RMetS

Royal Meteorological Society

Viticulture–climate relationships in Greece: the impacts of recent climate trends on harvest date variation

George Koufos,[a] Theodoros Mavromatis,[b*] Stefanos Koundouras,[c] Nikolaos M. Fyllas[d] and Gregory V. Jones[e]

[a] *Department of Environment, University of the Aegean, Mitilini, Greece*
[b] *Department of Meteorology-Climatology, School of Geology, Aristotle University, Thessaloniki, Greece*
[c] *Laboratory of Viticulture, School of Agriculture, Aristotle University, Thessaloniki, Greece*
[d] *Department of Ecology and Systematics, Faculty of Biology, University of Athens, Athens, Greece*
[e] *Department of Environmental Studies, Southern Oregon University, Ashland, OR, USA*

ABSTRACT: Climate characteristics and relationships with indigenous varieties in Greece are examined to better understand how these varieties perform in their native climate and assess the impact regional climate change has on the Greek wine industry. Thus, harvest dates (Δ_H) for eight indigenous varieties and regions, along with climate data, were gathered and systematically explored using linear regression models and principal component analysis for three 'effective' growing season time period definitions (calendar year, growing season and ripening period). The eight study regions had marked differences in their general climatic characteristics, mainly between mainland and island areas. Δ_H response was not particularly sensitive to time period definition. In five out of eight regions, a systematic shift of Δ_H was identified (earlier harvest), mainly driven by changes in maximum and minimum temperatures. Significant trends in climate parameters and viticulture–climate relationships were more evident for island regions when compared to mainland locations. Moreover, areas with late ripening varieties were shown to be less sensitive to climate changes. Only in one region harvest was delayed, possibly due to non-climate factors. The identification of up-to-date climate and grapevine phenology relationships could be an important step for broader and more confident future assessments of climate suitability for viticulture and climate change impacts in Greece, and provide insights into how lesser known varieties might perform in other regions.

KEY WORDS   viticulture; climate change; harvest dates; thermal climate; growing season definition; Greece

Received 16 August 2012; Revised 20 May 2013; Accepted 25 May 2013

1. Introduction

Observed climate changes as well as future predictions and their effects on natural and human systems have been well documented by the latest IPCC report (2007). Thus, many researchers have explored the impacts of climate change on different agricultural industries worldwide (Jones and Davis, 2000a; Lobell *et al*., 2006; Tao *et al*., 2008; Ramos *et al*., 2008; Urhausen *et al*., 2011). Although agricultural systems are managed ecosystems (Adams *et al*., 1998) and thus affected by agricultural practices, climate exerts a major control on crops. Temperature anomalies and changes in annual rainfall patterns could both have positive and negative impacts on the quantity and quality of agricultural production at a regional scale (Lavalle *et al*., 2009).

The potential effects of climate change on grape production have been previously discussed (e.g. Tate, 2001). Both past observations (Jones *et al*., 2005a; Grifoni

et al., 2006; Jones and Goodrich, 2008; Rodo and Comin, 2000) and predictive climatic–viticulture models (Webb *et al*., 2007; Cahill *et al*., 2007) have established significant relationships between viticulture and climate factors, mainly growing season temperatures. Viticulture experiences direct effects of climate change, mainly by a shift in grapevine phenological events and stages (Jones and Davis, 2000b). Grapevines (*Vitis vinifera* L.,) have four basic developmental stages: (1) budbreak, (2) flowering, (3) véraison (beginning of maturation) and (4) full ripeness (harvest). These main events have shown a 5–10 d response per 1°C of warming over the last 30–50 years averaged over many wine regions and varieties (Jones *et al*., 2005b; Ramos *et al*., 2008). The time between these events varies greatly with grape variety (Tomasi *et al*., 2011) but it is mainly influenced by temperature conditions of the growth period (Mullins *et al*., 1992). Warmer conditions due to climate change are generally associated with shorter intervals between phenological events and to earlier harvest dates (Bindi *et al*., 1996; Tomasi *et al*., 2011). The timing of harvest is related to the ability of the vine to yield and ripen fruit to optimum levels (Jones and Davis, 2000b). Grape

maturity and harvest have been reported to advance by 0.5–3.1 d per year in Australia for Cabernet Sauvignon, Chardonnay and Shiraz (Petrie and Sadras, 2008). In the Veneto region of Italy, grape maturity dates have trended 19 d earlier over 1964–2009 for numerous varieties (Tomasi *et al.*, 2011) and harvest dates for many varieties across numerous other locations in Europe have shown similar trends (Jones *et al.*, 2005b).

High temperatures during the maturation period also affect berry ripening due to increased synthesis of sugars in the must (Coombe, 1987). Thus, an increase in must soluble solids at harvest has been reported in some cases as a result of increasing ripening season temperatures (Ganichot, 2002; Gaudillère, 2007; Bock *et al.*, 2011). This effect is also likely to be the result of the shorter duration of between-stage periods and thus to an earlier beginning of maturation (Duchêne and Schneider, 2005), moving the ripening period to a warmer time of year. Grape ripening during the warmest part of the growing season (especially in semi-arid areas) is generally considered to be unfavourable to wine quality (van Leeuwen and Seguin, 1994) because metabolic processes and sugar accumulation may be impaired at temperatures above $30°C$ (Kriedemann and Smart, 1971).

Furthermore, climate change was found to constrain optimum ripening conditions to narrower geographic zones, in present (Jones *et al.*, 2005a) and future conditions (Kenny and Harrison, 1992). Especially, hot viticultural regions (like Greece) are expected to experience negative impacts from increased ripening period temperatures, imposing challenges in ripening balanced fruit and producing quality wine (Hall and Jones, 2009).

Recent work has shown that surface air temperatures in Greece have seen an increasing trend (Matzarakis *et al.*, 2007), mainly from 1990 until 2000 and remained at high levels thereafter (Nastos *et al.*, 2011). An increase in the annual number of tropical days (days with air temperature greater than $30°C$) was also reported (Nastos and Matzarakis, 2008) while no significant trend was recorded for consecutive dry days (Nastos and Zerefos, 2009) or rainfall (Mavromatis and Stathis, 2011).

Greece is one of the oldest wine-producing regions in the world. Today, the area cultivated with winegrapes covers approximately 67 000 ha (of which about 29 000 ha are under protected geographical indication) where about 200 indigenous varieties are cultivated (Lacombe *et al.*, 2011). The total production of wine reached 2 660 050 hL in 2012. The growing importance of wine industry to the Greek economy can be documented by the National Statistical Service of Greece (NSSG) which shows that the contribution of the wine industry to Greek beverage gross production value was 20.4% in 2007 (NSSG, 2008).

Despite the observed trends of climatic factors and the importance of the wine sector in the Greek economy, there has been a lack of studies of the impacts of climate change on Greek viticulture. Furthermore, there is little known about the climate–productivity response of indigenous grapevine varieties in Greece. Myles *et al.* (2011), in a comprehensive assessment of grapevine

genetic diversity, found that there has been a limited exploration of this diversity and that 'the long-term sustainability of the grape and wine industries will rely on the exploitation of the grape's tremendous natural genetic diversity'. Schultz and Jones (2010) stressed the importance of adaptation to climate change with new varieties that are more heat tolerant, but that little is known about the upper temperature suitability threshold of many common, let alone more rare indigenous varieties. Considering the importance and status of the wine industry in Greece and in order to provide more information to the growing interest in growth characteristics of grapevines, the aim of the present study is to (1) identify the climate characteristics in wine regions in Greece that have historically provided the conditions to ripen numerous lesser known indigenous varieties and (2) evaluate the impact of climate change on harvest trends in Greece, an already warm climate region for wine production.

2. Data and methods

2.1. Viticulture data

From the four basic developmental stages of grapevines, only harvest date is regularly recorded by grape growers in Greece. Overall, data for five white (W) and three red (R) winegrape varieties (*Vitis vinifera* L cvs), from six private wineries and two cooperatives (Limnos and Samos), covering a period of approximately 20 years or more, were obtained. These data series of harvest dates in Greece are, to the best of our knowledge, the longest available and were assembled from eight wine production regions, each representing a different winegrape variety (Figure 1 and Table I). The study regions also belong to areas of protected designation of origin (except for Anchialos and Pyrgos which are simple geographical locations). The harvest date series come from four mainland regions; Anchialos (cv. Roditis W), Nemea (cv. Agiorgitiko R), Pyrgos (cv. Mavrodaphni R) and Naoussa (cv. Xinomavro R), and four islands: Limnos (cv. Muscat of Alexandria W), Samos (cv. Muscat blanc W), Santorini (cv. Assyrtiko W) and Rodos (cv. Athiri W). Island areas represent 26% of the total area under winegrapes in Greece (about 17 500 ha).

Among the studied varieties, Roditis is the second most cultivated grape in Greece with a total of 9300 ha (13.8% of total area). Agiorgitiko and Xinomavro are the two most important red winegrapes with respective areas of approximately 3600 and 2300 ha (ranked 3rd and 4th respectively in plantation area). Assyrtiko and Muscat blanc are planted on around 1800 and 1600 ha respectively, and are the two major varieties in island locations. Athiri (∼700 ha), Mavrodaphni (∼500) and Muscat of Alexandria (∼700 ha) cover minor though important areas of cultivation.

