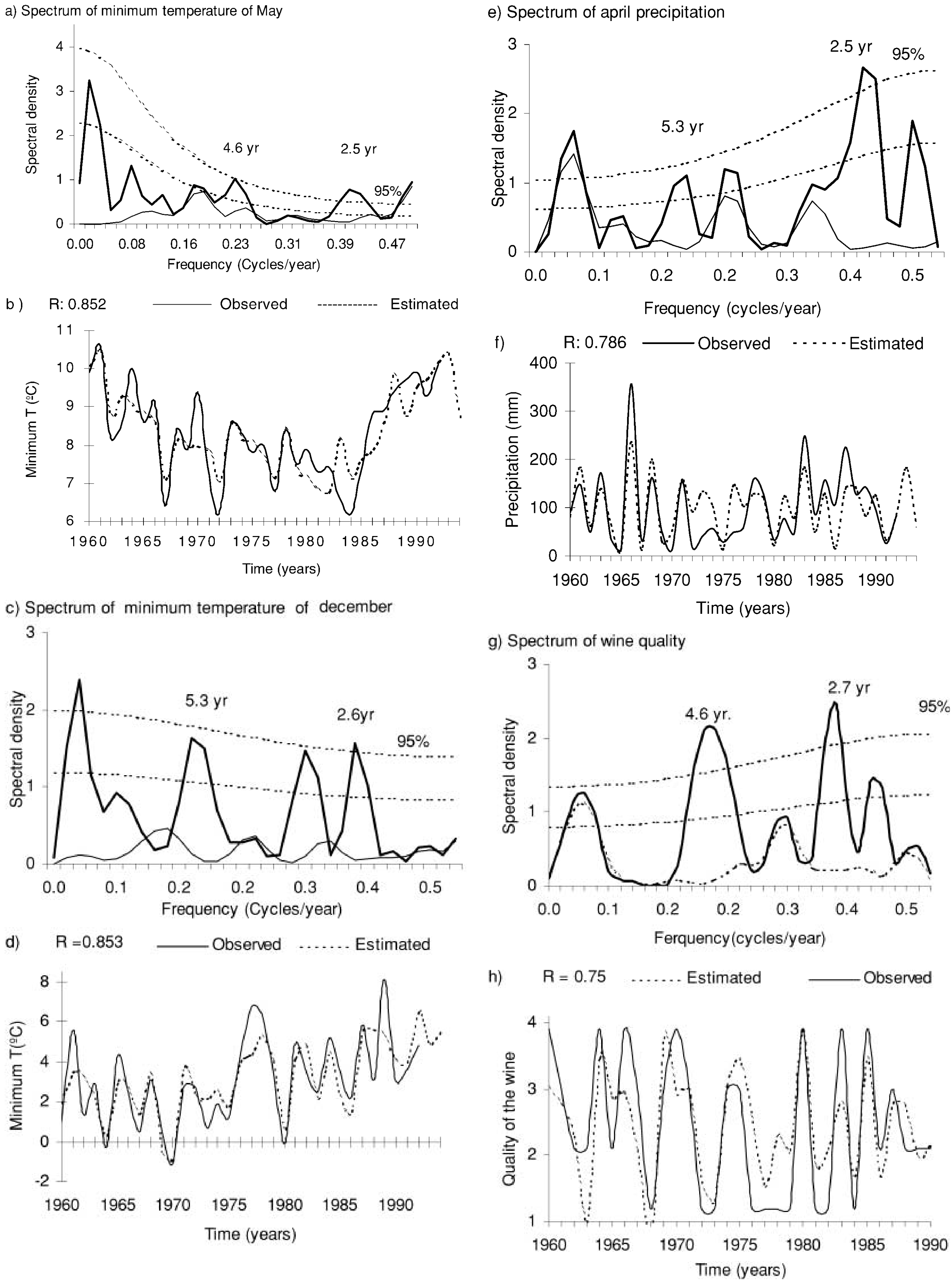
The teleconnection relationships are obtained by calculating the correlation matrix R, whose elements are the correlation coefficients r_{ij} between the time series of the variable of interest in point i of the grid with the time series in the point j. Column i provides the correlation pattern for point i and represents how point i of the grid is related to its neighbour.

