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A study on the effects of climate change on viticulture on Santorini Island

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ABSTRACT

The Mediterranean basin is regarded as one of the regions the most affected by climate change in the world. Traditionally, viticulture in this region copes with high temperatures, heat waves and drought. Such particularly extreme conditions, which induce severe abiotic stress on plants, are expected to intensify due to the predicted climate changes in the future. Our study focuses on the viticulture of Santorini Island, located in South Aegean (Greece). Vines have been cultivated on Santorini Island for thousands of years on their own roots owing to the phylloxera-free volcanic soil of the island. The vineyards of Mediterranean regions are already encountering difficulties because of ongoing climate change. The aim of this study was to analyse chronological climate data, evaluate the trends in the change of climate parameters and bioclimatic indices and correlate them with viticultural indices. In brief, the average annual temperature has increased in the last 45 years by almost 4 °C and a significant increase in the frequency of days with high temperatures has been recorded. Bioclimatic indicators correspond to warmer climates with warmer nights and longer periods of drought. Finally, it appears that the high temperatures occurring during the critical stages of the development and differentiation of the vine seem to affect production in the following growing season, while earlier harvest dates and higher sugar content than 45 years ago are observed.

KEYWORDS: Climate change; Bioclimatic indices; Grapevine cultivation; Greece; Assyrtiko

INTRODUCTION

According to the latest IPCC report (IPCC, 2021), climate projections show that the negative effects of climate change will intensify over the 21st century and will continue to impact nature, ecosystems and human activities. Several future scenarios have been developed with differing levels of intensity in terms of negative effects of climate change; all these scenarios point to an overall increase in global temperature. However, the predicted magnitude of temperature rise is largely dependent on the emissions scenario, which has high associated uncertainties (Denman *et al.,* 2007; Meehl *et al.,* 2007). Effort is being made to deal with the problems associated with climate change at a global level; however, the UN Agenda 2030 and the subsequent Paris agreement[1] (COP2, December 12, 2015) have not yet managed to transform global commitments into substantial actions. There has been no major advancement in complying with goal number 13 of the UN2030 Agenda on Sustainable Development Goals (SDGs) aiming to stabilise negative trends by around 2030.

Several studies have been conducted to measure the effects of climate change on different crops worldwide (Urhausen *et al*., 2011; Howden *et al.,* 2007). However, an exploration of the impacts of climate change on agricultural ecosystems reveals that the latter are locally managed systems inevitably affected by the decisions, choices, practices and habits of human beings, as well as by available resources and technology (Fischer *et al.*, 2005). Consequently, climate change tends to shift from being an exogenous to a semi-endogenous factor due to human activity (subject to human rationale and not decision-making), while undoubtedly continuing to exert major control on the productivity of crops (UNISDR, 2010).

Temperature anomalies and changes in annual rainfall patterns could have both positive or negative impacts on the quality and quantity of agricultural production at a regional or even local scale (Lavalle *et al*., 2009). When it comes to the potential effects of climate change on grape production, significant relationships between viticulture and climate factors have been established (Jones and Goodrich, 2008; Tomasi *et al.,* 2011; Koufos *et al.,* 2014).

Indeed, high temperatures and radiation, along with increasing atmospheric CO_2 concentration, all influence the yield of wine-producing grapes, grape maturity and physiology of the grapevine (van Leeuwen *et al.,* 2019; Kizildeniz *et al.,* 2015; Fraga *et al*., 2016; Fraga *et al.*, 2015; Lazoglou *et al.,* 2017). Environmental factors, such as air and soil temperature, precipitation, solar radiation and carbon dioxide concentration (CO_2), are expected to change (Webb *et al*., 2008; Costa *et al*., 2016) under the different climate scenarios. These factors play an important role in grape and wine colour and aroma (Kliewer and Torres, 1972; Kliewer, 1973; Tomana *et al.*, 1979). Some effects of high temperatures on grapevine physiology and berry composition have been reviewed by Venios *et al.* (2020), as presented hereafter. The optimum photosynthetic temperature for grapevine is between 25 and 35 °C (Kun *et al.,* 2018). At temperatures over 35 °C, heat acclimation mechanisms are activated (Bernardo *et al.,* 2018; Ferrandino and Lovisolo, 2014). Extremely high temperatures (i.e., above 40 °C) affect photosynthesis mainly because of disruption to the photosynthetic apparatus. Regarding berry composition, the increase in temperature is expected to lower the acidity and increase the sugar content of berries, resulting in unbalanced wines that have a higher alcohol content and are deprived of freshness and aromatic complexity (Bernardo *et al.,* 2018; van Leeuwen and Destrac-Irvine, 2016). Anthocyanin content is also reduced by high temperatures, and titratable acidity decreases as temperature increases, being lower at 30 °C than at 20 °C (Poudel *et al.,* 2009). Heat stress occurs, especially at the stage of grape maturity, increase of the potassium concentration of berries, thereby increase at the pH value and finally reduce of the total acidity (Bernardo *et al.,* 2018). When the temperature is relatively high during the day, a low night temperature is essential to ensure low pH; however, global warming due to climate change is expected to be associated with elevated temperatures at night rather than during the day, thus impacting the sustainability of the grape/wine sector. High temperatures also affect the sugar-acid balance. Heat stress restrains the formation of anthocyanins and flavour compounds in grapes grown in temperate regions (Poudel *et al.,* 2009). During the grape maturation stage, the ideal temperature for optimum formation of aroma compounds is within the range of 20 to 22 °C (Greer and Weedon, 2012). Colour formation has been found to decrease when the temperature exceeds 30 °C, and at temperatures of over 37 °C grape colour decreases and the volatilisation of aroma compounds increases (Bernardo *et al.,* 2018).

Climate simulation models have predicted a modification in global and regional environmental conditions, leading to the alteration of grapevine production regimes in terms of both quantity and quality (Santos *et al*., 2020; Stöckle *et al*., 2010; van Leeuwen *et al.*, 2019).

According to Hannah *et al.* (2013), most of winegrowing regions are expected to experience an increase in average temperature by 2 to 4 °C, resulting in major biochemical and physiological alterations to the vines (Chaves *et al*., 2010). Santorini does not appear to be an exception to this general trend. It therefore follows that climate change will require the winegrowers of Santorini Island to adapt their traditional practices and adopt adequate agronomic strategies to deal with the higher levels of heat and drought.

In particular, the following issues are of significant importance:

a) Extreme temperatures during longer summers are commonly observed with increasing frequency.

1 COP21 or Paris Agreement is a legally binding international treaty on climate change entered into effect on 2016. The agreement aims to limit global warming, preferably by 1.5 degree Celsius.