Table I shows that harvest occurs earlier, on average, in the island areas (early August to early September) compared to mainland locations (mid to late September). Harvest dates are traditionally used in viticulture research
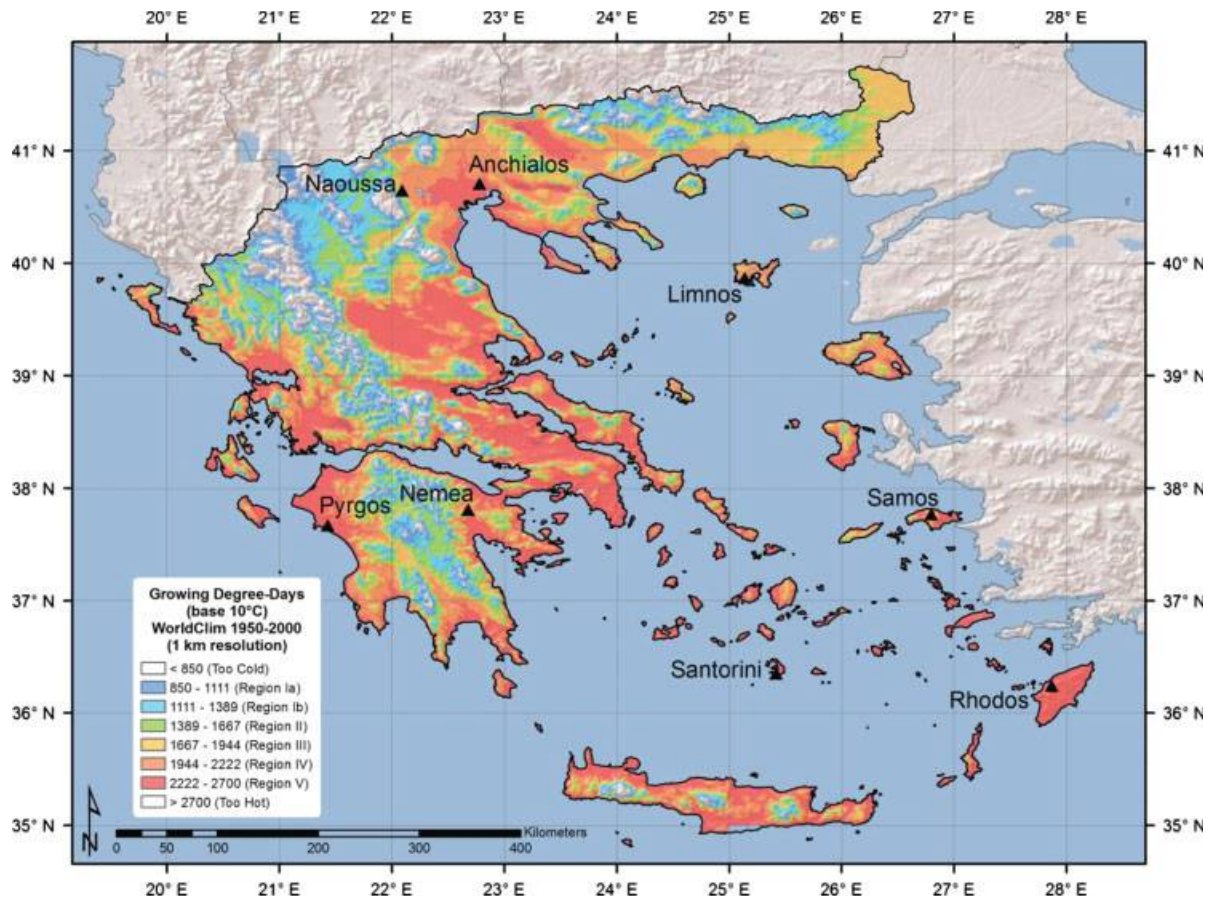
Figure 1. Map of Greece showing the eight locations used in this analysis and the mean GDD for the GS (1st April to 31st October) classified according to Winkler Regions (Winkler *et al*., 1974) for 1950–2000 (WorldClim database; Hijmans *et al*., 2005).

Table I. Descriptive statistics [mean values and standard deviation (Std.)] of the vineyard harvest dates (Δ_H) for the eight grape growing regions [study sites-(Is) for islands and (Mn) for mainlands] and varieties (name of variety given in parenthesis).

Site (variety)	Mean	Std. (days)	Period of record
Limnos (Is) (*Muscat of Alexandria*)	5-Sep.	7.7	1974–2010
Samos (Is) (*Muscat blanc*)	6-Aug.	5.3	1985–2010
Santorini (Is) (*Assyrtiko*)	10-Aug.	5.6	1993–2010
Rodos (Is) (*Athiri*)	20-Aug.	4.7	1990–2010
Anchialos (Mn) (*Roditis*)	23-Sep.	5.7	1982–2010
Nemea (Mn) (*Agiorgitiko*)	21-Sep.	10.6	1983–2009
Pyrgos (Mn) (*Mavrodaphni*)	19-Sep.	9.0	1989–2010
Naoussa (Mn) (*Xinomavro*)	25-Sep.	8.4	1981–2010

(1) for identification of the time-point at which, due to the optimum sugar levels, the harvest commences (Jones and Davis, 2000b) and (2) as a past climate indicator to reconstruct temperatures (Chuine *et al*., 2004). Grape composition data at harvest is not available for all locations in the study, although sugar levels (baumé degrees, B_D) were recorded in the Limnos and Pyrgos areas after picking of the grapes. Measurement of B_D is typically used by growers as an indicator of commercial maturity in order to commence harvesting.

2.2. Climate data

Climate data used in this analysis were obtained from the Hellenic National Meteorological Service (HNMS) for 46 weather stations across Greece (including the eight vineyard regions) for the period 1975–2004. Wine region stations were chosen based on their proximity to the vineyards where harvest information was used (<20 km away on average), while the remainder of the stations were used to develop a comparative spatial climatology for Greece. The data consisted of daily observations of mean (T_{mean}), maximum (T_{max}) and minimum (T_{min}) air temperature and, in five out of eight locations, daily precipitation (Prec.). Long-term climate data were then checked for errors and missing values were replaced from an alternative source (www.tutiempo.net/clima/Grecia). Specifically, if a missing value from HNMS occurred, the missing value was replaced by the alternative source if it existed. If two consecutive days were missing, the missing data were replaced by an average of the 2 d, both before and after the missing days. Finally, if more than 2 d were missing, the missing values were replaced using the linear regression equation on each variable for the study period. The percentage of missing observations

ranged from <0.4% (at seven stations) to 6.6% at Nemea. Climate data were computed for three periods: (1) calendar year (CY: 1st Jan. to 31st Dec.), (2) growing season (GS: 1st Apr. to 31st Oct.) and (3) ripening period (RP). The ripening phase starts at véraison and lasts about 45 d in the North Hemisphere, depending on the variety and the environmental conditions (Conde *et al.*, 2007). Therefore, for RP-based analyses, climate data of the last 45 d before harvest for each area/variety were used.

The primary climate parameters were used to derive other secondary variables commonly used in viticulture studies (Jones and Davis, 2000b):

1. Growing degree days, base $10°C$ (GDD: describe the heat energy received by the crop over the given time period). GDD are calculated by determining the mean daily temperature ($T_{max} + T_{min}/2$) and subtracting the base temperature (T_{base}) from it. According to Winkler *et al.* (1974), the T_{base} for physiological activity (e.g. photosynthesis, transpiration) is considered to be $10°C$. Daily GDD for 1 d was then represented by the following formula:

$$GDD = \left[\frac{(T_{max} + T_{min})}{2} \right] - T_{base} \qquad (1)$$

GDD calculations started the first day of each of the three periods. For each day, GDD were added to the previous total (when the mean temperature for the day was below T_{base}, it was set to zero).

2. Diurnal temperature range (DTR: the difference between maximum and minimum daily temperature) was calculated as:

$$DTR = T_{max} - T_{min} \qquad (2)$$

3. The number of days with extreme cold ($T_{min} < 0°C$) or heat ($T_{max} > 35°C$).
4. Harvest anomaly (Δ_H): the average difference between the annual harvest date for each year and the long-term mean harvest date. This anomaly was computed in three steps. Initially, the 1st of August was selected arbitrarily as the day-count reference baseline. Then, the calendar difference between the recorded harvest date of each year and the 1st of August was calculated (e.g. 14th Sep.−1st Aug. = 45 d). Finally, the difference between the average calendar date for the time-series of the study area [e.g. $(45 + 41 + \cdots + 33)$/number of years = 36.9] and calendar date for each year ($45 - 36.9 = 8.1$) was computed for each region as Δ_H.

2.3. Statistical analysis

The relationships between Δ_H and B_D and each one of the climate variables were initially explored using the basic linear regression model ($Y = a + bX$) for each region, with the estimated slope (b) of the equation expressing the average per year change of the variable of interest and X being time (Tao *et al.*, 2008; Lobell and Field, 2007; Lobell, 2007). This simple regression model was selected because having too many variables can easily lead to a model that has poor prediction accuracy (due to over-fitting) and is difficult to interpret (Lobell *et al.*, 2007). The least-squares fitting process was used to fit the line. The computed annual Δ_H and B_D were used to estimate potential associations with the key annual climate variables by estimation of the Pearson's correlation coefficient (r). In order to examine any possible trend in the time series of climate parameters, a two-tailed Student's *t*-test, with 95% level of significance, was applied to the slope of the regression line.

The pairwise correlations (Pearson's r) between Δ_H and the five out of eight primary and secondary climate parameters during the GS period for the eight vineyard regions were also estimated. $T_{min} < 0°C$ was excluded from the analyses because no days with temperature below $0°C$ ($T_{min} < 0°C$) were recorded in the island locations of Rodos, Samos and Santorini. Pearson's partial correlation coefficients represent the correlation between the dependent and an independent variable after common variance with other independent variables has been removed from both variables of interest (Legendre and Legendre, 1998). Consequently, after removing variance that the dependent and the variables independent have in common with other independent variables, the partial correlation coefficient expresses the correlation between the residualized independent and the residualized dependent variables.

