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Contribution to the study of the impacts of climate in Greek viticulture. Trends in grape production, wine quality, challenges, perspectives and uncertainties.

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Συμβολή στην μελέτη των επιδράσεων του κλίματος στην ελληνική αμπελοκαλλιέργεια: τάσεις στην παραγωγή και ποιότητα των οίνων, προκλήσεις-προοπτικές και αβεβαιότητες.

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Chapter 1: Introduction

1.1 Background

According to the latest report publish from the "Intergovernmental Panel on Climate Change" (IPCC, hereafter), earth surface temperature has increased, by approximately 1.0°C over the last two decades (i.e., 2001-2020) compared to the 1850-1900 period (IPCC, 2021). This observed warming is driven unequivocally by emissions of human activities through higher concentrations in the main greenhouse gases of the atmosphere (GHG) namely, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), a trend which is expected to continue in the future as well. In addition, marked seasonality and distribution of precipitation (which is slightly increased since 1950) occur on a global scale together with an expansion of both the frequency and intensity of the extreme events (IPCC, 2021). Extreme hot events (cold events) have become more (less) intense and more (less) frequent since the 1950s (IPCC, 2021). Easterling et al., (1997) in a comprehensive study, used data from 5400 weather stations located around the world to investigate the magnitude of trends in maximum and minimum air temperatures. Their analysis showed that minimum air temperatures increased at a faster rate than the respective maximum ones, regardless of the hemisphere analysed, resulting in significant decreases in diurnal temperature range (DTR). At a regional scale, similar studies observed that warming trends are seasonally and asymmetric in many countries of the globe (e.g., Karl et al., 1993, Nemani et al. 2001 among others).

In the future, global surface temperature response is being assessed by five GHG emission scenarios. In particular, under the very low, low and intermediate GHG emission scenario (i.e., SSP1-1.9, SSP1-2.6 and SSP2-4.5), temperature will be very likely to rise by 1.0°C to 3.5°C in the long run (i.e., 2081-2100). Further air temperature increment (by 3.5°C to 5.7°C) projected under the more severe scenarios (i.e., SSP3-7.0 and SSP5-8.5) by the end of the century, following a doubling of CO_2. The latter projection will result in more severe extreme events (i.e., heat – cold waves and heavy precipitation) in the future.

These observed temperature trends, as well as future predictions of GHGs atmospheric concentrations, may have profound implications on human health, water supply, energy resources (IPCC, 2021) as well as food security and biodiversity conservation (Muluneh, 2021). Terrestrial ecosystems are also expected to be affected by such rapid climatic changes and for this reason, many researchers have explored the impacts of climate change on different agricultural industries worldwide (Lobell et al., 2006, Lobell et al., 2007, Tao et al., 2008, Ramos et al., 2008, Jones and Davies 2000, Jones 2005). These impacts depend on the vulnerability of natural systems, the type of cultivation and the magnitude of climate extremes.

Temperature anomalies (heat or cold events) and changes in the distribution of annual rainfall (droughts, floods) could both have positive as well as negative impacts on quantity and quality of agricultural products. Although, agricultural systems are managed ecosystems (Adams et al., 1998) and thus affected by producers' decisions, climate is the major determinant on crop production and quality. For example, grape (species Vitis vinifera L.,) cultivation experiences direct effects of climate change by shifting its phenological stages (Jones and Davis, 2000). The time between these stages varies greatly and depends on grape variety, climate and geographic location (Jones and Davis, 2000). This timing it is also related to the ability of the vine to yield fruit (Mullins et al., 1992).

The potential effects of climate change on grape production and wine making have been previously discussed (Tate 2001). Air temperature variation alone, with only minor contribution from other climate parameters, controls the growing cycle of the plant species (Gladstones, 2011). In addition, topography, and soil characteristics along with human intervention (vineyard management and cultivation methods) and grapevine variety selection, combine the holistic component of *terroir* (van Leeuwen and Seguin, 2006, Jones 2018).

Over the last decades, several studies were particularly focused on the potential impacts of climate change on wine quality (e.g., Jones et al. 2005 among others). Significant relations between climate (mainly air temperature) and wine quality were identified in the majority of them (Jones et al., 2005, Grifoni et al., 2006, Davis et al. 2019, Gambetta and Kurtural 2020). Other studies showed association between ENSO (El Nino–Southern Oscillation) and wine quality (Jones and Goodrich, 2008, Rodo and Comin, 2000). Furthermore, climate-viticulture models have been used in many cases in order to evaluate the fate of wine quality under future climatic changes (Webb et al., 2007, Cahill et al. 2007). Moreover, climate change will probably pose challenges to maintain optimum ripening conditions to the traditional winegrape regions of the world (Jones et al., 2005).

One region of particular interest for vine cultivation is Greece, which is located in the north-eastern part of the Mediterranean base. In Greece, viticulture (i.e., the science of grape cultivation) and wine production, represent an economically and culturally activity since the ancient times. Greece is also a home country of many indigenous varieties which are yet unexplored. Although, a considerable amount of research work has been conducted in order to estimate the relative trends and future projection of the extreme events (total number of hot-cold days and dry days) in Greece over the last dacades (Feidas et al. 2004, Matzarakis et al. 2007, Nastos and Matzarakis 2008, Mavromatis and Stathis 2011, Nastos et al. 2011), there is a lack of studies regarding the impacts of climate change on Greek viticulture.