Summer temperatures that exceed +35 °C in the shade (that is, more than +40 °C in the sun) are considered 'negative' for the vine as they impair vine physiology and biochemistry C (Fraga *et al.,* 2020). The consequences of a total or even partial inhibition of plant function depend on the duration and frequency of elevated temperatures (Laget *et al*., 2008).

b) Earlier harvest is common. It is generally accepted that warmer conditions due to climate change are generally associated with shorter intervals between phenological events and earlier harvest dates (Bindi *et al*., 1996; Tomasi *et al*., 2011; Leolini *et al.,* 2020). Hence, the timing of harvest is associated with the ability of the vine to yield and ripen fruit to optimum levels (Jones and Davis, 2000). Grape maturity and harvest have been reported to be 0.5 to 3.1 days early per year in Australia for Cabernet-Sauvignon, Chardonnay and Shiraz (Petrie and Sadras, 2008). However, literature data on terroirs and varieties of grape vines, and their relationship with climate change in the Mediterranean zone and the south Aegean Islands, are scarce (Alba *et al*., 2021; Koufos *et al*., 2014). Few studies have explored or predicted the impact of climate change on grape vines, despite the importance of the viticultural sector at both the national and local economical scale (Laget *et al.,* 2008; Alba *et al.*, 2021; Koufos *et al*., 2017; Fraga *et al.,* 2017).

In this study, we aimed to analyse historical climatic data and evaluate the trends of grapevine performance with changing climate conditions on Santorini Island. We have created indicators using the collected data of climate conditions, as well as quantitative data related to grape production of the Santorini viticultural region over a relatively long period of time (1974–2019). Subsequently, the data were analysed longitudinally and correlations between parameters of interest were explored. This work aims at understanding the effects of climate change on the viticulture of Santorini in order to be able to contribute to the sustainable management of Santorini vineyards and help them adapt to the developing climatic conditions.

MATERIALS AND METHODS

1. Study area

Santorini is a part of the island complex of Cyclades, located in South Aegean (Figure 1). It has a surface area of 79.16 km^2. It is located at a geographical latitude of between 36°19'56'' and 36 °28'40''N and has a geographical longitude of between 25°19'22'' and 25°29'13''E. The viticultural region of the island comprises approximately 1000 ha from sea level to the terraces at 150 to 350 m above sea level. In this ancient, dry and phylloxera-free winegrowing region, two specific and unique training systems are used which are well-adapted to the island's specific climate and weather conditions: the "kouloura" (basket shape) and the "kladeftiko" (Figures 2a and b) (Xyrafis *et al.,* 2021). The main cultivated grape varieties (*Vitis vinifera* L.) are Assyrtiko, Aidani and Athiri (white) and Mandilaria and Mavrotragano (red) (Xyrafis *et al.,* 2021). The annual wine production is nearly 1.1 × 10^3 tonnes, representing approximately a mere 0.5 % of the annual Greek production. According to Köppen's classification (Peel *et al.,* 2007), Santorini's climate is characterised as being "dry-summer subtropical".

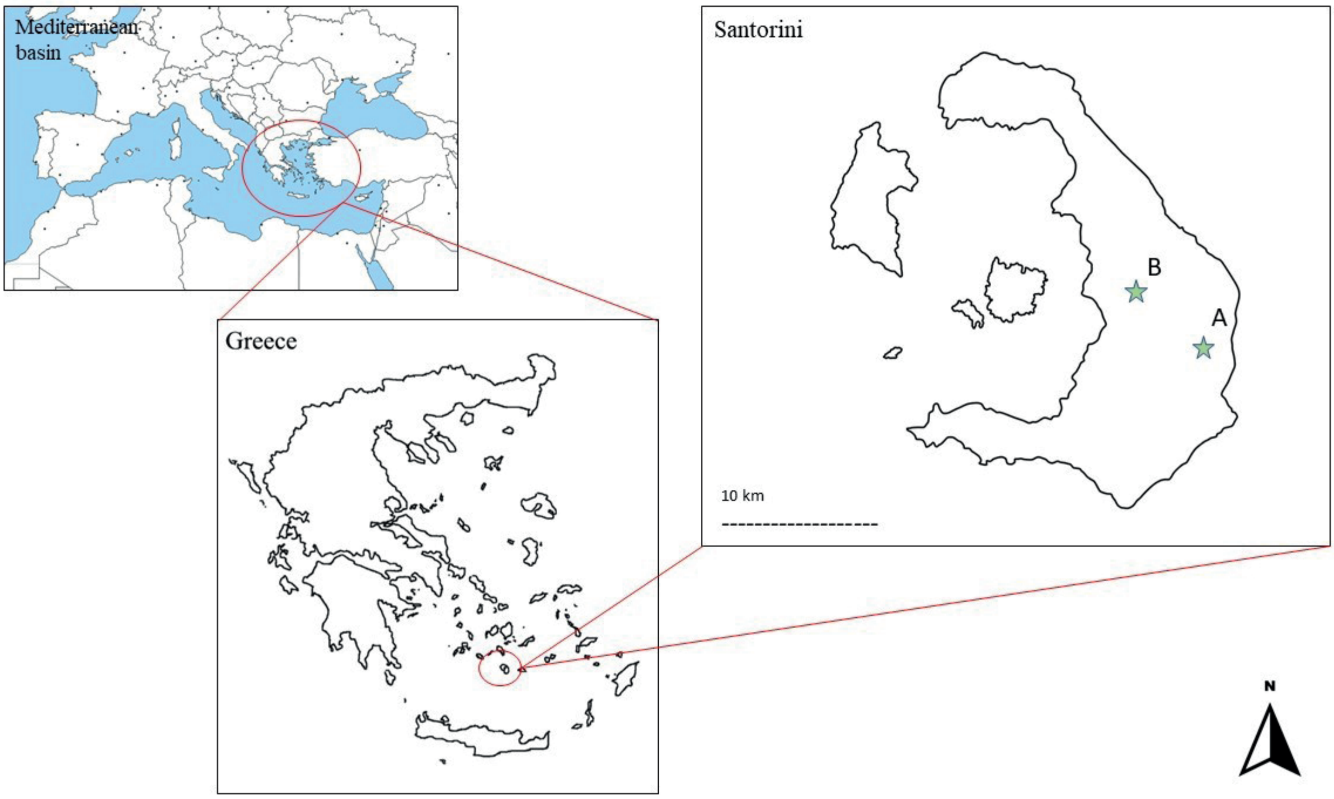

FIGURE 1. Study area and meteorological stations (A and B).

FIGURE 2. Traditional training systems of Santorini a) Kouloura and b) Kladeftiko.

Such climatic conditions are often referred as Csa "Mediterranean climate". The climatic system of Santorini comprises mild winters with low rainfall (mean annual precipitation 316 mm from 1974 to 2019) and cool springs. The rainy season of the last 45 years has lasted from October to April. Although breezes also characterise Santorini's climate, strong winds are extremely common and can result in the destruction of vines depending on the stage of their development. The annual mean air temperature is 18.4 ^{o}C. In the summer and near harvest periods, which last from the end of July to the end of August, weather conditions tend to be extreme with high temperatures (an average of three days was recorded with summer temperatures of > 35 °C during the period 1979–2019) and prolonged drought periods. However, the phenomenon of "*anedossa*", a type of floating sea fog that appears at night until early morning, probably offers some relief as it constitutes the only source of humidity available to the vines during the arid season (Kourakou, 2015).