The climate data were further analyzed with a two-stage multivariate procedure. Principal components analysis (PCA here after) was used initially, in S-mode, on the long-term mean climate (1975–2004) of 46 weather stations (including the eight vineyard regions) across Greece in order to (1) depict the spatial characteristics of the climate patterns over Greece and (2) use the components of the PCA as orthogonal independent variables in multiple regression analysis of Δ_H and B_D (not shown). PCA, which has seen only limited use in viticulture studies (Jones and Davis 2000a; Blanco-Ward *et al.*, 2007), is a powerful tool in avoiding multicollinearity and reducing the dimensionality of a dataset consisting of a large number of possibly inter-correlated variables. This is achieved by transforming the data matrix to a new set of variables, named principal components (PCs). These components are uncorrelated while retaining as much as possible of the variance present in the initial dataset (Jolliffe, 2002). In order to avoid negative reliability of a PC, 'the eigenvalues-greater-than-one rule' (Kaizer, 1960) was applied to discriminate the PCs. Since the variances of the variables are considerably different from each other, all the variables were standardized prior the application of PCA. The PCA of the climate variables was performed on the correlation matrix using the 'ade4' package (Chessel *et al.*, 2004).

In the second step, a cluster analysis (CA) on the site scores of the PCA procedure was performed. CA is a widely known tool which aims to divide objects of a

dataset into groups, called clusters. A cluster consists of observations that are as similar as possible to each other, whereas observations in a different cluster are dissimilar (Kaufman and Rousseeuw, 1990). There are several ways of clustering. The two most commonly used are (1) hierarchical and (2) partitioning methods. In hierarchical methods, algorithms yield an entire hierarchy based on the dataset either by merging clusters to form one large cluster (agglomerative methods) or split up clusters until each object is separated (divisive methods). On the contrary, partitioning methods divide the dataset into k clusters (Struyf *et al*., 1997). Two common ways of clustering data with partitioning algorithms are k-means and k-medoids. Basically, k-means arbitrarily divide the n objects into k clusters finding each centroid (geometrical centre of all the objects in the cluster) of a cluster. On the other hand, the k-medoids or partitioning around medoids (PAM) method searches for k representative objects called medoids (most representative object of a cluster). After finding a set of k medoids, k clusters are constructed by assigning each observation to the nearest medoid (Kaufman and Rousseeuw, 1990).

The non-hierarchical PAM method was applied in this study in order to (1) investigate how the selected vineyard regions are situated in relation to the broader scale climate structure in Greece (reflected by the 46 weather stations) and (2) use these clusters for further exploration of the harvest date variations for the studied regions. Unlike some of the previous viticulture studies (e.g. Jones and Davis 2000a; Blanco-Ward *et al*., 2007), the PAM method was employed for several reasons. Firstly, the PAM method has the advantage of specifying the number of clusters in advance taking into account the silhouette coefficient (Struyf *et al*., 1997). Secondly, this method is more robust because it minimizes a sum of dissimilarities instead of a sum of squared Euclidean distances. Lastly, it provides a novel graphical display, the so-called silhouette plot. The average silhouette width of this graph contributes to the interpretation of the results by showing to what degree an object (e.g. region) is situated within a cluster (Rousseeuw, 1987).

Finally, the effect of the time period used as the basis for each analysis (CY, GS and RP), i.e. the 'effective' GS definition, on the (1) frequency of significant viticulture (Δ_H, B_D)-climate relationships and (2) direction and magnitude of harvest time response was also explored. In all cases, statistical analyses were performed using the R software (R Development Core Team, Vienna, Austria).

3. Results

The results from the GS-based analysis are presented in Sections 3.1. and 3.2. as it showed a higher frequency of statistically significant viticulture–climate relationships when compared to CY and RP, as described in Section 3.3.

3.1. Overview of climate

3.1.1. Climatic characteristics of vineyard regions

Descriptive statistics for the base and derived climate parameters during the GS for the eight selected vineyard sites are summarized in Table II. Lower GS average temperatures are found at mainland stations, mainly Nemea ($T_{mean} = 18.9°C$, 1934 GDD); and higher on the islands (all except Limnos experienced temperatures and GDD $>22.5°C$ and 2600, respectively). On the other hand, the highest and lowest values of maximum and minimum temperatures, respectively, were identified at the mainland locations. These results show the overall moderating effect of the island locations where the DTR is lower than the mainland locations (5.8–9.5°C *vs* 11.2–14.9°C, respectively). GS precipitation ranged from 66 mm (Santorini) to 240 mm (Nemea) but exhibited high variability (not shown) over all locations (Table II). Heat stress events with maximum daily temperatures above 35°C also showed a general mainland/island difference, with 7–10 days mainland *versus* <1 d on the islands. The only exception to this pattern was Samos with 20 d per GS over 35°C which reflects its proximity to the mainland of Turkey (Figure 1). Cold events during the GS were rare across most stations with five locations experiencing no events, three locations with fewer than one event per GS, and Nemea experiencing four events per GS, on average.

3.1.2. Principal component analysis of thermal climate in Greece

Given that (1) precipitation was the least descriptive climate variable in correlation analysis and (2) that long-term precipitation data were only available in five out of eight vineyard regions (Table II), only temperature related variables (T_{mean}, T_{max}, T_{min}, GDD and DTR) were included in PCA across the 46 weather stations. The spatial distribution of the 46 weather stations (including the eight vineyard study sites) is presented in Figure 2. Because the number of days with extreme cold ($T_{min} < 0°C$) or heat ($T_{max} > 35°C$) was available in the eight study regions only, these two variables were also not used in PCA.

Two principal components explained 99% of total variability in the temperature parameters (Figure 3). The first component (PC1) was mostly loaded on T_{mean}, T_{min}, GDD and DTR explaining approximately 67% of the total variance. PC1 was characterized by the contrast between T_{min}, T_{mean} and GDD, which displayed positive loadings, and DTR presenting negative loadings. The second component (PC2), explaining 32% of the remaining variance, was mainly related to T_{max}.

Regarding the first axis (PC1), Nemea, a vineyard mainland region located in a mountainous area, was strongly defined by low T_{min}, T_{mean} and GDD values, while the island of Samos was found at the opposite side of this component (Figure 3). With regards to the second axis (PC2), three mainland regions (Pyrgos, Naoussa and, to a lesser degree, Anchialos) were characterized

Table II. Descriptive statistics for climate variables for the GS period [mean values for the period of record (see Table I) with standard deviations in parenthesis] for the eight selected grape growing regions.

	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	GDD (°C)	DTR (°C)	Prec. (mm)	$T_{max} > 35°C$ (d)	$T_{min} < 0°C$ (d)
Limnos	20.8 (0.6)	24.4 (0.6)	15.6 (0.6)	2308 (118)	8.8 (0.4)	181 (125)	0.6 (1.4)	0.0 (0.0)
Samos	23.7 (0.7)	27.7 (0.7)	18.2 (0.8)	2933 (138)	9.5 (0.5)	112 (58)	20.5 (9.9)	0
Santorini	22.6 (0.5)	25.3 (0.6)	19.4 (0.6)	2693 (111)	5.9 (0.4)	66 (48)	1.1 (1.3)	0
Rodos	23.4 (0.5)	26.2 (0.5)	20.4 (0.5)	2873 (103)	5.8 (0.3)	110 (93)	1.1 (1.6)	0
Anchialos	20.7 (0.7)	26.5 (0.9)	15.2 (0.9)	2301 (150)	11.2 (0.7)		7.1 (6.4)	0.1 (0.3)
Nemea	18.9 (1.6)	25.6 (1.0)	10.7 (1.2)	1934 (319)	14.9 (1.0)	240 (87)	10.4 (6.2)	4.0 (4.2)
Pyrgos	21.9 (0.7)	27.4 (0.7)	14.7 (0.9)	2551 (143)	12.8 (0.9)		9.5 (7.9)	0.0 (0.2)
Naoussa	20.8 (0.6)	26.2 (1.2)	14.2 (0.7)	2325 (121)	12.0 (1.6)		8.5 (6.0)	0.7 (1.3)

Empty cells indicate that the respective variable was not available; 0 indicates that no days with temperature below 0°C was recorded.
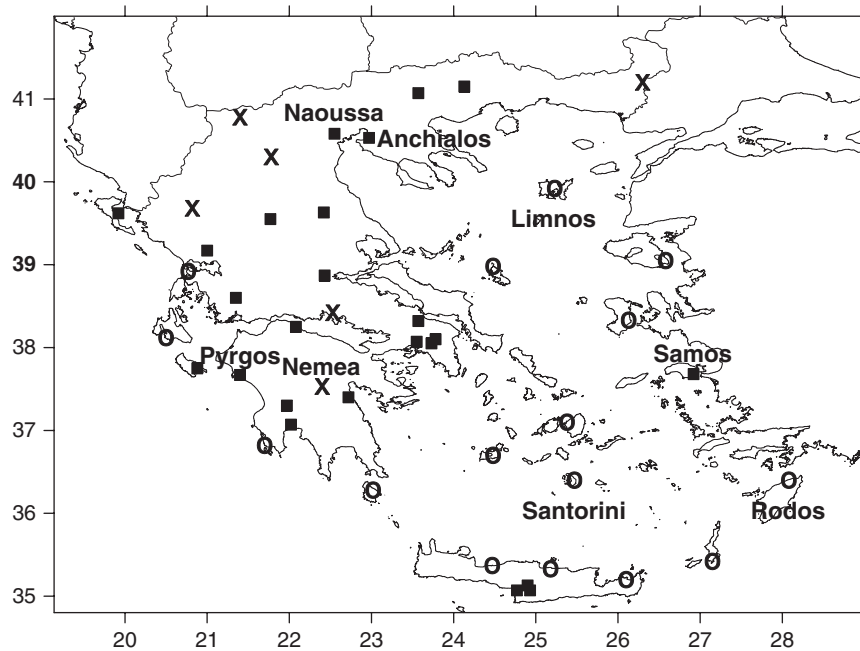
Figure 2. Spatial distribution of the 46 weather stations grouped in the three clusters (where open circles represent the coastal and island stations, X's represent the mainland stations and solid dots represent the remaining stations).

by high DTR values ($\geq 11.5°C$), positively associated with PC2, while the islands of Rodos and Santorini were characterized by low DTR.