The major obstacle is the lack of long-term datasets of viticultural records (e.g., dates of phenological phases, consistent sugar and acid measurements on critical time-points, yield records and ratings on quality attributes, among others) that could be sufficient for adequate data analysis. Additionally, datasets including soil characteristics (e.g., soil nutrients and moisture, depth, etc) and climate indices widely used in viticulture for each winegrape region would also be very important.

1.2 Purpose and research questions of the thesis

Therefore, one major objective in this thesis is to create large datasets of climate-related indices for each of the main wine-producing regions in Greece (database 1), viticultural records (database 2) and wine quality ratings (database 3) in order to answer the following research questions:

1. To what extent the winegrape regions in Greece will be at risk in the future according to the principal viticultural indices? Many studies that investigated future suitability of the best known winegrape regions of the world have used growing degree days, huglin index, biologically effective degree days, cool night index and dryness index among other indices (e.g., Hall and Jones, 2010 and Jones et al. 2010 for a good review).

2. How does recent and future warming influences harvest of greek indigenous varieties vs. to international ones? Does the varietal time of maturity (early, mid-season and late ripening varieties) play a significant role in varieties' resistance in climate change?

3. Will Greek wine quality benefits from future climatic conditions? Which climatic indices are best related to Greek wine quality variation?

1.3 Thesis outline

The current thesis consists of six chapters (Fig. 1). This chapter (i.e., Chapter 1) introduces the relevant topic of interest and defines the central research questions. The next chapter (i.e., Chapter 2) reviews the literature regarding the research questions, introducing winegrape phenology (section 2.2), berry composition and their relationships with climate (section 2.3) and wine quality (section 2.4). The next section (i.e., 2.5) reviews the climate and climate-related parameters trends for the well-known winegrape regions of the world. This chapter also introduces the current status of viticulture (i.e., winegrape phenology, production and wine quality) in Greece (section 2.6 "Viticulture in Greece").

Chapter 3 used historical daily values of air temperature and precipitation in order to create a large dataset (database 1) of climate indices in order to investigate climate- and viticulture-related indices evolution and categorize the main winegrape regions in Greece. In addition, future climate simulations were used to addresses the 1st research question regarding to what extent winegrape regions in Greece will be at risk in the future. Parts of this chapter were published as a peer-reviewed article in the *International Journal of Climatology* in 2017 (Koufos et al. 2017).

Chapter 4 investigated the relationships between harvest dates and berry composition with climate with the use of the climate dataset (database 1) created in Chapter 3. In addition, estimation of heat requirements of the most important indigenous varieties was attempted for the first time in Greece. Based on this analysis, the results were used to project future harvest dates and compare the level of response between indigenous and international varieties cultivated in Greek territory. For this reason, phenological data were obtained from representative wineries throughout the Greece (database 2). This chapter addresses the 2nd response question. Parts of this chapter were published in the *Oeno One* journal in 2020 (Koufos et al. 2020).

Chapter 5 used wine ratings (database 3) from the Thessaloniki International Wine and Spirits Competition (TIWSC) and the climate dataset from Chapter 3 to investigate wine quality trends and relationships with climate for the main indigenous and international varieties in Greece and to determine whether future climatic conditions would be beneficial to Greek wine quality in general. Parts of this chapter has been published in *Water* journal (Koufos et al. 2022). Finally, chapter 6 provides a discussion of all chapters, combining the findings of the thesis.