2. Datas and methods

2.1. Climate data sources and grapevine data

In the present study, climate data for Santorini were obtained from the Hellenic National Meteorological Service (HNMS), while climate data for the Monolithos region (Figure 1A) were obtained from the National Meteorological Society. The chronological series covers the period 1974–2019. The collected data were subsequently checked for errors and few missing values were replaced using a valid alternative source (weather station of Santorini in Fira provided by the National Observatory of Athens) (Figure 1B). More specifically, when a missing value was detected in the HNMS, it was replaced by the corresponding value from an alternative source (Figure 1B) when available, or missing values were replaced using standard linear interpolation. In Santorini, data were collected daily from a reference weather station set up on the island. The parameters measured were as follows: temperature (^{o}C), wind speed (knots), number of days with temperatures > 30 °C and > 35 °C, relative humidity (%) and rainfall (mm) (the latter is summarised in Table 1).

The collected grapevine data contained the following variables: the island's annual production (t/Ha), cultivated area (Ha) and organoleptic data (alcohol %, pH and total acidity) of the produced Protected Designation of Origin (PDO) wines. The selected chronological series covered the period 2005–2019 and the data were obtained from the Department of Rural Development of the Thira region (http://minagric.gr/index.php/en/). The harvest dates with corresponding sugar content (°Brix) for the Assyrtiko variety were obtained from the archive of the Santorini Agricultural Products Association, which provided the relevant chronological series from 1982 to 2019.

2.2 Viticultural agroclimatic indicators

Several other indicators were also measured as viticultural agroclimatic indicators, such as the Huglin Index (Huglin, 1978), Reference evapotranspiration ETo and Crop evapotranspiration ETc (mm), Dryness index (Riou *et al.,* 1994), Growing degree days (Gilmore and Rogers, 1958), Cool night index (Tonietto, 1999) and Diurnal temperature range. Climatic factors are important indicators of the level of grape ripening and wine quality (Jackson and Cherry, 1988; Seguin, 1983; Mérouge *et al.*, 1998; Carbonneau and Tonietto, 1998). All measurements and indicator calculations were carried out according to international norms and guidelines of the International Organization of Meteorology (World Meteorological Organization, 1971).

The Huglin index (HI), calculated and adapted to Santorini conditions, is defined as follows:

$$HI = \sum_{1stMarch}^{31stAugust} \left(\frac{((Tmean-10)+(Tmax-10))}{2} \right) * k,$$

where T_{mean} = mean air temperature in °C; T_{max} = maximum air temperature in °C; k = length of day coefficient, which has a value of 1.03 at latitudes between 42 °1 ‹ and 44 °0 ‹. This index enables different viticulture regions of the world to be classified in terms of the sum of temperatures required for vine development and grape ripening (Huglin, 1978). Specifically, it is the sum of the mean and maximum temperatures above +10 °C, which is the thermal threshold for vine development. The HI is calculated for a 6-month period (March to August) for Santorini and is useful for characterising areas according to their potential for viticulture (Huglin, 1978). Different grape varieties are classified according to their minimal thermal requirements for grape ripening; for example, the HI is 1700 for Chardonnay and 2100 for Syrah. The minimum HI for vine development is 1600 (Laget *et al.*, 2008). The HI is used as a helio-thermic reference in viticulture to compare and classify the major viticultural regions and to determine the plantations of different varieties of grapes (Koufos *et al.*, 2017).

The dryness index (DI) was measured based on an adaptation from the potential water balance of the soil index (Riou *et al.,* 1994), which was developed specifically for vineyard usage. The DI enables the characterisation of the water component of the climate in a winegrowing region and it takes into consideration the climatic demand of a standard vineyard, evaporation from bare soil and rainfall without deduction for surface runoff or drainage. The DI provides the potential water availability of the soil, which is related to the level of dryness in a region.

Adapted to the precise conditions of Santorini in the calculations described below, the dryness index is defined as:

$$DI = W = Wo + P - Tv - Es,$$

where W is the estimate of soil water reserve at the end of a given period, Wo (mm) is the initial useful soil water reserve (which can be accessed by tree roots), P (mm) is the precipitation, Tv (mm) is the potential transpiration of the vineyard and Es is the direct evaporation from the soil. The DI was calculated using data from the same six-month period as that used for estimating HI, which is acceptable for most vineyards worldwide. The W values in the initial and final Santorini-adapted dates (March 1 and September 30 respectively) in the northern hemisphere are reported as W = Wo reserve and W = DI respectively.

In the preceding formula, Tv and Es were calculated for each month using the following equation:

$$Tv = ETPk,$$

where, ETP (mm) is the potential evapotranspiration (total of monthly data) determined using the Penman method (Penman, 1948). ETp was calculated by means of CROPWAT 8.0 (FAO, 1992), which provides an Estimated ETp on the base of T_{max} and T_{min} when other climate data are missing. k is the coefficient of radiation absorption by vine plants, which is related to transpiration and depends on vine architecture as follows:

$$Es = ETP\ N\ (1 - k)JPm,$$

where N is the number of days in the month and JPm is the number of days of effective evaporation from the soil per month. JPm is the rainfall per month in mm/5 and it should be lesser than or equal to the number of days per month.

In the Northern hemisphere, k = 0.1 for March, 0.3 for April and 0.5 for the months from May to August (Adapted for Santorini).

W can be negative when there is a deficit in potential water; however, it should never be greater than Wo. The index was calculated per month based on monthly values of P, ETP, Tv and Es. DI is the W value obtained in the final dates following the rules described above and when Wo = 200 mm

Growing degree days (GDD) describes the heat energy received by the crop over a given time period. This index subtracts 10 °C (base temperature) from the daily mean temperature over the growing season. T_{max} and T_{min} are the daily maximum and minimum temperature (°C) respectively. These also define the Diurnal Temperature Range (DTR) by $DTR = T_{max} - T_{min}$

According to Winkler *et al.* (1974), the base temperature (T_{base} °C) for physiological activities (such as photosynthesis and transpiration) is considered to be 10 °C, and the daily GDD for 1 d can be calculated using the following formula:

$$GDD = \sum_{1stMarch}^{31stAugust} \left(\frac{Tmax+Tmin}{2} \right) - Tbase,$$

GDD is very useful for predicting phenological stages and, when classified according to Winkler Regions I–V, gives an indication of the potential ripening of varieties and wine styles that can be produced (Anderson *et al.,* 2012).

The Cool night index (CI) takes into account the mean minimum night temperatures during the months when ripening usually occurs beyond the ripening period (Tonietto, 1999). The purpose of using this index is to improve the assessment of the qualitative potential of wine-growing regions, notably in relation to secondary metabolites (polyphenols and aromas) of grapes.

The CI was determined as follows in the Northern hemisphere:

CI = average minimum air temperature during August (mean of minima).

2.3 Statistical analysis

Standard linear model analysis is used to assess the existence of linear trends for relationships with continuous variables, such as standardised production versus period of time in years. The Cochrane-Orcutt (Cochrane and Orcutt, 1949) procedure was used to adjust the linear model for serial correlation in the error term. Stata 16.1 (Stata Corp LLC, College Station, TX, USA) was used for data analysis and graphical illustrations. Statistical significance was set at $p < 0.05$.