Three groups were distinguished in the biplot of the two PCs due to similarities in their climatic characteristics (Figure 3). Traditionally cooler mainland regions (shown with X's) like Nemea, are isolated together in the lower left quarter due to their lower T_{min}, T_{max} and GDD. On the other hand, there is a clear tendency for most of the islands and coastal regions (including Santorini, Limnos and Rodos) to group together (shown with open circles in the lower right quarter) due to their similar higher T_{min} values. The remaining stations (shown with solid dots) are spread over the upper two quarters mostly related to higher T_{max} values.

3.1.3. CA of thermal climate in Greece

Applying the non-hierarchical PAM method to the site-scores of PCA, the highest overall silhouette width (s_i) was achieved with three clusters ($s_i = 0.56$ *vs* $s_i < 0.51$).

Generally, clusters with average $s_i < 0.51$ are considered statistically weak and may be artificial (Rousseeuw, 1987) when more (up to six) or fewer clusters were used (Figure 4). Furthermore, s_i was consistently greater than 0.51 in all three clusters. Each cluster is divided into shaded bars (representing the regions), ranked in decreasing order of s_i. According to s_i, clusters 1 and 2 are characterized as reasonable structures and cluster 3 is almost a strong ($s_i = 0.7$ with 0.71 the limit) structure.

More than half (24 out of 46) of the stations were grouped in cluster 1, representing the majority of mainland regions (18 sites) (shown with solid dots in Figures 2–4). This cluster is clearly forced by regions experiencing higher T_{max} than the other two clusters (Table III). Three out of four mainland wine regions (Pyrgos, Naoussa and Anchialos) were included in this cluster, although Anchialos resulted in a low s_i score ($0.38 < 0.51$), and together with Samos, (an island site included by the PAM analysis in this group but with the lowest $s_i = 0.18$), possibly belonged instead in cluster 2. The rest of the island sites (Santorini, Limnos and Rodos)
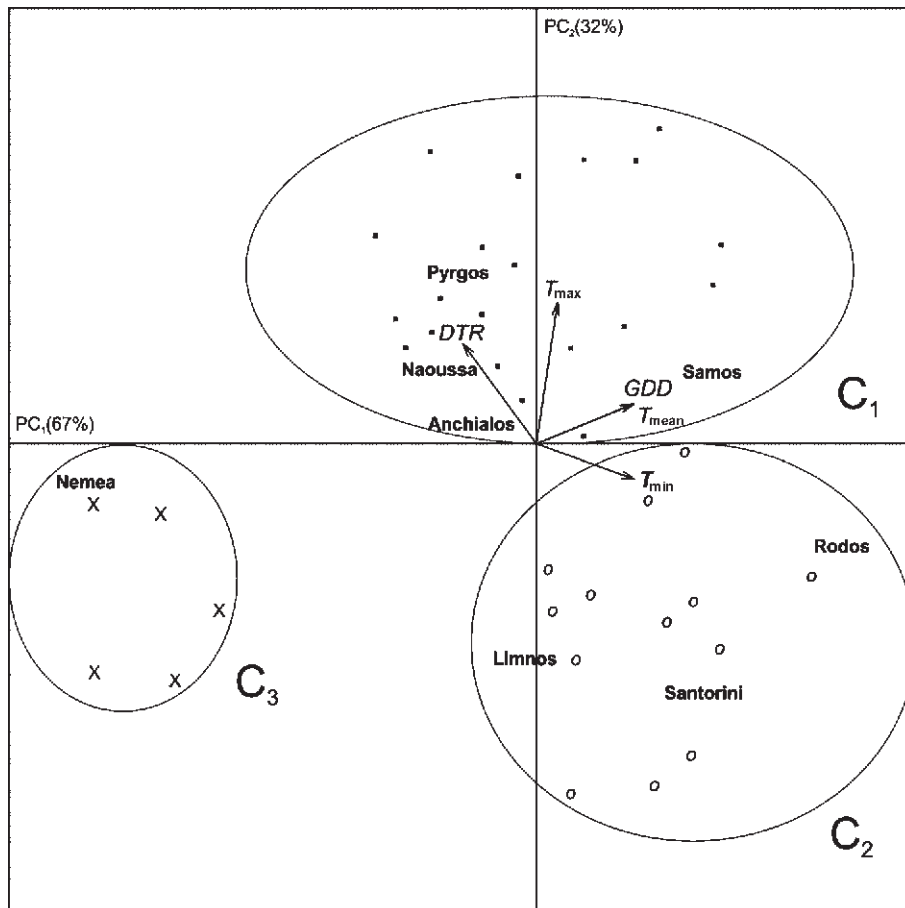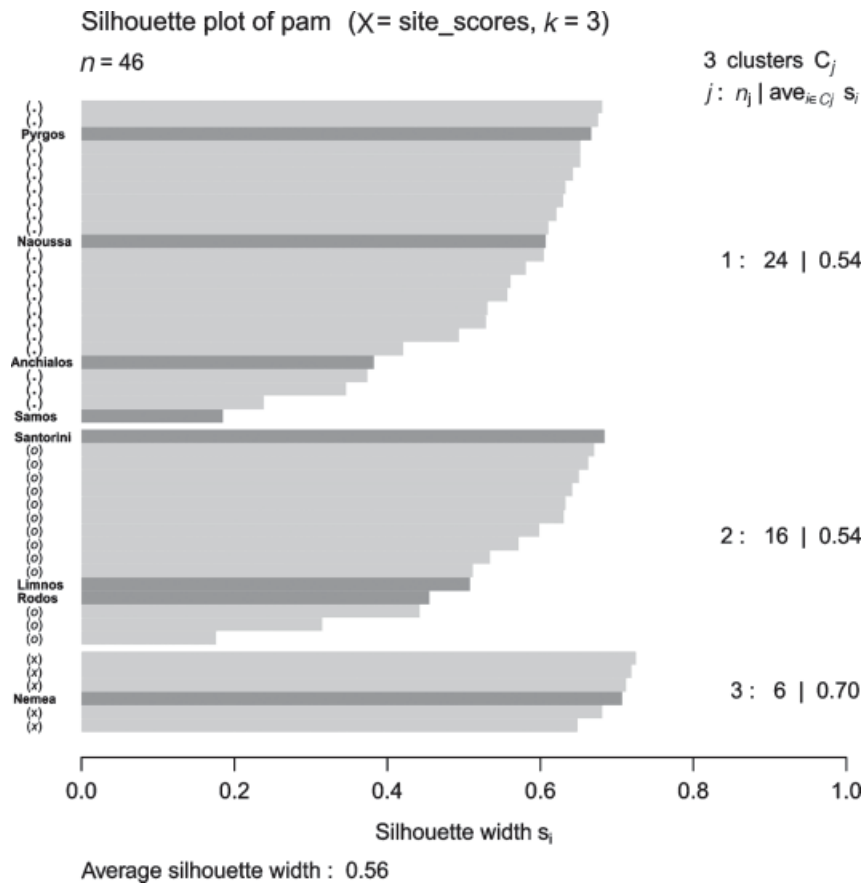
Figure 3. Biplot of the first two principal components of the mean GS temperature climatology of the 46 weather stations (where open circles represent the coastal and island stations, X's represent the mainland stations and solid dots represent the remaining stations). Variable descriptions are given in the text.

were grouped in cluster 2. This cluster includes 35% (16 sites) of the locations considered for PAM and represents the vast majority of the islands and coastal locations (shown with open circles in Figures 2–4). This group is forced by the higher T_{min} and lower DTR during the growing season (Table III) reflecting the milder climate due to the influence of the sea. Finally, cluster 3 contains the last six sites (or 13% of the set of locations used in PAM analysis) in the dataset, but with only Nemea from the wine region study sites. Locations in this cluster are typically higher elevation mainland regions (shown with X's in Figures 2–4), with lower temperatures (T_{min} was substantially lower than T_{max}) than the other two clusters and therefore lower GDD (Table III). The average s_i of this cluster is greater than the others, meaning this cluster is statistically more pronounced.

3.2. Trends of climate and viticulture data

3.2.1. Climate trends

The majority of the climate parameters during GS exhibited statistically significant positive trends across most locations (Table IV), except for DTR (negative trends in Samos, Anchialos, Pyrgos and Naoussa) and T_{max} (negative trend in Naoussa). A similar number of climatic

variables with significant trends over time were identified in island (13) *versus* mainland regions (12). Furthermore, in island regions, 10 out of 13 significant cases were found in two islands, namely Limnos and Samos. The increase of T_{min} with time was the most frequently observed significant climatic trend (six out of eight cases) (Figure 5). In contrast, no significant trends for $T_{min} < 0°C$ were identified.

3.2.2. Harvest date trends

Viticulture data analysis showed a statistically significant earlier occurrence of harvest (Δ_H) in five out of eight locations (Table V and Figure 6). Naoussa and Nemea exhibited positive but non-significant trends over time, while only the island location of Rodos showed grape harvest dates that were significantly delayed by $0.4\,days\,yr^{-1}$ over the examined time period. The harvest dates for the other three island locations (Limnos, Samos and Santorini) advanced by 0.31 to $0.55\,days\,yr^{-1}$, while the harvest dates in two out of four mainland locations (Anchialos and Pyrgos) advanced by 0.35 and $0.77\,days\,yr^{-1}$, respectively. Between the two locations where grape ripeness data (B_D) were available, a significant declining trend was observed in Limnos while

Figure 4. Silhouette plot of PAM of the mean GS temperature climatology of the 46 weather stations (where open circles represent the coastal and island stations, X's represent the mainland stations and solid dots represent the remaining stations).