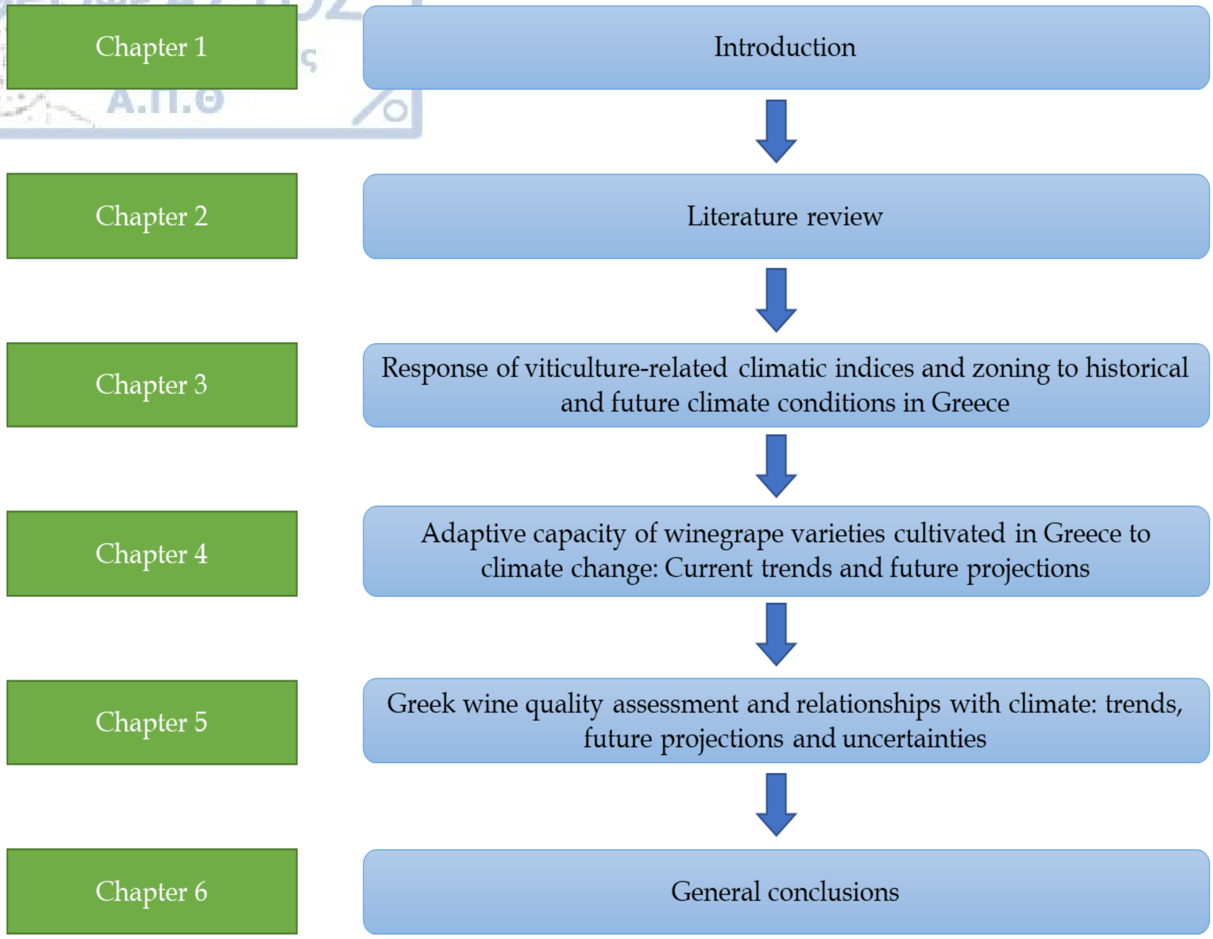

Figure 1. Flow diagram of the chapters.

Chapter 2: Literature review

2.1 Introduction

2.1.1 The historical importance of grapevines and wine

Grapevines belong to the botanical family of *Vitaceae* (which contains almost 1000 species) which are mainly woody, tree-climbing plants or shrubs and are characterized by the appearance of tendrils on the other side of leaves (Mullins et al. 1992). Among the number of genera that comprised in the *Vitaceae* family, genus *Vitis* occurs mainly in the temperate zones of the world (Mullins et al. 1992, Keller 2010). Within the latter genus, species *Vitis vinifera* L., which is responsible for thousands of winegrape varieties (approximately 10.000 cultivars) that cultivated today to produce wine, table grapes and raisins (Keller 2010), originated from Eurasia, and has evolved, and spread in many areas of the world.

The history of viticulture dates back to ancient times. For example, Barnard et al. (2011) performed archeological excavations in a cave in Southeastern Armenia and discovered a fully equipped installation of a winery almost 6000-year-old. The tradition of viticulture appeared on mosaics, pottery and amphorae of ancient civilizations (Dougherty 2012). In addition, the art of wine making through poets and old scripts demonstrates wines privileged position in ancient communities and cultures such as Greek, Roman and Egypt for many years (Mullins et al. 1992, Dougherty 2012). Wine production was so important that in fact, the location of a vineyard played a key role in determining, to a large degree, the distribution of the economic functions and activities such as merchant's and port establishment of an area (de Blij, 2007).

Today, grape growing is one of the most economically important cultivations on a global scale (de Blij, 2007). This geographically distinctive crop industry is of great importance to many economies and can be easily confirmed from the annual reports of International Organisation of Vine and Wine regarding the global value of wine exports that reached over 29 billion Euros (OIV, 2020). The total surface area of the world with grape plantations (for all purposes), is estimated around 7.3 million hectares (ha) from which, Europe (the so-called "Old world" for viticulture), has a dominant position with 3.3 million ha in total (45% of the world). Moreover, European countries account for 63% of vinified production and almost half (i.e., 48%) of the world consumption (OIV, 2020). Seven countries (i.e., Germany, Greece, France, Italy, Portugal, Romania and Spain) each have more than 1 million ha of vineyard surface area and accounted for over 90% of the total cultivated area within Europe (OIV, 2020). In addition, three countries namely Italy, France and Spain produce more than half (52%) of the total wine production. On the other hand, United States of America, Argentina and Chile ranked sixth, seventh and eighth regarding the total surface area and are the major representatives of the so-called "New World" countries for viticulture. Finally, Australia, New Zealand and South Africa contribute by 10.6, 10.4 and 3.3 million hectoliters in 2020, respectively (OIV, 2020).

2.1.2 Climate zones for grape growing

Grapevines, as temperate-zone plants, need warm to hot summers with dry maturation period for optimum photosynthesis and a balanced ripening period, lack of extreme cold events (grapevines cannot withstand lower than -17°C temperatures), moderate winds and high amount of insolation which is beneficial for sugar accumulation (Mullins et al. 1992, Gladstones 2011, Jones 2012). As a result, grapevines thrive between the geographic ranges of 30° N and 50° N in the Northern hemisphere and 30° S and 40° S in the Southern hemisphere where climate conditions are ideal for high quality wines (Jones et al. 2005). Grapevines are currently cultivated as north as Germany while the southernmost vineyard is located in Chile. Today, these limits have been expanded, due to climate change that leads to warmer conditions, and viticulture is viable once for example again in southern England (Nesbitt et al. 2016).

The main climatic limitations for high quality wine production in other climate types of the world, are the high amount of precipitation, which is a huge disadvantage for pests control, a facet that mainly referred to oceanic climates. In contrast, the lack of the adequate winter chilling for bud breaking and water availability are the limiting factors in regions around equator (Mullins et al., 1992).