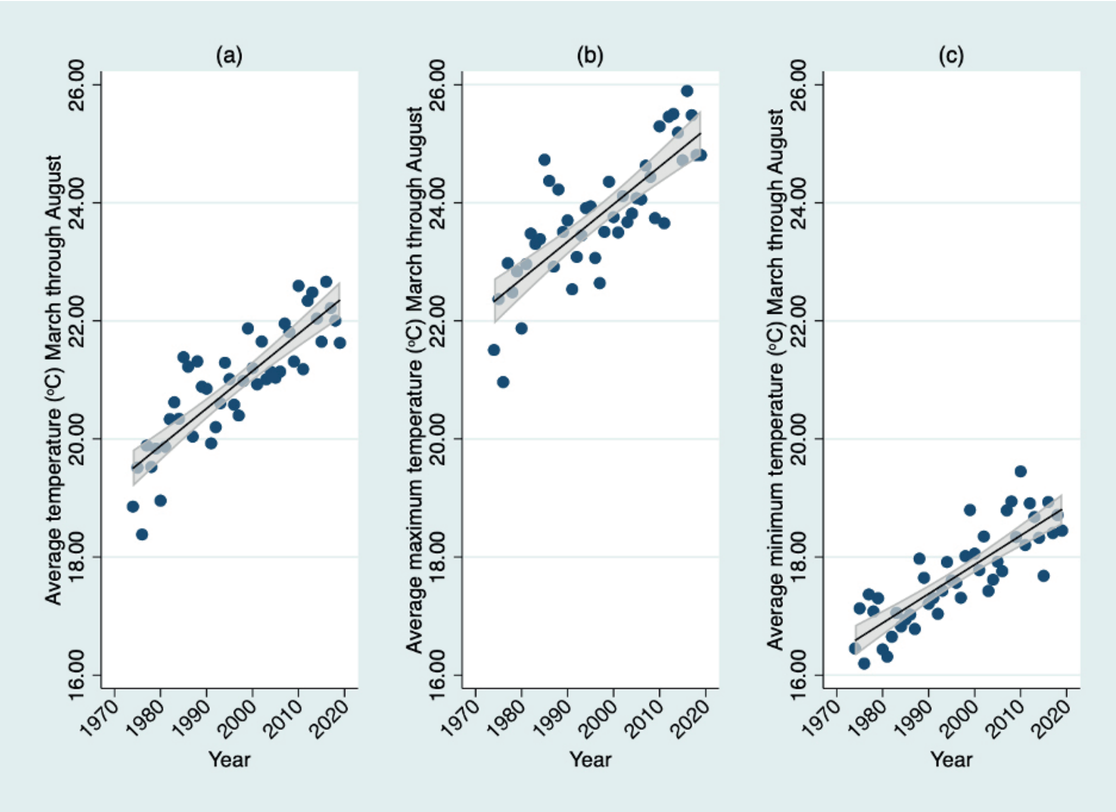

FIGURE 3. Trends of temperatures (mean (a), maximum (b), and minimum (c)) for the period March–August during 1974–2019.

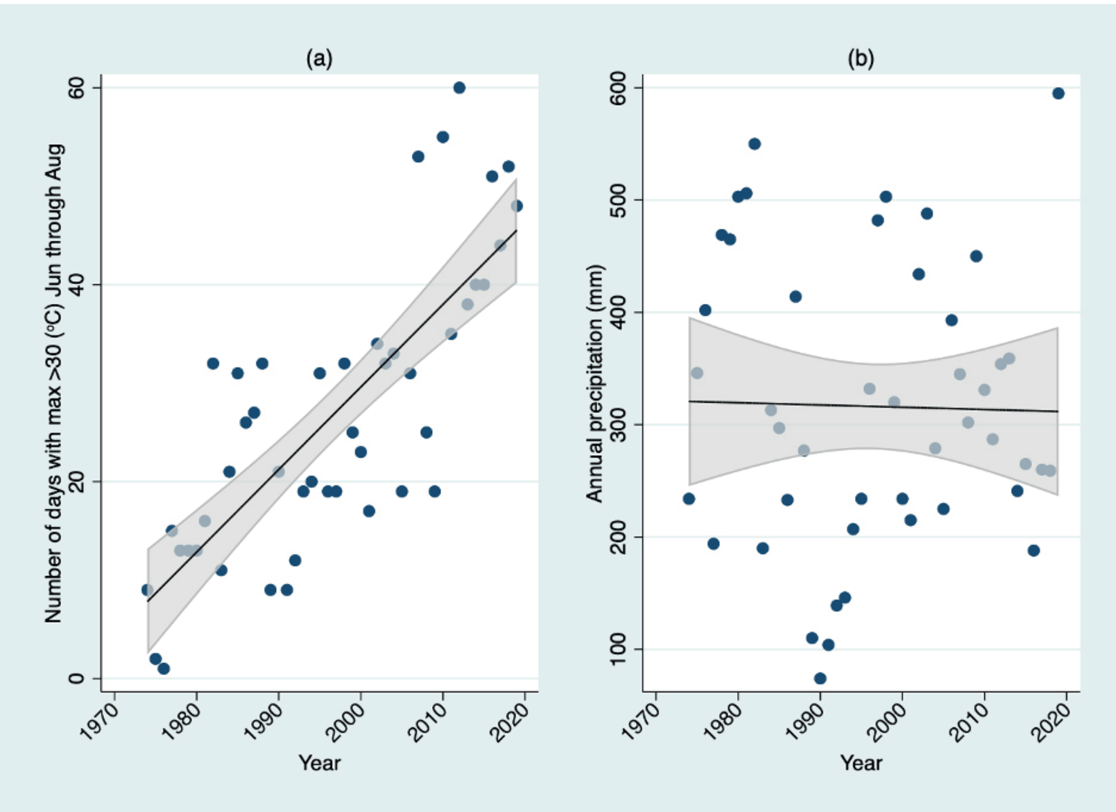

FIGURE 4. Trend in the number of days with maximum temperature > 30 °C in June–August, 1974–2019 (a). Trend of annual precipitation in 1974–2019 (b).

RESULTS

1. Development of mean, maximum and minimum temperatures for different cultivation periods

A characteristic of Santorini vineyards is that the cultivation period for the main variety, 'Assyrtiko', an indigenous white grape, starts in March and ends in August. Bearing this in mind, we observed that in the last decade harvest on the island has mostly taken place during the first two weeks of August. Figure 3 (a) shows the average temperature of the period March to August from 1974 to 2019; the corresponding linear equations are summarised in Table 2. A constant annual increase during the last 45-year period by 0.06 degrees per year (95 % CI: 0.04, 0.08) is observed, with a total increase of approximately 3.8 ^{o}C. A similar pattern occurs for average maximum and average minimum temperatures; i.e., 0.06 (95 % CI: 0.04, 0.08) for maximum and 0.05 (95 % CI: 0.04, 0.06) for minimum temperatures respectively (Figures 3(b), 3(c) and Table 2).