This teleconnection study is strongly related to the climatic series that we are considering here; the patterns present quasi-periodic behaviour, its variability is concentrated in different known inter-annual frequency bands, (for example 2–3 years or 4–6 years for El Niño and Southern oscillation (ENSO). These oscillations are detected from many other series all over the world, and may be related to the quasi-biennial oscillation and ENSO (Burroughs 1992).

These bands are identified in the spectral analysis of the global data that characterise the phenomenon and are responsible for the quasi-periodic behaviour of the climatic variables and the quality of the wine.

Rodriguez-Puebla et al. (1998) found a heterogeneous correlation pattern between the April East-Atlantic pattern and annual precipitation and the pattern constituted by the first rotated empirical orthogonal function (EOF) of annual precipitation over the Iberian Peninsula. The region that we considered in this paper is included in this significant pattern.

The East-Atlantic pattern consists of the north–south dipole that spans the entire North Atlantic Ocean with centres near 55°N, 20–35°W and 25–35°N 0–10°W.


a) Spectrum of minimum temperature of May
Spectral density
4.6 yr
2.5 yr
95%
Frequency (Cycles/year)
b) R: 0.852 Observed Estimated
Minimum T (ºC)
Time (years)
c) Spectrum of minimum temperature of december
Spectral density
5.3 yr
2.6yr
95%
Frequency (Cycles/year)
d) R =0.853 Observed Estimated
Minimum T(ºC)
Time (years)
e) Spectrum of april precipitation
Spectral density
2.5 yr
95%
5.3 yr
Frequency (cycles/year)
f) R: 0.786 Observed Estimated
Precipitation (mm)
Time (years)
g) Spectrum of wine quality
Spectral density
2.7 yr
4.6 yr.
95%
Ferquency(cycles/year)
h) R = 0.75 Estimated Observed
Quality of the wine
Time (years)

Corte-Real et al. (1998) related the large-scale pressure at sea level to monthly rainfall in Portugal.

We have tried to explain the significant oscillations by finding associations with the teleconnection indices NAO and SOI, the aim being to find a connection between the minimum air temperature in May and December, the precipitation in April and wine quality and the following correlations were observed:

- Minimum temperatures in December and the SOI in August, r=–0.453
- Precipitation in April and the NAO in April, r=–0.40
- Quality of the wine and the SOI in August, r=0.40
- SOI in August and the minimum temperature in May, r=0.405.

Several authors applied these teleconnection indices on the Iberian Peninsula, for example Rodo et al. (1997) have identified a significant influence of El Niño for the spring precipitation at Easter on the Iberien Peninsula.Other authors, like Zorita et al. (1992, 1995), found a significant relationship between the rainfall and other atmospheric and oceanic indices, which can be used for down-scaling.

The most significant oscillations of time series for the teleconnection indices that were significantly coherent with the climatic series observed, were filtered by fitting the data to five harmonic functions and estimating the amplitude and phase using SYSTAT 5.0 software. The residual series was fitted to an autoregressive model and found to be significant, and a bivariate Fourier cross-spectrum was used to demonstrate a squared coherence.

Figure 4 shows the spectra of the series corresponding with: (a) the SOI in January, (b) the SOI in August, (c) the NAO in April.

We found an oscillation of 4.6 years corresponding to SOI, explaining 25% of the variance in January and 16% in August, and an oscillation of 5.3 years corresponding to NAO, explaining 9% of the variancein April; the latter had a significant variance of 8.4% in the stochastic part of the autoregression.