3.3. Viticulture–climate relationships

A summary of the Pearson's correlation analyses between climate data and Δ_H is presented in Table VI. Δ_H showed significant negative relations with T_{mean}, T_{min}, T_{max} and GDD for the GS period in three (Limnos, Samos, Santorini) out of four islands, with increasing temperatures (Table IV) leading to an earlier harvest (Table V). Mainland locations (with the exception of Nemea) exhibited a similar behaviour, but more markedly in Anchialos and Naoussa. In all regions Δ_H was negatively correlated with $T_{max} > 35°C$ (but significantly only in Samos, Anchialos and Naoussa). No significant correlations were identified in Rodos while in Nemea, Δ_H was only positively correlated with Prec. B_D was statistically associated only with GDD in Limnos (data not shown).

The viticulture–climate bivariate relationships were additionally explored during the GS, using the partial Pearson coefficient (data not shown). The climate variables used in this case were T_{mean}, DTR, $T_{max} > 35°C$, $T_{min} < 0°C$ and Prec. (where available). The $\Delta_H - T_{mean}$ association remained significant at the three islands identified previously (Limnos, Samos and Santorini) (data not shown). The negative relationship between DTR and Δ_H was also confirmed in Naoussa.

3.4. Sensitivity of viticulture–climate relationships to growing season definition

The GS-based analysis, described in detail above, presented the most frequently significant viticulture–climate relationships (26 cases) (Table VII). T_{mean}, T_{max}, T_{min} and GDD were the most dominant climate factors for the island locations while T_{mean}, T_{min}, GDD, DTR and $T_{max} > 35°C$ were the most important factors for the mainland locations. The number of significant viticulture–climate relationships was reduced when analysis was based on CY and RP (24 and 15 significant cases, respectively). T_{min} and T_{max} were the most dominant climate factors in the RP-based analysis. These variables were negatively related to harvest date variation during RP except for T_{min} in Naoussa (not shown).

The direction and, to a lesser degree, the magnitude of harvest time responses were not particularly sensitive to the choice of 'effective' growing season definition (Table VIII). A negative harvest response was identified for all variables except for the non significant effect of Prec. in Nemea, $T_{min} < 0°C$ in Limnos and Pyrgos, T_{min} in Naoussa and DTR in Anchialos. Minimal harvest responses were found with GDD and $T_{max} > 35°C$ trends. Comparing 'effective' growing season definitions (CY, GS and RP), slightly weaker magnitudes of mean harvest responses to recent climate trends of T_{mean},

Table III. Descriptive statistics for climate variables for the GS period, during 1975–2004, for the vineyard regions and clusters.

	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	GDD (°C)	DTR (°C)	s_i	N
Cluster 1							
Pyrgos	20.8	27.4	14.2	2311	13.2	0.67	2
Naoussa	20.9	26.6	14.0	2335	12.6	0.61	2
Anchialos	20.6	26.3	14.8	2265	11.5	0.38	2
Samos	22.4	27.1	17.7	2661	9.3	0.18	2
Median	21.2	27.3	15.0	2391	12.5		
Q25	20.8	27.0	14.2	2312	10.9		
Q75	22.0	27.9	16.2	2566	13.0		
Cluster 2							
Santorini	21.7	24.7	18.6	2503	6.1	0.68	1
Limnos	20.8	24.3	15.5	2307	8.7	0.51	1
Rodos	23.0	26.0	19.9	2777	6.1	0.45	1
Median	21.7	25.2	18.2	2498	7.1		
Q25	21.0	24.6	17.3	2355	6.1		
Q75	21.9	25.5	18.7	2551	8.4		
Cluster 3							
Nemea	17.7	25.3	10.2	1658	15.1	0.71	1
Median	18.0	24.9	11.3	1713	13.5		
Q25	17.8	24.2	10.7	1669	12.3		
Q75	18.2	25.3	11.9	1766	14.5		

Silhouette widths (s_i) and possible neighbours (N) are also shown. For each cluster, the median, 1st quartile and 3rd quartile of the climate variables are presented.

Table IV. Direction and slope [°C/yr for all climate variables except for Prec. (mm/yr)] (in parenthesis) of the linear regressions between climate variables during the GS period and time for the eight selected grape growing regions.

	T_{mean}	T_{max}	T_{min}	GDD	DTR	$T_{max} > 35$°C	$T_{min} < 0$°C	Prec.
Limnos	**+ (0.01)**	**+ (0.03)**	**+ (0.03)**	**+ (4.1)**	−	**+**	**+**	**+**
Samos	**+ (0.04)**	+	**+ (0.08)**	**+ (8.2)**	**− (0.05)**	**+ (0.66)**	0	**+ (3.1)**
Santorini	+	+	+	+	+	−	0	**+ (4.2)**
Rodos	+	**+ (0.05)**	**+ (0.03)**	+	+	+	0	−
Anchialos	**+ (0.05)**	+	**+ (0.09)**	**+ (11.6)**	**− (0.07)**	**+ (0.34)**	**+**	
Nemea	**+ (0.10)**	+	+	**+ (21.6)**	−	**+**	**+**	−
Pyrgos	−	+	**+ (0.1)**	−	**− (0.08)**	**+**	**+**	
Naoussa	**+**	**− (0.06)**	**+ (0.04)**	+	**− (0.10)**	**+**	**+**	

Bold signs indicate significant slopes; empty cells indicate that the respective variable was not available; 0 indicates that no days with temperature below 0°C was recorded.

T_{max} and T_{min} were found at three stations (Limnos, Samos and Santorini) when the analysis was based on GS compared to CY periods (7 *vs* 8 d, on average). The RP-based analysis resulted in even weaker harvest responses (almost 4 d, on average) in the same stations. Similar harvest responses were produced by the trends of T_{mean}, T_{max} from both GS- and CY-based analyses in Naoussa and trends of T_{mean} in Pyrgos. A lower negative harvest time response to DTR trends was found in the same region with RP analysis (2.2 d *vs* 4.0 d for CY and 3.3 d for GS). Finally, weaker harvest responses were identified in Anchialos when the analysis was based on GS compared to CY analyses.

4. Discussion

In this study, warmer growing seasons, mainly driven by increasing T_{min} and T_{max} were identified in three out of four island locations examined, while Nemea and Anchialos were the mainland regions with significantly

consistent climate changes among eight key wine producing areas of Greece (Table IV). In terms of the general pattern of the Greek climate, island vineyard regions are characterized by milder climatic conditions (lower T_{max} and DTR) while mainland ones are generally warmer (increased GDD) (Table III). These increasing temperature trends led to significantly higher GDD over the time period. Furthermore, the more recent time periods used in this study show a 200 GDD increase over the 1950–2000 time period (Figure 1) ranging from 103 GDD at Anchialos to 362 at Samos. These observations are in agreement with previous research reporting significant GS temperature increases in the majority of European wine regions (e.g. France, Germany, Spain, Italy and Slovakia) (Jones *et al*., 2005b) including Greece (Matzarakis *et al*., 2007; Nastos *et al*., 2011; Nastos and Matzarakis, 2008). It is also important to note that T_{min} exhibited greater increases compared to T_{max} in the majority of the locations examined in this study. This is in line with the findings of Easterling *et al*. (1997) in many regions of the world. Jones (2005) showed that wine regions across
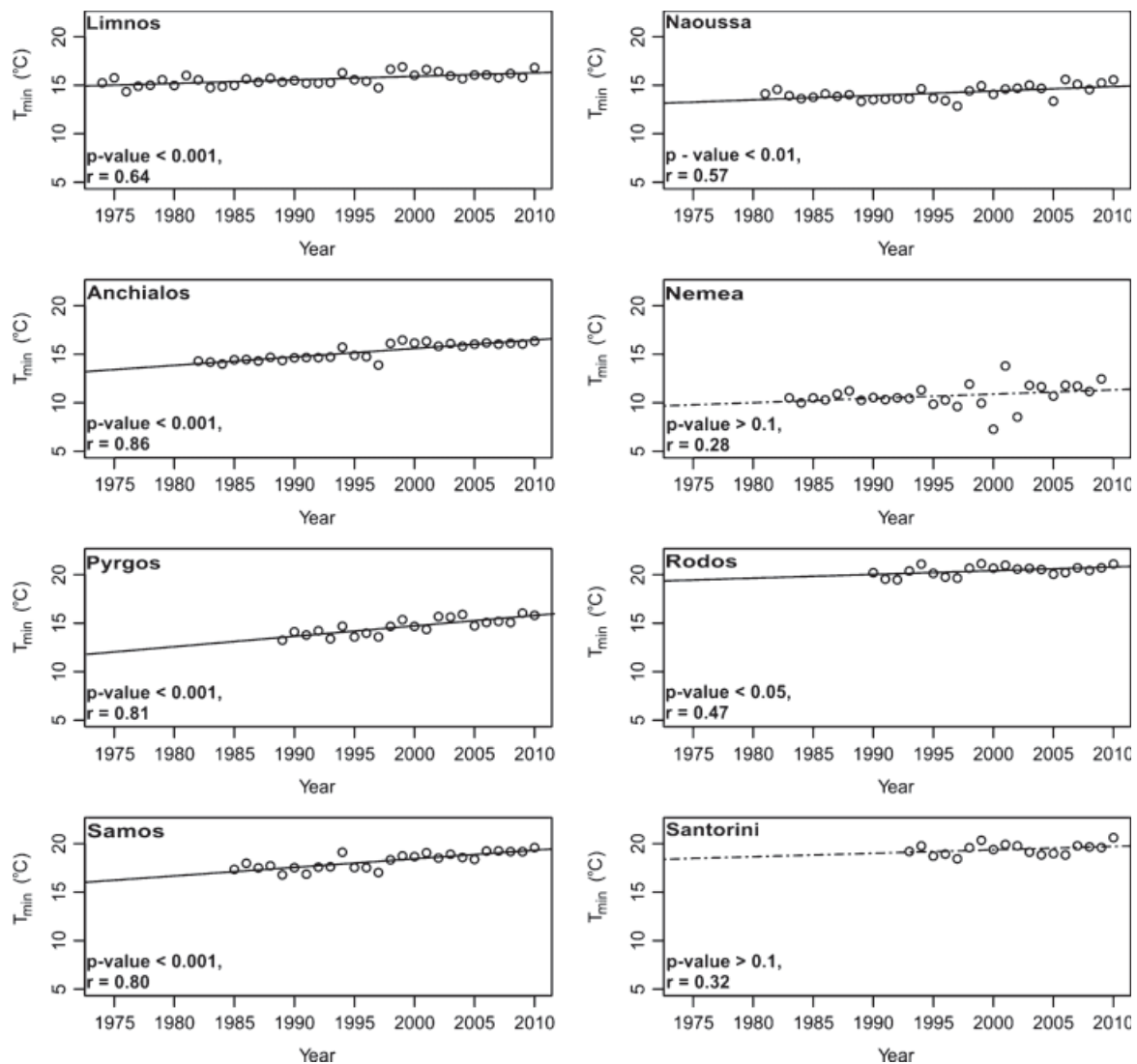
Figure 5. Time series of minimum air temperature (T_{min}, °C) at each of the eight locations. Solid lines indicate statistically significant trends ($p < 0.05$) while dotted lines indicate non-significant trends ($p > 0.05$).