Similar trends for T_{mean} and T_{min} were observed for the remaining periods of interest (May 15 to June 15, July 10 to August 10, June–August). Due to bud differentiation occurring from May 15 to June 15, this period is critical for the productivity of the vineyard in the following year. Relevant research on Greek varieties has revealed that bud differentiation starts 5–6 weeks after bud burst (Carolus, 1970; Logothetis and Vlachos, 1967). The maximum temperature during these crucial for bud differentiation few weeks, has increased annually by 0.03 (95 % CI: 0.02, 0.04) since 1974, reaching critical temperatures. A similar increase was observed for the T_{max} temperature from July 10 to August 10 and from June to August.

2. Frequencies of days with maximum temperatures exceeding 30 °C and rainfall trends

Figure 4 (a) shows the trends in the number of days with maximum temperature > 30 °C for June, July and August. The number of days with maximum temperatures > 30 °C increased significantly from 1974 to 2019. Specifically, the number of days with temperatures exceeding 30 °C was 9 in 1974 and reached 48 in 2019. Over the past 45 years, a constant, linear increase of 0.8 per year (95 % CI: 0.6, 1.0) has been recorded in the number of days with temperatures of 30 ^{o}C. One can safely conclude that there is a significant shift towards a long-term warming tendency.

Figure 4 (b) illustrates that there were no significant changes in rainfall trends over the observed 45-year period (p = 0.9) (Table 2). However, changes have been observed in the yearly distribution of rainfall, with lower observed amounts of precipitation during the springs and summers of the last vicennial relative to the first part of the study period (25 years). Specifically, there is a decrease in mean spring and summer precipitation of from 100 mm (1974-1999) to 75 mm (2000–2019) and from 30 mm (1974–1999) to 8 mm (2000–2019) respectively (Table 1).

3. Bioclimatic indicators

Figure 5 (a) shows the development of the Dryness index (DI) in March–August over the period 1974–2019. The trend is negative with a marginally non-significant decrease of -0.84 per year (Table 2). The size order of the index for Santorini is mainly characterised as moderately dry DI + 1 according to the categorisation of Tonietto and Carbonneau (2004).

There were no significant variations in the reference evapotranspiration ETo and the crop evapotranspiration ETc (mm) during the study period.

Figure 5 (b) shows the trends in the Huglin Index for the period March–August during the time series 1974–2019. The index increases significantly (p < 0.001) by 11.5 per year (95 % CI: 8.3, 14.8). The same trend was observed for the periods April–September, May 15–June 15 and July 10–August 10. Figure 5 (b) shows the development of HI over March–August (which is the development cycle period of vine on Santorini). The Huglin Index can be classified as temperate (1800 HI d 2100) from 1974 to 1981, "temperate-warm" (2100 > HI d 2400) from 1981 to 2008 and as "warm" (2400 > HI d 3000) from 2008 to 2019.

Figure 6 (a) shows the trends in Growing days degree (GDD) for the period March–August for 1974–2019. GDD increased significantly (p < 0.001) by 10.4 per year (95 % Cl 8.4, 12.3) (Table 2). For the period March–August, GDD was 1741 (Region III) from 1974 to 1982, it was 1951 (Region IV) from 1982 to 2006, and 2162 (Region IV) from 2006 to 2019. Overall, there was a transition from Region III (Warm) to Region IV (Hot) (Amerine and Winkler, 1944).

Figure 6 (b) shows the trend in Diurnal temperature range (DTR) for the period March–August of 1974–2019. Although DTR displayed a slightly increasing trend, it was not statistically significant (Table 2).

TABLE 1. Development of seasonal rainfall distribution from 1974 to 2019 split into two arbitrary periods: the first 25 years *vs.* the following 20 years.

Seasons	1974–1999 total seasonal rainfall (mm) and yearly % year	2000–2019 total seasonal rainfall (mm) and yearly %
Winter	140 (44 %)	177 (54 %)
Spring	100 (32 %)	75 (24 %)
Summer	30 (10 %)	8 (3 %)
Autumn	42 (14 %)	60 (19 %)

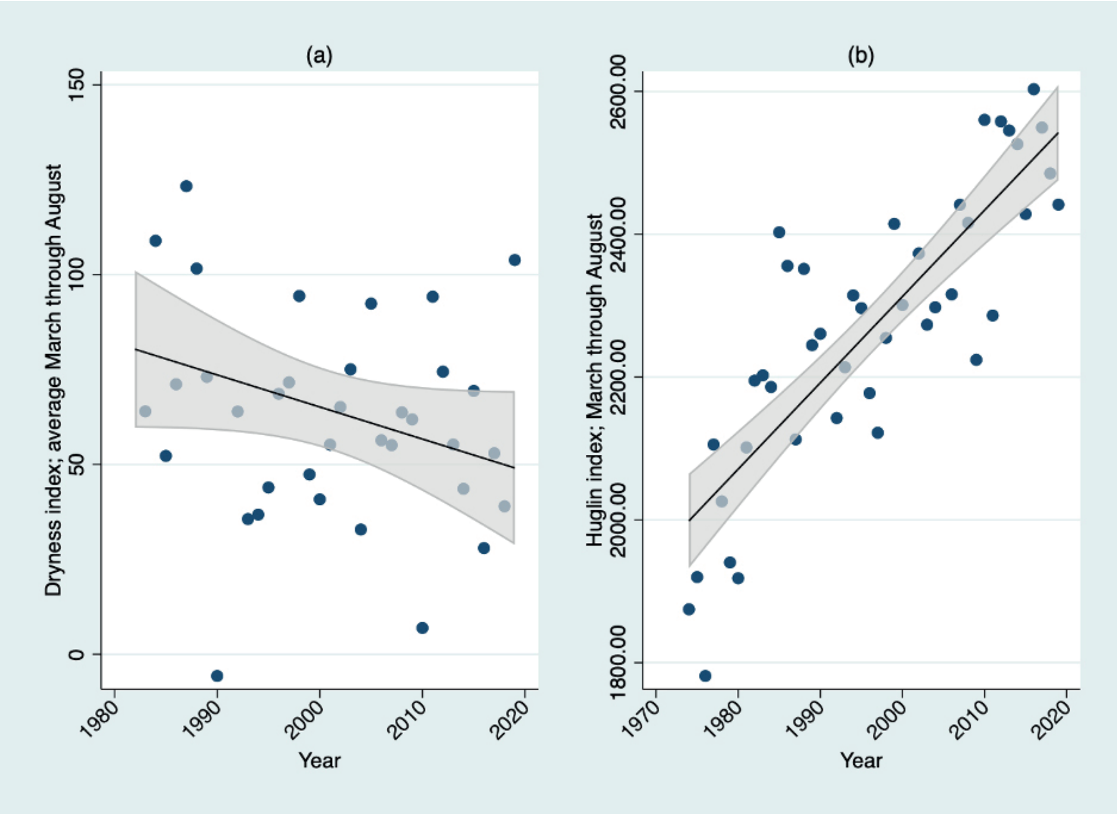

FIGURE 5. Dryness index trend over March–August for 1974 to 2019 (a). Huglin index trends over March–August for 1974–2019 (b).