In the spectra of Fig. 4 the wine quality show oscillations of 4.6 and 2.7 years with a squared coherence of 0.469 and 0.554 with SOI in January and 2.5 and 6.4 years with a squared coherence of 0.728 and 0.624 with SOI in August. The minimum temperature in May shows an oscillation of 4.6 years with a squared coherence of 0.614. The minimum temperature of December shows oscillations of 2.5 years and 6.4 years with a squared coherence of 0.716 and 0.624 respectively. The precipitation in April shows oscillations of 2 years and 32 years with a squared coherence of 0.755 and 0.905 respectively. The NAO in April correlates with the minimum temperature in May peaking at 2.5 years with a squared coherence of 0.917.

◀ **Fig. 3a, c, e, g** Spectra of the series. **a** Spectrum of minimum temperature of May, **c** spectrum of minimum temperature of December, **e** spectrum of April precipitation, **g** spectrum of wine quality. **b, d, f, h** Observed and estimated series. **b** Minimum temperature of May, **d** minimum temperature of December, **f** April precipitation, **h** wine quality.The observed and estimated correlation coefficients are shown

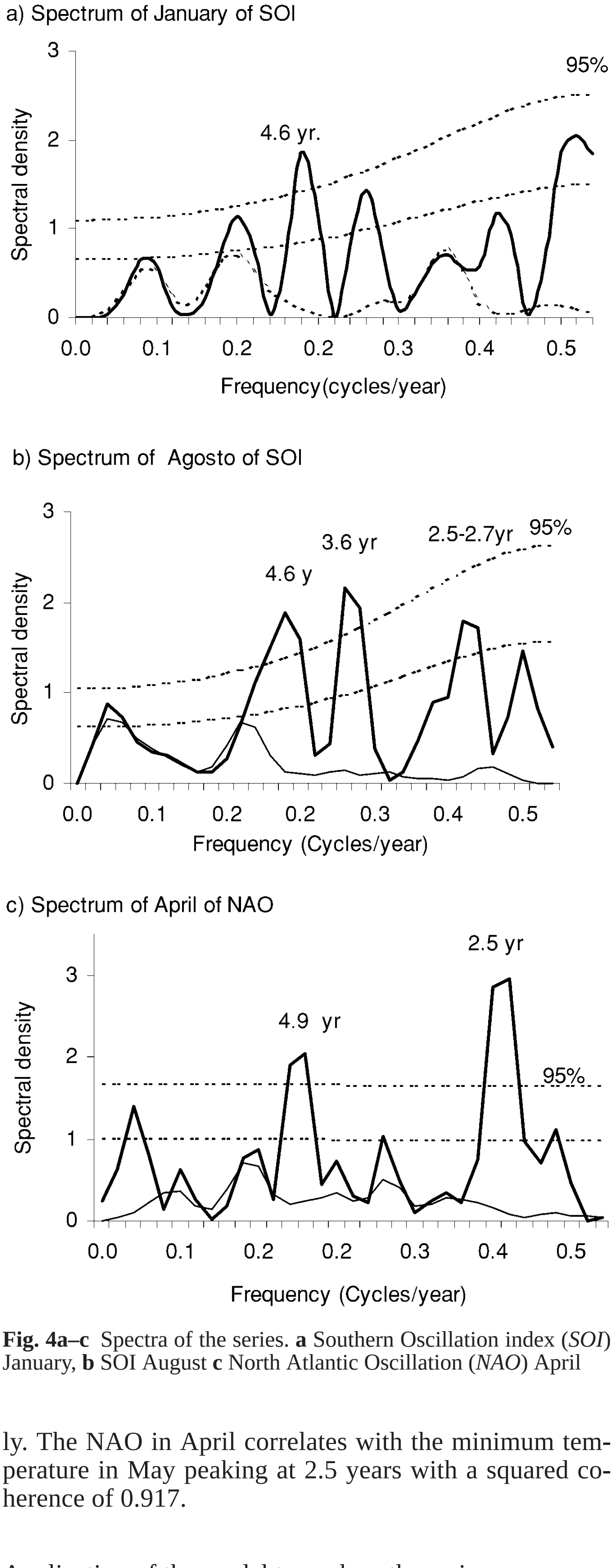


Fig. 4a–c Spectra of the series. **a** Southern Oscillation index (*SOI*) January, **b** SOI August **c** North Atlantic Oscillation (*NAO*) April