Table V. Direction and slope (days/yr) (in parenthesis) of the linear regressions between harvest date (Δ_H) and time for the eight selected grape growing regions.

	Limnos	Samos	Santorini	Rodos	Anchialos	Nemea	Pyrgos	Naoussa
Δ_H	**− (0.48)**	**− (0.31)**	**− (0.55)**	**+ (0.40)**	**− (0.35)**	+	**− (0.77)**	+

Bold signs indicate significant slopes.

the western United States have experienced warmer GSs, driven largely by changes in T_{min}, while Ramos *et al.* (2008) and Tomasi *et al.* (2011) reported the opposite in three Spanish wine regions and for the Veneto region in Italy, respectively. In Alsace, an increase of T_{min} was found only during the autumn (Duchêne and Schneider, 2005).

This study also examined the long-term characteristics in harvest date anomalies (Δ_H) (Table V). In five out of eight locations, a systematic shift of harvest time was identified (earlier harvest), mainly driven by changes in T_{min} and T_{max} (Figure 5). However, in the two regions where grape composition data were available

(baumé degrees, B_D), there was no clear trend despite the significant climate changes. Grape ripeness decision is also subject to human judgment. As a result, grape growers tend to harvest grapes at relatively constant sugar levels in the must, based on winery specifications, commercial targets, market constraints and other factors (de Orduña, 2010).

Harvest date was not particularly sensitive to the 'effective' growing season definition (CY, GS and RP), although CY-based analysis introduces extra variability of weather for the time period following harvest. The number of significant viticulture–climate relationships was slightly reduced when analysis was based on CY or
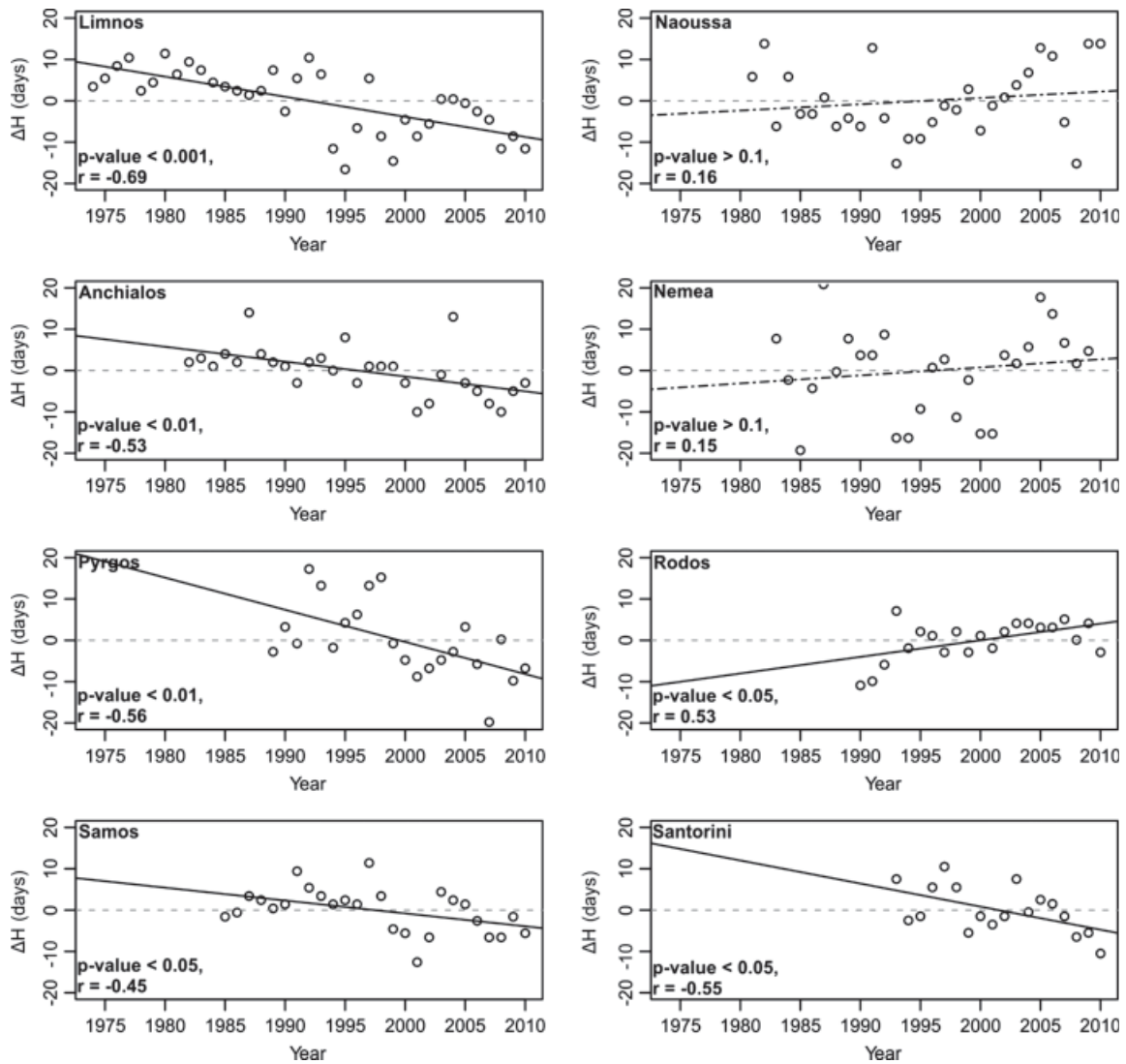
Figure 6. Time series of harvest dates at the eight locations. Solid lines indicate statistically significant trends ($p < 0.05$) while black dotted lines indicate non-significant trends ($p > 0.05$). The zero x-axis horizontal (light grey dotted) reference lines are also shown.

Table VI. Pairwise correlations (Pearson's r) between Δ_{H} and the climatic variables during the GS period for the eight vineyard regions.

	T_{mean}	T_{max}	T_{min}	GDD	DTR	Prec.	$T_{\text{max}} > 35^{\circ}\text{C}$	$T_{\text{min}} < 0^{\circ}\text{C}$
Limnos	**−0.61**	**−0.64**	**−0.73**	**−0.61**	0.10	−0.01	−0.17	0.01
Samos	**−0.72**	**−0.66**	**−0.66**	**−0.71**	0.23	0.05	**−0.62**	0
Santorini	**−0.66**	**−0.64**	**−0.73**	**−0.66**	0.19	0.09	0.08	0
Rodos	0.25	0.29	0.29	0.25	0.02	−0.26	0.43	0
Anchialos	**−0.42**	−0.23	**−0.52**	**−0.42**	**0.38**		**−0.40**	0.08
Nemea	0.10	−0.19	0.07	0.10	−0.27	**0.41**	−0.17	−0.28
Pyrgos	−0.08	−0.20	**−0.56**	−0.08	0.39		−0.04	0.1
Naoussa	**−0.41**	**−0.62**	0.34	**−0.40**	**−0.62**		**−0.43**	0.03

Bold letters indicate significance at $p < 0.05$. Empty cells indicate that the respective variable was not available; 0 indicates that no days with temperature below 0°C was recorded.

RP periods as compared to GS. However, the direction and magnitude of harvest time responses was slightly higher for CY.

Phenological shifts of the basic developmental stages and shortening of the between-stage periods have also been identified in other studies that examined the effects of changing climatic patterns on viticulture (Duchêne and Schneider, 2005). Jones and Davis (2000b) found an advance in the occurrence of budburst, flowering, véraison and particularly harvest in the Bordeaux area, for the varieties Cabernet-Sauvignon and Merlot. In coastal California areas, the start of the GS advanced by 18–24 d

Table VII. Frequency of significant viticulture (Δ_H)–climate relationships for the three definitions of 'effective' growing season.