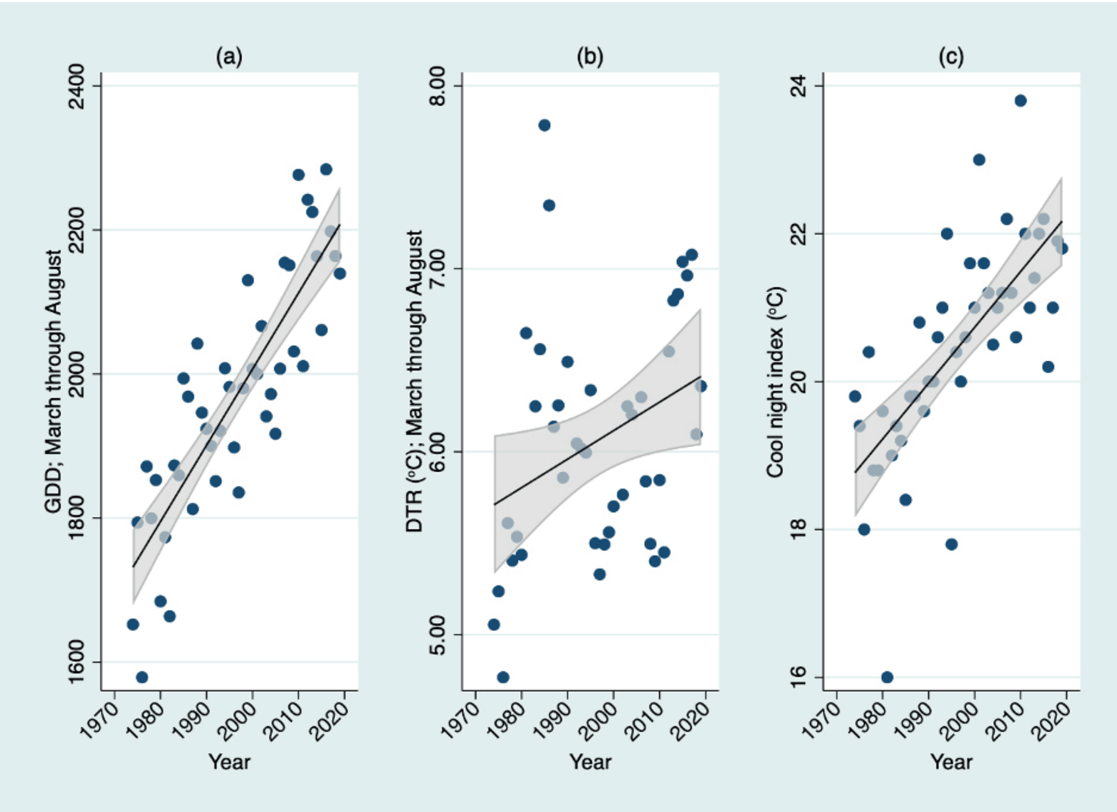

FIGURE 6. Trends in GDD over March–August for 1974–2019 (a). Trends in DTR over March–August for 1974–2019 (b). Trends in the Cool night index for 1974–2019 (c).

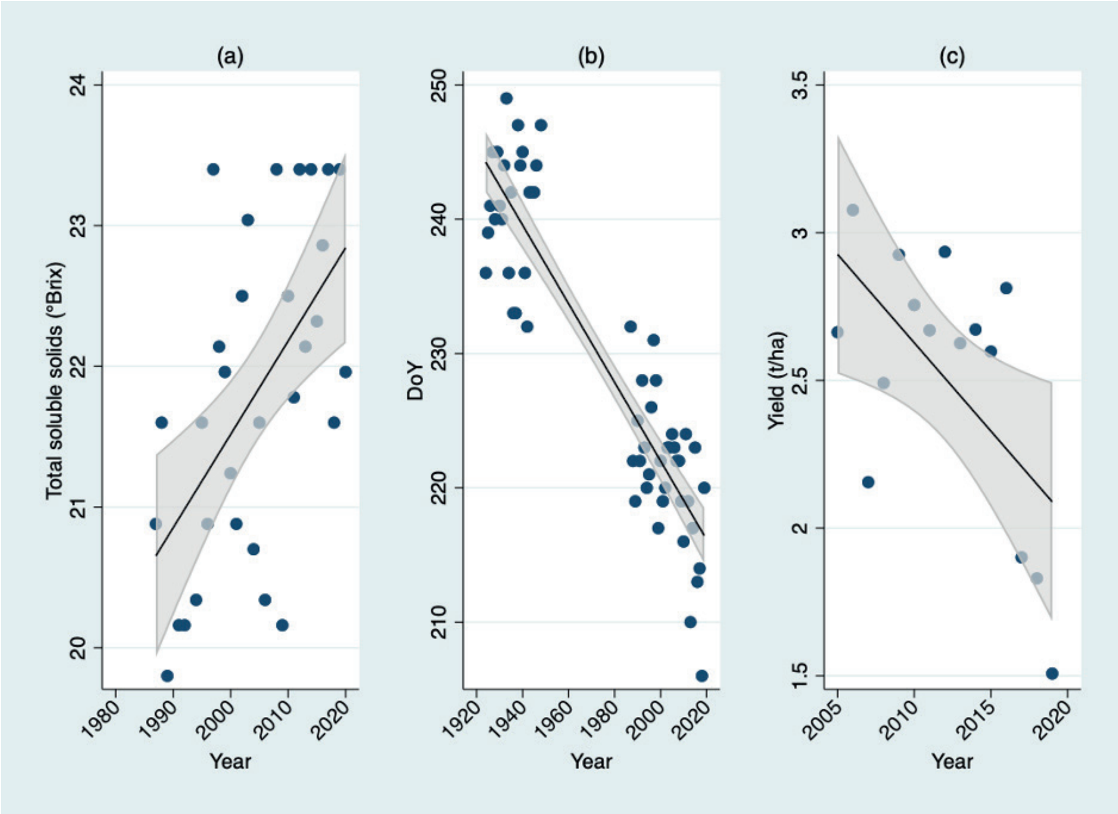

FIGURE 7. Increasing trends in sugar content (°Brix) (a) and decreasing trends in harvest start date (DOY) (b) and yield (c). Reliable historical data for 1920–1940 were used.