2.2 Grapevine phenology

The term phenology refers to the developmental stages of a plant and how these are influenced by climate variations and other factors (e.g., soil, elevation). In viticulture, as with all other crops, vines experience a development of vegetative (e.g., leaves and shoots) and reproductive organs (e.g., flowers) during a period called growth cycle (Mullins et al. 1992). In the literature, there are three systems for identifying grapevine growth stages namely: (i) Baggiolini, (ii) the BBCH system and (iii) Eichhorn and Lorenz (E-L system). The later was modified by Coombe (1995) to meet global requirements for grapevines and describes 47 grapevines stages from "Winter bud" (stage 1) to "End of leaf fall" (stage 47).

It is important to note that the identification and knowledge of the growing stages of the grapevine developmental cycle is of utmost importance: (i) for the scientific community to conduct sufficient grapevine experiments to better understand the influence of climate and other factors to vegetative and reproductive growth and (ii) the wine producers by providing wine producers the relevant information they need in order to (a) carry out several vineyard operations (e.g., management practices, disease control) and (b) to select the appropriate variety at a suitable location to produce high wine quality (Keller, 2020).

Grapevines (*Vitis vinifera* L.,) have four major developmental stages: (i) budbreak or budburst (débourrement in French), (ii) flowering (floraison), (iii) véraison (beginning of maturation) and (iv) full ripeness (most commonly estimated by harvest date although the latter is also influenced by factors other than berry chemistry or physiology of ripening). The time between these events varies greatly with grape variety (Tomasi et al. 2011) and geographic location (Jones and Davis 2000) but it is mainly influenced by temperature conditions of the growth period (Mullins et al. 1992). For example, an early ripening variety is better suited to a cooler region where growing season is short while late maturing varieties are cultivated to warmer regions, with longer growing seasons where grape maturity can be accomplished (Jones and Davis 2000). In general, warmer conditions are often associated with earlier phenological occurrences and eventually harvest dates (Koufos et al. 2014).

2.2.1 Dormancy to budbreak (or budburst)

Grapevines are entering a winter dormancy phase where vine's growth and activity has ceased. During that period, grapevines utilize the energy stored (carbohydrates and mineral nutrients) into their trunks and roots to maintain their protection from cold temperatures (grapevine can withstand low temperatures up to -17 ºC). At this point, a minimum effective chilling hour period and a free-frost period is required to induce the onset of budbreak (Mullins et al. 1992). Once dormancy has ended, prolonged days with sunshine and mean air temperature above 10 ºC initiate growth (Jones 2012). This stage commences approximately, around mid-March for early ripening varieties (mid-September for the South hemisphere) or mid-April for late maturity varieties (mid-October for the South hemisphere) and labelled as stage 4 according to the modified E-L system (Coombe 1995). Some studies reported that specific viticultural practices (such as pruning timing) prior to budbreak affect the onset of budbreak (Friend and Trought 2007).

2.2.2 Budbreak to flowering

After budbreak shoots are elongating, numerous leaves are separated, and inflorescence becomes clearly visible leading to cluster formation (Jones 2012). Once 16 leaves are separated, the flowering stage begins (this corresponds to stage 19 on the modified E-L system) and the flower caps start to fall off from each cluster (Mullins et al. 1992). When 100% of the caps fell off, the vine is at full-bloom (i.e., stage 23 on the modified E-L system). In general, flowering stage occurs around mid-May to mid-June in the Northern hemisphere (mid-November to mid-December in the Southern hemisphere).

Air temperature and sunshine hours during these months highly determines the total number of inflorescences appearing in the shoots the following year (Mullins et al. 1992) with different thermal and light intensity requirements for inflorescences formation, between varieties (Buttrose 1970).

2.2.3 Fruit set and berry development to véraison

In general, each bud may contain 1-3 inflorescences which in turn, may contain hundreds of flowers. Approximately, 70-80% of them will remain unpollinated and eventually will fail to be transformed into fruits (Mullins et al. 1992). Therefore, the term fruit set corresponds to the number (or percentage) of flowers per cluster that indeed transform into berries. Thus, the so-called fruit set, includes the first green berries (almost 2mm in diameter) that had been successfully fertilized and start to enlarge. Within the next 2 months the berries start to face downward (i.e., stage 29 on the modified E-L system). At this point the berries are too acidic and actively grow as a result of cell division and enlargement.

According to Mullins et al. (1992), berry development follows a double-sigmoid curve with three distinguishable stages: (i) rapid green berry growth, (ii) the so-called "lag phase" and (iii) maturation. The first stage is characterized by a rapid berry increase and accumulation of organic acids and tannins (i.e., measured by the titratable acidity). During the next stage (i.e., véraison or "lag phase") acidity reaches a maximum level, the skin becomes transparent, and color (in red varieties) starts to appear (they turned from green to translucent yellow for white varieties or red-purple for the red varieties). The véraison stage (i.e., stage 35 on the modified E-L system) generally occurs around late-July to early-August in the Northern hemisphere and late-January to early-February in the Southern hemisphere. Finally, the highlights of the maturation stage are the vivid decrease in titratable acidity, the acceleration of sugar accumulation, softening and onset of anthocyanin and volatile compound synthesis.