	CY:tot[a] (mnl.[b]/isl.[c])	GS:tot[a] (mnl.[b]/isl.[c])	RP:tot[a] (mnl.[b]/isl.[c])
T_{mean}	5(2/3)	5(2/3)	2(0/2)
T_{max}	4(1/3)	4(1/3)	3(1/2)
T_{min}	5(2/3)	5(2/3)	4(2/2)
GDD	4(1/3)	6(2/4)	2(0/2)
DTR	1(1/0)	2(2/0)	2(2/0)
Prec.	0(0/0)	1(1/0)	0(0/0)
$T_{max} > 35°C$	3(2/1)	3(2/1)	2(1/1)
$T_{min} < 0°C$	2(1/1)	0(0/0)	0(0/0)
Total	24(10/14)	26(12/14)	15(6/9)

CY: calendar year, GS: growing season and RP: ripening period.
[a]Total number of significant viticulture (harvest-dates)–climate relationships.
[b]Mainland: total number of significant viticulture–climate relations for Nemea, Naoussa, Pyrgos and Anchialos
[c]Islands: total number of significant viticulture–climate relations for Limnos, Samos, Santorini and Rodos.

between 1951 and 1997 (Nemani *et al*., 2001). Lebon (2002) observed grape ripening (véraison) to advance by 3–5 weeks in southern France with a 2–4°C increase in temperature as compared with the baseline calculated from 1973–1992 averages. Tomasi *et al*. (2011) found trends in budburst, bloom, véraison and harvest dates of 13 to 19 d earlier, a shortening of the intervals between events, and a robust climate–phenology relationship of eight days per 1.0°C across numerous varieties in Veneto, Italy.

However, the response of harvest date to climate characteristics in this research was not uniform in all of our study locations, with island sites being slightly more affected than mainland sites. Among mainland locations, Δ_H significantly advanced only in Anchialos and Pyrgos. On the other hand, in Naoussa, harvest date showed no significant trend despite the strong correlation of harvest date anomalies (Δ_H) with climate variables (Tables V and VI). Furthermore, in Rodos, harvest date was delayed despite the significant increasing trend in T_{min} and T_{max}.

According to Lobell *et al*. (2007), a significant crop-climate linear regression indicates that either (1) the climate variable may in fact exert an important control on the crop response, (2) the climate variable may simply be correlated with another climate variable which drives the crop response; and/or (3) the statistical significance arises purely by chance and there is no physical connection between the climate variable and the crop response. In the conditions of our research, the different sensitivity of viticultural variables to climate factors among regions might be explained by several reasons:

1. Temperature anomalies do not affect every region in the same way. According to Jones *et al*. (2005a), GS warming exhibited statistically significant trends in the Northern Hemisphere, while in the Southern Hemisphere (less covered by land), the majority of wine regions experienced lower or non-existent warming trends. In our study, more significant temperature trends were observed in the island wine regions than in the mainland locations (Table IV) with Limnos and Samos being the most vulnerable regions to climatic changes. In these areas, harvest was affected (advanced) by the majority of the temperature-based climate variables.

2. Responses to temperature changes may differ across varieties, mainly related to their temperature threshold for optimum ripening (Jones *et al*., 2005a). For example, in wine regions where varieties currently grown are close to their optimum ripening temperature (thus are systematically harvested at maximum sugar levels), warming would result in earlier sugar ripeness and, consequently, an earlier start of harvest. On the other hand, in more temperate areas (and/or with late ripening varieties) that experience a maturation period that does not allow sugars to accumulate to favourable levels (thus grapes are usually marginally harvested at sub-optimal sugar levels), warming would improve sugar content at harvest but without necessarily a shift in the harvest time. This is probably the reason for the absence of change in harvest dates in Nemea and Naoussa despite the increasing trends in temperature; these areas have late ripening varieties (van Leeuwen *et al*., 2008) and harvest dates occurring at the end of September. In recent research exploring viticulture and climate change relationships in the Veneto region (Italy), late maturing cultivars were found to react at a lower rate than early maturing cultivars to warming conditions (Tomasi *et al*., 2011).

3. Grape ripeness and harvest time decision is also subject to human judgment. As a result, grape growers tend to harvest grapes at relatively constant sugar levels in the must, based on winery specifications, commercial targets, market constraints and other factors (de Orduña, 2010). For example, in Rodos island, the delayed harvest for the Athiri grapes (despite warming conditions over the studied time series) could be related to stylistic wine production factors for sparkling wine production, which is the main usage of the grapes of that region (S. Hatzisav-vas, personal communication). Thus, later picking of grapes could be an adaptation for the production of table wines requiring higher sugar levels for sparkling wines. This is also supported by the fact that Rodos was the only one among the 8 study sites where no significant correlations were recorded between harvest anomaly and any of the climatic variables (Table VI) suggesting that the observed trend in harvest time was not climate-dependent.

4. The ability of the grape growers to foresee the signs of climate change and to adapt viticultural practices to delay grape ripeness (van Leeuwen *et al*., 2007) may possibly mask the effect of climate change on grape ripening and minimize harvest anomalies. Ripeness can be delayed in most cases by the implementation of viticultural practices (minimum leaf removal, reduced

Table VIII. Direction (bold numbers show negative trend) and magnitude of harvest time response (days/GS) to the 'effective' growing season definitions.

	Periods[a]	T_{mean}	T_{max}	T_{min}	GDD	DTR	Prec.	$T_{max} > 35°C$	$T_{min} < 0°C$
Limnos	CY	**−10.6**	**−8.6**	**−10.0**	**0**[b]				0.4
	GS	**−8.5**	**−7.6**	**−9.1**	**0**				
	RP	**−4.8**	**−3.6**	**−4.2**	**−0.1**				
Samos	CY	**−6.2**	**−6.8**	**−4.4**	**0**			**−0.3**	
	GS	**−5.9**	**−5.4**	**−4.2**	**0**			**−0.3**	
	RP	**−2.9**	**−2.8**	**−2.6**	**−0.1**			**−0.5**	
Santorini	CY	**−8.2**	**−8.3**	**−7.5**	**0**				
	GS	**−7.1**	**−6.4**	**−7.0**	**0**				
	RP								
Rodos	CY								
	GS								
	RP								
Anchialos	CY	**−4.3**		**−4.4**	**0**			**−0.4**	
	GS	**−3.3**		**−3.4**	**0**	2.9		**−0.4**	
	RP			**−2.4**				**−0.8**	
Nemea	CY								
	GS						0		
	RP					**−5.0**			
Pyrgos	CY	**−5.9**							0.6
	GS	**−5.8**							
	RP								
Naoussa	CY	**−6.1**	**−4.3**		**0**	**−4.0**		**−0.6**	
	GS	**−6.0**	**−4.5**		**0**	**−3.3**		**−0.6**	
	RP		**−2.9**	3.1		**−2.2**			

Only significant viticulture–climate relationships are shown in the table. Blank cells indicate no statistically significant viticulture–climate relationships.
[a]CY: calendar year, GS: growing season and RP: ripening period.
[b]0: correspond to lower than 0.1 d.

leaf area/fruit weight ratio etc.) and in extreme cases by grafting on certain rootstocks or the use of late ripening clones or varieties. However, there is no evidence to support this possibility in our study.

5. Conclusions

From this research it is evident that regional climate change has affected Greek viticultural areas with increases in temperature parameters at both seasonal and RP time scales. This is especially evident in the island locations, where the moderating effects of being near the sea appear to not be sufficient to buffer changes in climate. These observations are important as many wine regions worldwide have coastal zone influences in which it is often thought that they may be less prone to climate change. The changes in Greek viticultural region climates were found to exert a significant impact on harvest time and similar results have been found in wine regions worldwide (Jones *et al.*, 2005b; Webb *et al.*, 2007; Tomasi *et al.*, 2011). In the future Greece is expected to experience further warming [i.e. increased ripening temperatures, increased frequencies of exceptional hydrological and meteorological events (Mavromatis, 2012)] producing challenges in ripening balanced fruit. While much of the climate change and wine region research has focused on more moderate mid-latitude regions (Jones *et al.*, 2005a), this research documents significant changes in one of the world's warmer viticultural regions. Other warm wine regions worldwide such as Greece are at the upper temperature limit for many varieties and further changes in climate may push them past suitability for viticulture. To meet some of these challenges, a greater effort by growers should be given to adapt viticulture to future climate characteristics and trends, especially in the warmest areas and where early ripening varieties are currently cultivated. A greater effort should therefore be given to systematic observation of dates of previous development stages (e.g. budburst, bloom, véraison, etc.) and the growth intervals between them, because they are inextricably linked to harvest date across different areas and varieties in Greece. The identification of up-to-date climate and grapevine phenological relationships could be an important step for broader and more confident future assessments for viticultural suitability and sustainability in Greece. Given that Greece is one of the world's warmer wine regions, a better understanding of these relationships could provide others worldwide with knowledge of upper temperature limits to viticulture and adaptability to changes in climate.

References

Adams RM, Hurd BH, Lenhart S, Leary N. 1998. Effects of global climate change on agriculture: an interpretative review. *Climate Research* **11**: 19–30.

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F. 1996. Modeling the impact of future climate scenarios on yield and variability of grapevine. *Climate Research* **7**: 213–224.

Blanco-Ward D, Garcia-Queijeiro JM, Jones GV. 2007. Spatial climate variability and viticulture in the Miño River Valley of Spain. *Vitis* **46**: 63–70.

Bock A, Sparks T, Estrella N, Menzel A. 2011. Changes in the phenology and composition of wine from Franconia, Germany. *Climate Research* **50**: 69–81.

Cahill KN, Lobell DB, Field CB, Bonfils C, Hayhoe K. 2007. Modelling climate change impacts on wine grape yields and quality in California. Réchauffement climatique, quels impacts probables sur les vignobles? Dijon, France.

Chessel D, Dufour AB, Thioulouse J. 2004. The ade4 package—I: one-table methods. *R news* **4**: 5–10.

Chuine I, Yiou P, Viovy N, Seguin B, Daux B, Le Roy LE. 2004. Grape ripening as a past climate indicator. *Nature* **432**: 289–290.

Conde C, Silva P, Fontes N, Dias ACP, Tavares RM, Sousa MJ, Agasse A, Delrot S, Gerós H. 2007. Biochemical changes throughout grape berry development and fruit and wine quality. *Food* **1**: 1–22.