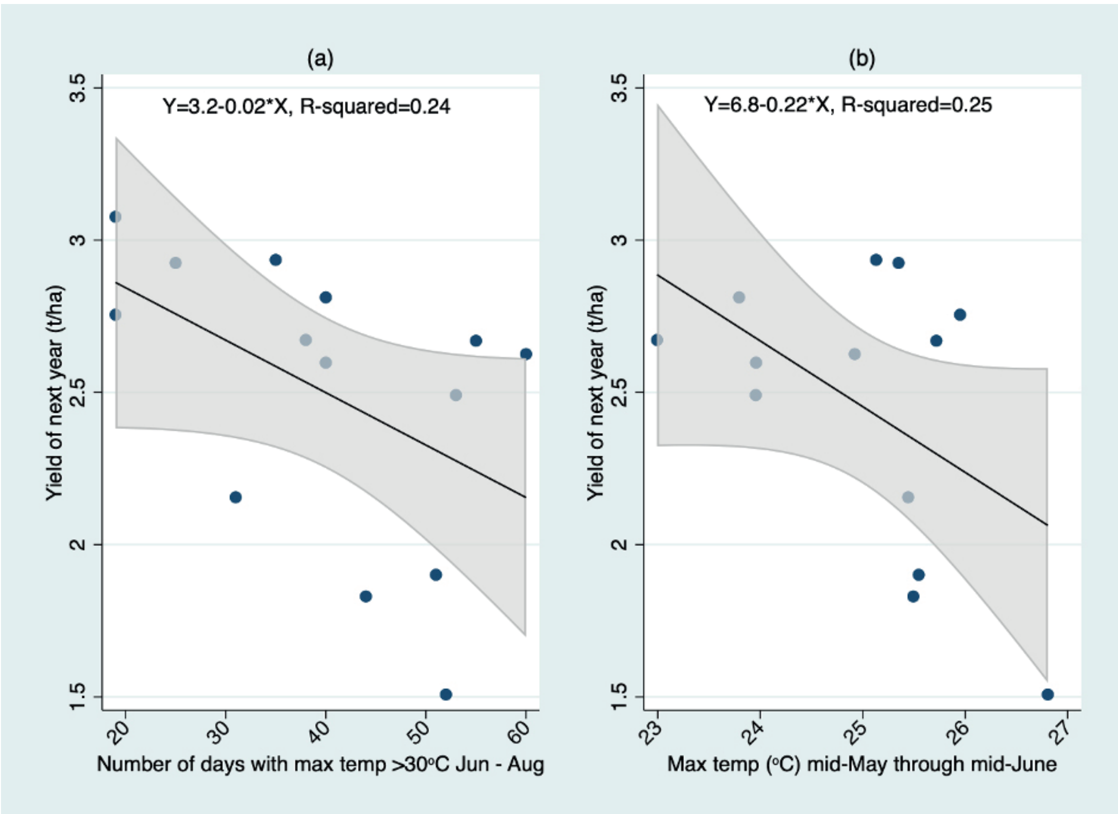

FIGURE 8. (a) Relationship between the number of days with temperatures > 30 °C for the period June–August and the yield of the following year, (b) Relationship between the maximum temperature during May15–June 15 and the yield of the following year. Quantitative projections are possible based on derived equations.

TABLE 2. Linear model equations referring to the linear relationships of the studied parameters, along with corresponding R^2 and model p-value. Beta1 corresponds to the annual change in Y for the studied period. Short term predictions based on these models are possible.

Y	Beta0 (constant)	Beta1 (*Year)	R^2	P-value
Mean Temperature in °C, March–August	-101.0073	0.0611	0.669	<0.001
Maximum average Temperature in °C, March–August	-96.8811	0.0604	0.540	<0.001
Minimum average Temperature in °C, March–August	-79.9415	0.0489	0.656	<0.001
Number of days with max > 30 °C, June–August	-1653.726	0.8417	0.603	<0.001
Annual Precipitation (mm)	169.2671	0.0781	0.000	0.976
DI (Mar-Aug)	1754.949	-0.8449	0.085	0.080
H-index	-20786.8	11.5522	0.590	<0.001
GDD (Mar-Aug)	-18737.49	10.3727	0.737	<0.001
DTR in °C	-7.4227	0.0068	0.004	0.701
Cool night index in °C	-136.4908	0.0786	0.517	<0.001
Sugar content (°Brix)	-96.3912	0.0590	0.375	0.001
Harvest start day after 1 January	815.9962	-0.2971	0.813	<0.001
Yield (t/ha)	169.582	-0.083	0.347	0.021

Figure 6 (c) shows the trend in the Cool night index for 1974–2019. The trend was positive, with a statistically significant increase. The index increased annually by 0.08 (CI: 0.05, 1.1) (Table 2). The Cool night index falls within a range characterised as warm night CI-2 according to the categorisation of Tonietto and Carbonneau (2004).

4. Harvest and grape chemistry

Figure 7 shows the trends of the ripening parameter °Brix, harvest start date and yield for available data (1985–2019, 1921–2019 and 2005–2019 respectively). From 1987 to 2019, there was an increase in sugar content by about 2 °Brix. It can be observed that °Brix had increased significantly by 0.06 per year (95 % Cl 0.03, 0.09) (Table 2) during the study period, increasing from about 21 °Brix to about 23 °Brix (Figure 7a).

On the other hand, the day of the year (DoY) of harvest start date decreased significantly by -0.3 (95 % Cl -0.5, -0.1) days per year (Table 2). Specifically, the harvest start period moved from the end of August to early August (1920–2019) (Figure 7b). At the same time, the corresponding yield dropped by 0.08 units per year (Figure 7c). The island's annual yield has decreased significantly since 2005 ($p = 0.04$).

5. Relationships between climate data and yields

Figure 8 (a) shows the linear relationship between the number of days with temperatures greater than 30 °C from June to August with the yield of the following year for 2005–2019. There is a negative correlation of $r = -0.49$ ($p = 0.055$). Figure 8 (b) shows that the annual maximum temperature for the period 15 May–15 June is negatively correlated with the yield of the following year, with $r = -0.5$ ($p = 0.052$).

Favourable temperature conditions prevailing during the flowering and fruiting period are positively correlated with the number of inflorescences that appear on the stem in the next germination period (Alleweldt, 1963), as well as with the number of flowers on the inflorescence (Palma and Jackson, 1981). In the Muscat of Alexandria variety under controlled conditions, the number of flower meristems increases from a minimum at a temperature of 20 °C to a maximum at 35 °C, beyond which a decrease can be observed, which in most varieties leads to low bud fertility. For the Sultanina variety under controlled conditions, the maximum number of flower cluster primordia was reached at 25 °C while a significant decrease was observed at 32 °C (Sánchez and Dokoozlian, 2005).

DISCUSSION AND CONCLUSIONS

The present study highlights that climate change can potentially influence the important winegrowing region of Santorini. The increasing temperatures over the last few decades, combined with a decrease in precipitation and water availability, are leading to alterations in the grapevine physiological attributes, which in turn affects phenological timings, yields and quality. Our results show that mean annual temperature has increased by 3.8 °C over the last 45 years (mean annual increase of about 0.06 °C). The above results are consistent with Laget *et al.* (2008) who presented an increase of 1.3 °C for the period 1980-2006 (mean annual increase of 0.06 °C) in the Hérault region in the South of France.

Summer temperatures are considered to be extreme when maximum temperatures exceed +35 °C in the shade. Vine physiology and biochemistry is inhibited or even blocked at temperatures exceeding +35 °C, while at temperatures exceeding +30 °C some grapevine parameters (e.g., berry shriveling, sugar accumulation disorder, titrable acidity, pH and anthocyanin content) are affected (Venios *et al.*, 2020; Deloire *et al.,* 2021; Lager *et al.,* 2008). Grape harvest dates may also be affected by these extreme heat events. Regarding the elevated temperatures during summer, we observe that there is a significant increase in the numbers of days with temperatures > 30 °C. In fact, extreme examples of high summer temperatures were recorded on five days in 2000, 2007, 2012 and 2014 and seven days in 2017. These elevated temperatures happened during the crucial stage of maturity, thus affecting the harvest potential.