2.2.4 Grape maturity to harvest

After véraison, during the ripening period, the concentration of sugar increases while the respective levels of titratable acidity decrease. Usually, the berries are considered fully ripe when a target sugar-acid ratio is achieved according to the desired wine style. Ideally, a quality harvest (i.e., stage 38 on the modified E-L system) ranges between 10 September to 10 October in the Northern hemisphere (van Leeuwen et al. 2016). This stage needs to be carefully considered since is not an actual stage and it is

based on subjective evaluations and other factors (de Orduna, 2010). For example, a producer may decide to harvest earlier or later (shorter/longer hang times) targeting to lower/higher sugar/acid levels and also phenolic and aromatic maturity.
Several studies have used grape harvest date (GHD) records as climate proxy to reconstruct temperature variations in traditional winegrape areas over the centuries (e.g., Chuine et al. 2004, de Cortaza-Atauri et al. 2010). For example, Chuine et al. (2004) used grape harvest dates from 1370 to 2003 in order to reconstruct spring-summer temperatures anomalies in Burgundy. In a similar study, Meier et al. (2007) used GHD records from 1480 to 2006 to reconstruct April-August temperatures for Switzerland. The results confirmed previous studies regarding the extreme warm summer during the year 2003 that occurred in Europe. Recently, Cook and Wolkovich (2016) used GHD records from 1600 to 2007 along with climate data in France and Switzerland and found that earlier harvest occurred during warmer and drier summers.

2.3 The influence of air temperature on grapevine phenology

2.3.1 Historical effects

Wine production in the European countries of Spain, France, Portugal, Germany, Switzerland, Italy and Greece, among others, has been a long-standing tradition and hence, in most of them, wine-producers or relevant responsible research institutes (e.g., INRA in France) have been keeping records for several aspects of viticulture (such as phenology dates) for many decades. A large database of viticultural parameters is a valuable information in the hands of a scientist to study the relevant associations between climatic factors and viticulture.

Numerous research articles have been published exploring to the relationships between grapevine phenology and climate, predominantly air temperature, within the co-called "old world" and "new world" winegrape regions (e.g., Jones et al. 2005, Duchene and Schneider 2005, Tomasi et al. 2011, Bock et al. 2011 and Petrie and Sadras 2008 among many others). In general, a temporal advancement of the main four developmental stages [see section 2.2] and a significant shortening of the between-stage periods have been identified in the majority of the cases studied.

More specifically, in France, increasing air temperatures are highly responsible for the earlier occurrence of the basic developmental stages. In Lower Franconia (Germany), phenological stages have significantly moved forward for Muller-Thurgau, Silvaner and Riesling varieties, mainly driven by the warmer historical conditions (Bock et al. 2011). Similar results were identified in Southern Palatinate (Germany) for a period of 40 years (with adequate phenological records of the main four grapevine stages) for 5 winegrape varieties (i.e., Muller-Thurgau, Silvaner, Riesling, Pinot Gris and Pinot Noir). A gradual shift toward earlier phenological stages has also been identified with harvest dates being the stage with the greater magnitude in trend (by almost a month, Koch and Oehl 2015). Budburst, bloom, véraison and harvest dates have been reported to become earlier by 13 to 19 days along with a shortening of the intervals between these events for numerous varieties in the Veneto region, Italy (Tomasi et al. 2011). Finally, these main events have also shown a 5-10 days earlier response per 1℃ of warming over the last 30-50 years averaged over many other regions and varieties (Jones et al. 2005, Ramos et al. 2008). Concurrently with warmer conditions, bloom and véraison showed the most significant trend (earlier occurrence) for the winegrape varieties of Macabeo, Xarello, Parellada and Pinot Noir [except for Chardonnay where the analysis revealed significantly earlier harvest dates under warmer growing season in northeast Spain (Ramos et al. 2008)]. Finally, in a continental study in Europe (which included five countries), Jones et al. (2005) reported significantly earlier occurrences of the phenological stages as a result of warmer conditions, and at the same time, the shortening of the between-stages, in the vast majority of the study cases.

Analogous results were found in many other studies carried out in other winegrape regions of the “new world”. In coastal California areas, the start of the growing season advanced by 18-24 days over the period 1951-1997 (Nemani et al. 2001). Grape maturity and harvest have been reported to advance by over 0.5-3.1 days per year in Australia for the varieties of Cabernet Sauvignon, Chardonnay and Shiraz (Petrie and

Sadras, 2008). Webb et al. (2011) also found significant advancements in maturity timing, ranging from 0.8 to 1.7 days, for the Australian winegrape regions.

However, the results differed and depended on: (i) the stage itself, (ii) the varieties involved and (iii) the winegrape region. For example, in a study conducted in Slovakia, despite the fact that the onset of the main stages occurred earlier during the years, no trend on harvest was found or it was only marginally significant (Bernath et al. 2012). Such studies revealed that cooler areas (where late ripening varieties are currently cultivated) are still benefited from warmer conditions allowing farmers to pick the berries at the desired level of sugar.

2.3.2 Future effects

Many studies carried out in the Mediterranean basin report that air temperature is projected to increase at a higher rate compared to other winegrape regions of the world (Kenny and Harisson 1992, Moriondo et al. 2013). However, while the impacts of climate change generally considered as regional- and variety-specific, altitude also has influential role in grapevine phenology. The temperature increase is projected to be more pronounced in areas at higher altitudes resulting in earlier occurrence in the phenology of the studied varieties (Alikadic et al. 2019).