Coombe B. 1987. Influence of temperature on composition and quality of grapes. In *Proceedings of the International Symposium on Grapevine Canopy and Vigor Management*, Vol. **XXII IHC**. ISHS Acta Horticulturae 206: Davis, CA; 23–35.

Duchêne E, Schneider C. 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agronomy for Sustainable Development* **25**: 93–99.

Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK. 1997. Maximum and minimum temperatures for the globe. *Science* **277**: 364–366.

Ganichot B. 2002. Evolution de la date des vendanges dans les Côtes du Rhône méridionales. In *6emes Recontres Rhodaniennes*. Institut Rhodanien: Orange, France; 38–41.

Gaudillère JP. 2007. Les réponses de la vigne face aux changements climatiques à Bordeaux. In *8èmes Journées Techniques du CIVB Actes*, 13 Mars, Bordeaux-Lac, France, 81–89.

Grifoni D, Mancini M, Maracchi G, Orlandini S, Zipoli G. 2006. Analysis of Italian wine quality using freely available meteorological information. *American Journal of Enology and Viticulture* **57**(3): 339–346.

Hall A, Jones GV. 2009. Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Australian Journal of Grape and Wine Research* **15**: 97–119.

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**: 1965–1978.

IPCC. 2007. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge.

Jolliffe IT. 2002. *Principal Component Analysis*. Springer: New York.

Jones GV. 2005. Climate change in the western United States grape growing regions. *Acta Horticulturae (ISHS)* **689**: 41–60.

Jones GV, Davis RE. 2000a. Using a synoptic climatological approach to understand climate-viticulture relationships. *International Journal of Climatology* **20**: 813–837.

Jones GV, Davis RE. 2000b. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture* **51**(3): 249–261.

Jones GV, Goodrich GB. 2008. Influence of climate variability on wine regions in the western USA and on wine quality in the Napa Valley. *Climate Research* **35**: 241–254.

Jones GV, White MA, Cooper OR, Storchmann K. 2005a. Climate change and global wine quality. *Climate Change* **73**: 319–343.

Jones GV, Duchêne E, Tomasi D, Yuste J, Braslavksa O, Schultz HR, Martinez C, Boso S, Langellier F, Perruchot C, Guimberteau G. 2005b. Changes in European winegrape phenology and relationships with climate. In *XIV International GESCO-Viticulture-Congress*, Geisenheim, Vol. 1, 55–61.

Kaiser HF. 1960. The application of electronic computers to factor analysis. *Educational and Psychological Measurement* **20**: 141–151.

Kaufman L, Rousseeuw PJ. 1990. *Finding Groups in Data: An Introduction to Cluster Analysis*. Wiley: New York.

Kenny GJ, Harrison PA. 1992. The effects of climate variability and change on grape suitability in Europe. *Journal of Wine Research* **3**(3): 163–183.

Kriedemann P, Smart R. 1971. Effect of irradiance, temperature and leaf water potential on photosynthesis of vine leaves. *Photosynthetica* **5**: 6–15.

Lacombe T, Audeguin L, Boselli M, Bucchetti B, Cabello F, Chatelet P, Crespan M, D'Onofrio C, Eiras Dias J, Ercisli S, Gardiman M, Grando MS, Imazio S, Jandurova O, Jung A, Kiss E, Kozma P, Maul E, Maghradze D, Martinez MC, Muñoz G, Pátkova JK, Pejic I, Peterlunger E, Pitsoli D, Preiner D, Raimondi S, Regner F, Savin G, Savvides S, Schneider A, Spring JL, Szoke A, Veres A, Boursiquot JM, Bacilieri R, This P. 2011. Grapevine European catalogue: towards a comprehensive list. *Vitis* **50**: 65–68.

Lavalle C, Micale F, Durrant Houston T, Camia A, Hiederer R, Lazar C, Conte C, Amatulli G, Genovese G. 2009. Climate change in Europe 3 impact on agriculture and forestry: a review. *Agronomy for Sustainable Development* **29**: 433–446.

Lebon E. 2002. Changements climatiques: quelles conséquences pour la viticulture. In *6emes Recontres Rhodaniennes*. Institut Rhodanien: Orange, France; 31–36.

Legendre P, Legendre L. 1998. *Numerical Ecology*, 2nd English edn. Elsevier: Amsterdam.

Lobell DB. 2007. Changes in diurnal temperature range and national cereal yields. *Agricultural and Forest Meteorology* **145**: 229–238.

Lobell DB, Field CB. 2007. Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letters* **2**: 014002.

Lobell DB, Field CB, Cahill KN, Bonfils C. 2006. Impacts on future climate change on California perennial crop yields: model projections with climate and crop uncertainties. *Agricultural and Forest Meteorology* **141**: 208–218.

Lobell DB, Cahill KL, Field CB. 2007. Historical effects of temperature and precipitation on California crop yields. *Climatic Change* **81**: 187–203.

Matzarakis A, Ivanova D, Balafoutis C, Makrogiannis T. 2007. Climatology of growing degree days in Greece. *Climate Research* **34**: 233–240.

Mavromatis T. 2012. Changes in exceptional hydrological and meteorological weekly event frequencies in Greece. *Climatic Change* **110**: 249–267.

Mavromatis T, Stathis D. 2011. Response of the water balance in Greece to temperature and precipitation trends. *Theoretical and Applied Climatology* **104**: 13–24.

Mullins MG, Bouquet A, Williams LE. 1992. *Biology of the Grapevine*. Cambridge University Press: Cambridge.

Myles S, Boyko AR, Owens CL, Brown PJ, Grassi F, Aradhya MK, Prins B, Reynolds A, Chia JM, Ware D, Bustamante CD, Buckler ES. 2011. Genetic structure and domestication history of the grape. *PNAS* **108**: 3530.

Nastos PT, Matzarakis AP. 2008. Variability of tropical days over Greece within the second half of the twentieth century. *Theoretical and Applied Climatology* **93**: 75–89.

Nastos PT, Zerefos CS. 2009. Spatial and temporal variability of consecutive dry and wet days in Greece. *Atmospheric Research* **94**: 616–628.

Nastos PT, Philandras CM, Founda D, Zerefos CS. 2011. Air temperature trends related to changes in atmospheric circulation in the wider area of Greece. *International Journal of Remote Sensing* **32**: 737–750.

Nemani RR, White MA, Cayan DR, Jones GV, Running SW, Coughlan JC, Peterson DL. 2001. Asymmetric warming over coastal California and its impact on the premium wine industry. *Climate Research* **19**: 25–34.

NSSG. 2000–2008. National Statistical Service of Greece 2000–2008. The Annual Industry Survey, Athens.

de Orduña RM. 2010. Climate change associated effects on grape and wine quality and production. *Food Research International* **43**: 1844–1855.

Petrie PR, Sadras VO. 2008. Advancement of grapevine maturity in Australia between 1993 and 2006: putative causes, magnitude of trends and viticultural consequences. *Australian Journal of Grape and Wine Research* **14**: 33–45.

Ramos MC, Jones GV, Martinez-Casasnovas JA. 2008. Structure and trends in climate parameters affecting winegrape production in northeast Spain. *Climate Research* **38**: 1–15.

Rodo X, Comin FA. 2000. Links between large-scale anomalies, rainfall and wine quality in the Iberian Peninsula during the last three decades. *Global Change Biology* **6**: 267–273.

Rousseeuw PJ. 1987. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics* **20**: 53–65.

Schultz HR, Jones GV. 2010. Climate induced historic and future changes in viticulture. *Journal of Wine Research* **21**: 137–145.

Struyf A, Hubert M, Rousseeuw PJ. 1997. Clustering in an object-oriented environment. *Journal of Statistical Software* **1**: 1–30.

Tao F, Yokozawa M, Liu J, Zhang Z. 2008. Climate-crop yield relationships at provincial scales in China and the impacts of recent climate trends. *Climate Research* **38**: 83–94.

Tate AB. 2001. Global warming's impact on wine. *Journal of Wine Research* **12**: 95–109.

Tomasi D, Jones GV, Giust M, Lovat L, Gaiotti F. 2011. Grapevine phenology and climate change: relationships and trends in the Veneto Region of Italy for 1964–2009. *American Journal of Enology and Viticulture* **62**(3): 329–339.

Urhausen S, Brienen S, Kapala A, Simmer C. 2011. Climatic conditions and their impact on viticulture in the Upper Mosel region. *Climate Change* **109**: 349–373.

Van Leeuwen C, Seguin G. 1994. Incidences de l'alimentation en eau de la vigne, appréciée par l'état hydrique du feuillage, sur le développement de l'appareil végétatif et la maturation du raisin (Vitis vinifera variété Cabernet franc, Saint-Émilion, 1990). *Journal International des Sciences de la Vigne et du Vin* **28**(2): 81–110.

Van Leeuwen C, Bois B, Pieri P, Gaudillère J-P. 2007. Climate as Terroir Component. Congress on climate and viticulture, Zaragoza, 10–14 April 2007, 1–12.

Van Leeuwen C, Garnier C, Agut C, Baculat B, Barbeau G, Besnard E, Bois B, Boursiquot JM, Chuine I, Dessup T, Dufourcq T, Garcia-Cortazar I, Marguerit E, Monamy C, Koundouras S, Payan J-C, Parker A, Renouf V, Rodriguez-Lovelle B, Roby J-P, Tonietto J, Trambouze W. 2008. Heat requirements for grapevine varieties is essential information to adapt plant material in a changing climate. In *Proceedings of the 7th International Terroir Congress*, Murisier F, Zufferey V (eds). Suisse: Nyon; 222–227.

Webb LB, Whetton PH, Barlow EWR. 2007. Modelled impact of future climate change on the phenology of winegrapes in Australia. *Australian Journal of Grape and Wine Research* **13**: 165–175.

Winkler AJ, Cook JA, Kliewer WM, Lider LA. 1974. *General Viticulture*. University of California Press: Berkeley, CA.