The period from May 15 to June 15 is critical for vineyard productivity in the following year due to bud differentiation. The maximum temperatures during these crucial few weeks have drastically increased, thus reaching critical temperatures (> 30 °C). Martin and Dunn (2000) have estimated the temperature of buds forming of European varieties at 24–28 °C. Elevated temperatures of up to 30 °C (depending on the cultivars) increased the number of inflorescence primordia per bud and their individual weight, whereas the reverse effect was observed above that temperature threshold (Dunn, 2005).

The seasonal distribution of precipitation during the spring and summer seasons has decreased, resulting in a longer drought period on Santorini Island. Our findings are consistent with those of the Hérault region in the South of France (Laget *et al.*, 2008*).* Mean summer precipitation has significantly decreased in most of southern Europe, while increases of up to 18 mm per decade have been recorded in parts of northern Europe. Moreno *et al.* (2005) show trends in Spain of much drier springs and summers and lower annual rainfall, while Ramos *et al.* (2008) found declining precipitation during the spring and summer, which, when combined with the observed warming in the same regions, resulted in an increase in water demand of 6–14 % in the already semiarid regions.

*C*limatic indicators have been observed to reach values corresponding to warmer climates, with warmer nights and higher drought levels.

Santorini island is characterised as moderately dry (DI+1) and DI has significantly decreased over the last 45 years. These results are in line with Fraga *et al.* (2012) who reported DI in the south part of Portugal as being moderately dry under current climatic conditions (1976–2005). Changes in DI represent an important threat or challenge to the viticultural sector because of the severe dryness that is likely to occur in the future.

The Huglin index (1974 to 2008) has been re-classified from temperate to temperate warm and as warm over the last decade (2008–2019). A similar trend was observed by Laget *et al.* (2008) in the Hérault region in the South of France. In the central and southern regions of Portugal the Huglin index reveals high values (1800–3000). In the near future, an overall increase in these values is expected in the innermost regions reaching values above 3000 (highest HI class) (Helder *et al.,* 2012). In the Italian region of Apulia, which is well-known for table grape production, the HI was classified as temperate warm for the period 1961–1990 and warm for the period 1991–2020 (Alba *et al.,* 2021). In terms of changes in the suitability of viticulture in Europe, Stock *et al.* (2005) showed increases in 100–600 heat units (Huglin Index) that will probably result in broad latitudinal shifts with new areas on the northern fringes becoming viable, changes in cultivar suitability in existing regions, and southern regions that may become so hot that overall viticulture suitability will be challenged.

In terms of the classification of the Growing days degree for the period 1974–1982 till 2019, there is a transition from Region III (Warm) to Region IV (Hot) respectively (Amerine and Winkler, 1944). Alba *et al.* (2021) describe a transition from Region III (1961) to Region IV and V (1991–2020) for the biggest part of the Apulian region in Italy. According to Fraga *et al.* (2016), GDD in the south part of Portugal was classified as Region III and IV for the period 1950–2000. Future projection-scenarios (2041–2070) suggest large increases, reaching the excessively hot Region V category.

The Cool night index increased significantly from 1974 to 2019 with temperatures > 18 °C. This increase is associated with warm nights CI-2, which is the highest category according to the categorisation of Tonietto and Carbonneau (2004). The CI pattern clearly shows a warming of the nights in August, which may have important implications on the wine quality and must be taken into consideration.

Another prominent effect of climate change on viticulture is the increase in berry sugar content. Our study shows that from 1987 to 2019, there was an increase in sugar content by 2 °Brix. The harvest DOY decreased significantly from end of August to early August (1920–2019). Warmer conditions due to climate change are generally associated with shorter intervals between phenological events and earlier harvest dates (Bindi *et al.,* 1996; Tomasi *et al.,* 2011). Accelerated ripening has serious consequences for precocious varieties in that they enter into the final phase of ripening under increasingly warmer conditions; this has the potential implications of high temperatures, especially when associated with drought, inhibiting certain biochemical pathways or physiological processes essential for the production of quality grapes (Deloire *et al.*, 2004).

The annual yield in Santorini has drastically decreased from 2.9 to 1.5 t/ha (2005–2019). This could be due to a reduction in plant density on the island (due to biotic and abiotic parameters), the aging of the vineyard, non-optimal management (due to the lack of specialised personnel and the proper cultivation practices), as well as the impact of climate change.

Furthermore, it seems that the high temperatures that prevail during the critical stages of vine development and differentiation significantly affect production in the following growing season. The above findings are first evidence of the impact of climate change on grape yield on Santorini Island. On the above basis, the prediction, modeling and action can be consider inviting for further research.

During the last 30–70 years, many of the world's wine regions have experienced a decline in frost frequency, shifts in the timing of frosts, and warmer and longer growing seasons with greater heat accumulation. Recent research on Europe shows similar results with warming trends over the last 30–50 years occurring annually and across most seasons, typically greatest in the spring and summer (Jones *et al.,* 2022*).* In Italy, growing season average temperatures have increased by 2.3 °C, while annual and seasonal precipitation amounts have not changed significantly. Furthermore, in Europe in general, grapevine phenological timing has showed strong relationships with the observed warming, with events occuring 6–25 days earlier depending on cultivar and location (Jones *et al.,* 2005). Observed changes were greatest for veraison and harvest dates that typically show the stronger, integrated effects of a warmer growing season. The lengths of the intervals between the main phenological events also decreased, with the intervals between bud break and bloom, veraison or harvest decreasing by 14, 15, and 17 days respectively. Averaged over all locations and cultivars, grapevine phenology shows a 5- to 10-day response per 1 °C of warming over the last 30–50 years (Jones *et al.,* 2012).

When examining changes in many of the world's prominent wine regions, Jones *et al.* (2005) found that an average warming of 2 °C is predicted in the next 50 years. For regions which produce high quality grapes at the margins of their climatic limits, these results suggest that future climate change might exceed climatic thresholds, so that the ripening of the balanced fruit required for existing cultivars and wine styles will likely become progressively more difficult.

Moriondo *et al.* (2013) showed the potential for dramatic changes in the landscape for winegrape production in Europe due to changes in climate. In addition, to examine grapevine responses to climate change, Lebon (2002) used climate model output to show that the start of Syrah ripening (veraison) in southern France would shift from the second week of August at current temperatures to the third week of July with a 2 °C warming and the first week of July with a 4 °C warming.

Adaptation measures must be planned and applied (Metzger and Mark*,* 2011) in order to maintain the sustainability of the vineyard; several adaption options have been reported for use in viticulture (Fraga and Santos, 2018; Koundouras *et al.,* 2008; Duchene *et al.,* 2012). The wine industry is a leading economic activity for the island, which is closely linked to tourism. The industry's decision makers will have to cope with these developments rapidly and introduce innovative solutions. Public policy will also have to take into account developments linked to climate change, establish scenarios and take action alongside all relevant stakeholders. Any structural change or transition from a current model that becomes outdated to a new one will require resources (e.g., investment in infrastructure, landscape planning and scientific research). These measures must be taken into account by the stakeholders and decision-makers of the Santorini viticultural sector. Furthermore, since the willingness to adopt these measures is tied to the perception of climate change, it is important for Santorini winegrowers to become aware of the climate change impacts on their vineyards, highlighting the importance of studies such as this one and subsequent analyses of future climate conditions.

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