In the "new world" winegrape regions such as Chile, Jorquera-Fontena and Orrego-Verdugo (2010) suggest the interval from budburst to harvest for the Gewurtztraminer variety to shorten by approximately 28 to 46 days by applying two emission future climate scenarios. In Australia, Webb et al. (2007) by examining the impacts of climate change to grape ripening of Cabernet Sauvignon and Chardonnay also found that grapevine phenology is expected to become earlier in two near future periods (i.e., 2030 and 2050) under various emission scenarios. An earlier study by Bindi et al. (1996) in Italy reported 19 and 21% reduction in growth phase duration in two varieties (Sangiovese and Cabernet Sauvignon) as a result of increased temperatures. That means that phenological timings of many international winegrape varieties may undergo significant advancements by approximately 1 month or more in 8 countries (i.e., Croatia, France, Germany, Italy, Portugal, Slovakia, Slovenia and Spain) (Fraga et al. 2016). In Ribera del Duero (Spain), the projected phenological response of

Cabernet Sauvignon and Tempranillo showed great sensitivity to climate variation (Ramos et al. 2015).

The above-mentioned studies and many more that are not cited here demonstrate the direct effects of climate change trends on grapevine phenology. These effects could probably also affect berry chemical composition (i.e., sugar concentration and acid degradation) and organoleptic characteristics which in turn might be detrimental to wine quality (van Leeuwen and Darriet 2016).

2.4 The influence of climate conditions on berry composition, yield and wine quality

Grape compositional parameters such as sugar content and acid levels are frequently used as an overall indication of potential wine quality (Jones and Davis 2000). The relative impact of climate (mainly air temperature) on these parameters has been previously confirmed in different winegrape regions and varieties. High temperatures, for example, mainly during the maturation period affect berry ripening due to increased synthesis of sugar in the must (Coombe 1987) while water availability significantly related with berry composition in most cases (Ramos et al. 2015).

More specifically, over the last 40 to 50 years in south central (Lower Franconia) and southeastern Germany (Palatinate), significant mean air temperature increases during the growing season resulted in wines with higher alcohol content for the studied varieties (Bock et al. 2013, Koch and Oehl 2018). Two other studies in Alsace (France) and Emilia-Romagna (Italy) (two traditional winegrape regions), showed that favorable ripening conditions driven by higher temperatures, had led in wines with higher potential alcohol levels (by 0.08% per year) for the Riesling and Sangiovese varieties, respectively (Duchene and Schneider 2005, Teslic 2016). Similar results were identified for 6 white and red winegrape varieties in Northwest France (i.e., Loire Valley) where berry composition (i.e., sugar and acid levels) considerably changed (sugar increased and acid decreased) due to higher temperatures over the study period (Neethling et al. 2012). Jones and Davis (2000) found significant changes in sugar to acid ratio (mainly driven by significant decrease in acid levels) that related with vintage quality, for the internationally cultivated varieties of Cabernet Sauvignon and Merlot in Bordeaux winegrape region. They concluded that Merlot is generally more climatically sensitive than Cabernet Sauvignon. Finally, Webb et al. (2011), by analysing total soluble solids records for numerous varieties in Australia, showed that when average growing season temperature was higher, the designated TSS (total soluble solids, a common surrogate for sugar levels) was achieved on a faster rate leading to earlier maturity.

The acceleration in synthesis of must soluble solids at harvest has been reported in many cases as a result of increasing season temperatures (Ganichot 2002, Gaudillere 2007) moving ripening period to a warmer part of the season. All of these are considered to be unfavorable to wine quality because metabolic processes and sugar accumulation might be impaired at temperature above 30°C (Kriedemann and Smart 1971) and affect aroma and color compounds (Kliewer 1973). As a result, a scientific debate of potential dislocation and/or significant reduction of the traditional winegrape regions of the world has been risen (White et al. 2006, Moriondo et al. 2013, Hannah 2013).

However, this has not been proved to be the case in less warm winegrape regions where growing seasons lengthened. In such regions, higher temperatures by 1°C can result in higher vintages of around 10 to 22 wine quality points depending on wine type (Jones et al. 2005). Moreover, future projection analysis estimated an upper temperature limit for some of the varieties, suggesting that the relationships between wine quality and climate change probably will be a multitask facet. In the Napa Valleys (USA), minimum air temperatures increased by almost 3.0°C over the period of records while the total number of frost days significantly decreased, resulting in higher quality vintages (Jones and Goodrich 2008).

Regarding total yield variation, water deficit plays an important role. The combination of total precipitation amounts and thermal conditions on a given region (during critical periods of the vine), significantly drive evapotranspiration thereby affecting total vine water relations and physiology, ultimately affecting total grape production (van Leeuwen and Darriet, 2016). Camps and Ramos (2012), investigated grape yield responses of the main cultivated varieties (Subirat Parent, Macabeo, Xarello and Parellada) in north-east Spain. The results indicated lower yields under severe water deficit. Moreover, irregular rainfall annual distribution (e.g., high intensity of precipitation) can lead to: (i) significant evapotranspiration increases which is highly responsible for winegrape yield variations in north-east Spain (Ramos and Martínez-Casasnovas, 2010) and (ii) severe plant damages and diseases due to excess water prior harvest in Argentina (Agosta and Canziani, 2012). Similarly, Lorenzo et al. (2013), reported that precipitation was negatively (positively) related with grape production during the budbreak and veraison (bloom) phases. In this context, the implementation of irrigation plans might be the reason why total production and drought conditions are not highly related in South Africa winegrape regions (Araujo et al. 2016). Finally, historical winegrape yield modelling in California showed that higher precipitation during early summer (June) and the month before harvest (September) favoured grape production (Cahill et al. 2007). Despite grapevine's resilience to drought, grapevines could be negatively affected by water deficit and severe dryness during their growing season (Koundouras et al., 2006) causing adverse effects on growth and productivity (Cifre et al., 2005). The above-mentioned results suggested that future rainfall distribution will probably be a major concern, probably rendering water availability as a limiting factor to grape production, forcing irrigation practices to increase in many traditional winegrape areas.