Application of the model to analyse the series

The model we propose is based on Wold's decomposition theorem (Priestley 1981) and uses the following tech-

Table 3 Validation of the model for 1993 with the estimated and observed values of the climatic series and the quality of the wine based on the statistical model

Climatic element	Year	Estimate	Observed
Minimum temperature in May (°C)	1993	9.1	8.8
Minimum temperature in December (°C)	1993	4.	4.8
Precipitation in April mm	1993	182.2	124.1
	1994	60.3	54.7
Wine quality	1993	1.3	1

niques of: (1) spectral analysis of the series to study the deterministic part of the temporal variability of the series; (2) non-linear regression to obtain each predictor from the Fourier series; (3) linear regression for rebuilding the series from its deterministic component; (4) autoregressive methods as a stochastic correction to reconstitute the series.

Though we obtained the deterministic part, which embodies most of the series variances, we have yet to add the probability component to this model, since the series is stochastic and, in this case, it will be an autoregressive model. Another description of the model can be found in Rodriguez-Puebla et al. (1998), and Nieto (1997). The discriminating model is applied to the series of values for the quality of Dão wine, to investigate which model better accounts for the quality of the wine and to reconstruct the series to diagnose wine quality in an empirical form. The findings predict that the Dão wine for 1993 would have been average. This wine quality prediction for 1993 can be obtained with the model using the data up to 1992. These data are represented in Table 3.

The precipitation values for 1993 are somewhat high and, for this reason, we thought it appropriate to include the estimate for 1994. Considering that the determining model for this series should have included other regional factors (frost and minimum temperatures), which are included in other studies we are undertaking, we aim to improve the prediction. The wine quality increases as the minimum temperatures decrease in December and the pressures increase in August and January with the SOI. This means that the quality of the wine shows significant negative correlation with the SOI. The pressure difference between Darwin (12°S,131°E) and Tahiti (17°S,150°W) increases, while the quality of the Dão wine is of lower quality.

We did not find a relationship between the NAO (the dipole of pressure that is produced by a pressure gradient between the high-pressure subtropical area of the Azores and the low-pressure subpolar area of Iceland) and the quality of the wine, but we did find a connection with the precipitation in April.

It is worth noticing the strong correlation between the minimum temperatures in December and the SOI in August, the precipitation in April and the NAO in April, and the minimum temperature in April and the SOI in August.

We found a negative correlation with the NAO index (leading to increased westerly surface geostrophic winds in Portugal) and suggest that this is associated with an increased incidence of very low surface pressures (below 98 kPa) over the central North Atlantic and of intermediate pressures (above 98 kPa) in North-Western Europe. It is suggested that these distant low surface pressures have no direct influence on the local Portuguese precipitation.

Summary and discussion

Viseu (Portugal) is situated at an altitude of 443.0 m, at 40° 40’ N and 7° 51’W, with a warm marine mass of polar air that is more frequent in spring (42.8%) and winter (37.0%). The type of weather associated with these conditions is rainfall when it is under the influence of the cold section of the depression, and more continuous rain nearer the front. The presence of this mass of air is usually associated with situations of high zonal indices.

The Dão wine is considered one of the best in Portugal. Around 80% is red wine and the rest white. Dão wines and all Portuguese wines have the highest levels of glycerol (between 10 gl^{-1} and 12 gl^{-1}), which is responsible for their smoothness. The factors influencing wine production are, on the one hand, natural (soil, climate, grape variety) and, on the other hand, technical, depending on the farmer’s decisions. Climate plays an important role in the quality of the wine.