2.5 Climate trends in the main winegrape regions of the world

According to the French, the components of climate, soil, topography, variety and tradition (e.g., husbandry methods), together define the term “terroir” which highly determines the viability of a region to produce superior wines (Jones 2018). Among them, growing season (i.e., April – October for the Northern hemisphere and October – April for the Southern hemisphere) climate conditions constitute the most critical factor (van Leeuwen and Seguin, 2006). The climate structure of a region determines whether a given variety can be grown or not. Therefore, future climate conditions are of major concern within the scientific community where numerous studies conducted in order to estimate and compare the climate trends of the most pronounced winegrape regions of the world (Jones et al. 2005a).

For example, mean air temperature analysis showed a warming trend of approximately 2°C in the Alsace region (France), over the period of records (i.e., 30 years) (Duchêne and Schneider 2005). The authors also reported that maximum air temperatures increased at a faster rate compared to the respective minimum, during Spring, Summer and Winter months. Consequently, the total number of favourable days (i.e., mean air temperature > 10°C) significantly increased resulting in an expansion of growing season length. Growing season length is an important parameter to consider for selecting the appropriate variety. On the contrary, precipitation has not changed significantly. In Spain, Ramos et al. (2008) reported analogous results in the Vilafranca del Penedès, Cabacès and Lleida winegrape regions over the period of records. Maximum air temperatures exhibited higher rates of changes than minimum temperatures, in every study region. On the other hand, absolute values and precipitation related indices presented the least significant cases. Similar results were identified in other winegrape regions across the European continent. More specifically, Jones et al. (2005b) showed significantly warmer growing season conditions resulting in an increase of 1.7°C on average, while precipitation remain unchanged in the vast majority of the regions.

The pattern remained the same when we are moving to the Sonoma and Napa valleys in the USA (Nemani et al., 2001). The authors of this study concluded that this warm was diurnally asymmetric with nighttime temperatures increased at a higher rate than daily maximum temperatures. The overall trend was 2.06°C over the period of records (47 years) leading to a noticeable decrease in the total number of frost (days with Tmin <0°C) days (that is the total number of days with minimum temperatures below zero). Finally, Webb et al. (2011) calculated the trends of growing season average temperatures in many vineyard locations in Australia, reported upward trends for all but one region (i.e., Margaret river).

2.6 Viticulture in Greece

Greece is considered one of the oldest wine-producing regions of the world with great tradition in grape cultivation and wine making. Today, the area cultivated with winegrapes covers approximately 67 000 ha (of which about 59 000 ha are under geographical indication) where more than 200 indigenous varieties are cultivated (Lacombe et al. 2011). According to the Greek legislation, the produced wines can be either categorized either as protected designation of origin (PDO) or simple protected geographical indication (PGI), the rest being qualified as varietal wines. According to the latest report published by International Organisation of Vine and Wine (OIV, hereafter), Greece ranked 17th, among the major vine-producing countries of the world (6th among the European countries), in total surface area covered with grape plantation and 17th (8th) in wine production with 2.3 mhl (OIV, 2020). However, Greece is second (behind Romania) regarding the diversity of varieties cultivated, of which >90% are indigenous.

Grapes are cultivated throughout the Greek territory and for convenience we can distinguish 9 main wine-producing regions:

1. Thrace (North-eastern Greece). The majority of cultivated areas are located at an altitude of around 350 meters above sea level (m.a.s.l. hereafter). The dominant varieties within this area are the international varieties of Chardonnay and Sauvignon blanc (white varieties) while the main representatives of the red varieties are the widely cultivated varieties of Merlot, Syrah and Cabernet Sauvignon. Additionally, a significant number of indigenous varieties (e.g., Mavroudi) are also cultivated.
2. Macedonia (North Greece). This viticultural zone consists with some of the most important winegrape areas of Greece (Amyndeon, Naoussa, Kavala and Drama) and many of the produced wines are labelled as PDO. Grape cultivation within this region differs significantly regarding the elevation (grapes are cultivated between 100 and 750 m.a.s.l. or more), geology and climatic conditions. Xinomavro is the indigenous variety that principally cultivated with the most important international varieties being Cabernet

Sauvignon, Merlot, Syrah, Chardonnay and Sauvignon blanc. Other indigenous varieties include Malagouzia (white) and Limnio (red).