We have determined, according to the Mann-Kendall tendency test, that the minimum-temperature series for December (τ=0.29) shows a trend. The same is not true for the minimum temperatures of May and precipitation in April, which do not show a trend. The minimum temperatures in December are increasing and the minimum temperatures of May and precipitation in April remain stationary.

As mentioned in the Introduction, the Regional Federation of the Viticulturists of the Dão Region (CVRD-FVD) classifies the wine into four grades: average = 1, good = 2, very good = 3, excellent = 4.

The minimum temperatures in December and May and the precipitation in April are all found to be significantly correlated to the quality of the wine (r>0.60). These climatic and wine quality time series were normalized by dividing the anomalies by the standard deviation. The most significant oscillations of all the time series observed were filtered by fitting the data to four harmonic functions and estimating the amplitude and phase. Table 2 shows the percentage of the variance explained by these oscillations. We found that all the series show significant oscillations of 2–3 years and 4–7 years with plenty of variance. The precipitation in April, the minimum temperature in December and the SOI in August present autoregression, which means that these series contribute a stochastic part. The most important oscillations are 4–7 years for the quality of the wine: 2–3 years of the January and August SOI, and the April NAO and at least 16 years for the minimum temperature of May and December.

We found a significant correlation with the teleconnection indices such as the SOI and NAO and we concluded that the wine is of higher quality when the pressure anomalies of the August SOI increase (r=0.40), the pressure anomalies of the January SOI decrease (r=–0.42), and when the pressure anomalies of the April NAO (r=–0.40) and the minimum temperature anomalies of the December SOI decrease (r=–0.453).

In the same way, the quality of wine is better when the minimum temperature in December decreases and the precipitation in April increases. The model is able to warn the wine producers of Dão when the teleconnection indices and the climatic series indicate the onset of a probable extreme event so that they may harvest before it occures. We have shown that the values predicted for 1993, which were obtained from the model using data up to 1992, correspond only very approximately to the observed values. This means that the determining model for some series should have taken into account other regional factors (minimum temperatures and frosts), which require further investigation. The model is able to reproduce wine quality and climatic dates with good correspondence to what is observed.

The spectral characteristics of these wine series for the 4.6-year period show a known variance of 17%, the oscillation of 5.3 years a known variance of 14% and the oscillations of 2.5 and 2.7 years show a known variance of 25%, which is reflected in the quality of the wine. The spectrum of the January SOI shows oscillations of 4.6 years with a known squared coherence of 0.469. The spectrum of the August SOI has coherence in the wine quality for the peak of 2.7 years and whose known squared coherence is 0.728.

The correlation coefficients with teleconnection circulation indices obtained are:

For the minimum December temperatures and the August SOI, r=–0.453; for the April precipitation and the April NAO r=–0.397; for the wine quality and January SOI, r=–0.415; and for August the SOI and minimum August temperatures r=0.405.

The models that define the climatic series take into consideration the oscillations of 4.6, 2.5 and 5.3 years for the minimum air temperatures of May, oscillations of 5.3, 2.6 and 3.3 years and the autoregression model for the minimum air temperatures of December, oscillations of 2.5, 2.7, 5.3 and 2.1 years and the autoregression model for the precipitation of April and oscillations of 4.6, 5.3, 2.3, and 2.7 years for the quality of the wine.

The quality of the wine is improved when the pressure of the SOI in August increases the pressure of the SOI in January decreases, and the pressure of NAO in the North Atlantic in April decreases.

The quality of the wine also improves when the minimum temperature of December is lower and when the precipitation in April increases.

This model can alert the viticulturists in the Dão region, since the teleconnective indices and the climatic series refer to the months prior to the grape harvest, and help them produce a wine of international renown.

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