3. Ipiros (North-western Greece). The major winegrape areas within this region are Zitsa and Metsovo. Most vineyards are located above 500 m.a.s.l. and the dominant variety is the indigenous white variety Debina which produces mainly young as well as sparkling wines with the most important international variety being Cabernet Sauvignon.
4. Thessalia (North-Central Greece). A range of important varieties are included. The major indigenous ones being Xinomavro, Limniona and Mavro Mesenikola as well as the international variety Muscat de Hamburg in regions like Rapsani, Tyrnavos and Mesenikola among others.
5. Ionian islands (Western Greece). Kephalonia is the major wine-producing area mainly covered with grapes of the indigenous variety of Robola (white variety) followed by Lefkada with its local red grape, Vertzami.
6. Central Greece. The main production takes place within Athens, Voiotia and Euvoia. The dominant variety is the indigenous variety Savvatiano (the most cultivated variety in Greece), along with the widely known Roditis.
7. Peloponessos (Southern Greece). This region is divided in two important winegrape areas. In central Peloponessos the main cultivated varieties are the indigenous varieties of Moschofilero (white variety) and Agiorgitiko (red variety). The north-eastern part is mainly covered with the indigenous varieties of Roditis (white variety) and Mavrodaphni (red variety).
8. Aegean Islands (South Island Greece). Within the Aegean islands the emblematic indigenous variety of Assyrtiko is the most important one (mainly cultivated on Santorini) followed by Athiri, Aidani (white) and Mandilaria (red). Muscat blanc and Muscat of Alexandria are also cultivated for the production of dessert wines.
9. Crete Island (Southern Greece). Crete is one of the oldest wine-producing areas of Greece. The winegrape areas within this region is the hometown of important indigenous varieties including Vilana, Vidiano, Daphni (white varieties), Kotsifali, Liatiko and Mandilaria (red varieties) among others.

From the above-mentioned varieties, Savvatiano (10350 ha) and Roditis (9300 ha) are the most widely cultivated varieties in Greece (almost 30% of the total plantation area in Greece). Agiorgitiko and Liatiko are the two most important red winegrape varieties with respective areas of approximately 3600 and 2600 ha (ranked 3rd and 4th respectively in plantation area). Xinomavro is the most important variety cultivated in the Northern part of Greece (2300 ha). Assyrtiko and Muscat blanc are planted on around 1800 and 1600 ha respectively and are the two major varieties in island locations. Athiri (approximately 700 ha), Mavrodaphni (approximately 500) and Muscat of Alexandria (approximately 700ha) cover minor though important areas of cultivation. Island areas represent 26% of the total area under winegrapes in Greece (about 17500 ha).

Chapter 3: Response of viticulture-related climatic indices and zoning to historical and future climate conditions in Greece.

3.1 Introduction

It is unequivocal that global climate change is one of the most debatable issues in the scientific community. According to the latest report of the IPCC the last four decades has been warmer compared to 1850-1900 period. Moreover, the average global temperature has risen by almost 1°C (i.e., 0.99°C) over the first two decades of the 21st century (IPCC, 2021). In addition, the frequency of cold days and nights (warm days and nights) have been significantly decreased (increased) in the majority of the regions. Furthermore, global averaged precipitation reported to increase at a higher rate since 1980s resulting in alterations on the frequency and intensity of heavy rainfall (IPCC, 2021). Evidently, such changes it is very likely to have profound impacts on both natural and socio-economic systems (IPCC, 2021) and thus an important number of researchers have been triggered to investigate the relationships between climate and agriculture (Adams et al., 1998; Lobell et al., 2006; Tao et al., 2008; Mavromatis, 2014 among others).

Viticulture is a climatically-sensitive crop (it is also one of the most economically important cultivations of the world) and therefore it is highly controlled by climate variations (Blanco-Ward et al., 2007; Parker et al., 2011; Fraga et al., 2012). In particular, grapevines require specific climatic conditions (thermal and hydrological) during the annual cycle in order to viably grow and yield a quality fruit (Jones et al., 2005b). Winegrape varieties have heat accumulation needs to drive growth. For example, few days of mean temperature above 10°C could initiate budburst, while extremes beyond what is considered optimum are very likely to result in an early onset of the ripeness stage and harvest (Duchêne and Schneider, 2005 and also Chapter 2 for more details). Moreover, prolonged periods with temperatures greater than 30°C can cause problems in assimilate translocation from leaves to berries during the maturation phase, thereby affecting sugar and acid concentrations of grapes as well as berry secondary metabolism (Mori et al., 2007).

Several effects of changing climate on grapevine phenology have already been reported in France (Jones and Davis, 2000, Duchêne and Schneider 2005), Spain (Ramos et al., 2008), Germany (Bock et al., 2011, Koch and Oehl 2018) and elsewhere (Jones et al., 2005a, Webb et al., 2011, Fraga et al., 2016). In Greece, significant advancement in harvest dates of several mainly indigenous grape varieties, ranging from 8 to 18 days over the last 20–40 years, was reported by Koufos et al. (2014). The displacement was significantly associated with increasing temperatures during the growing season. Moreover, Duchêne and Schneider (2005) found that budbreak, flowering and véraison stages have trended earlier by approximately 2 to 3 weeks in Alsace for the Riesling variety, while the duration of the period between budburst and harvest significantly moved forward and shortened. Jones and Davis (2000) studied the phenology of Cabernet Sauvignon and Merlot varieties in the Bordeaux region over a period of 46 years (1952-1997) and reported significant advance in harvest dates by almost 2 weeks. In addition, Lebon (2002) observed véraison dates to advance by 3-5 weeks in Southern France with a 2-4°C increase in air temperature. Earlier, Bindi et al. (1996) showed that increasingly future warmer conditions could lead to an overall reduction in growth phase duration from 19 to 21% for two key winegrape varieties cultivated in Italy.

Vine phenology and air temperature are deeply interlaced and thus several bioclimatic indices have been developed and widely used for viticultural zoning (see Section 3.5 “Bioclimatic Indices”). The use of high resolution gridded data (derived from regional climate models or reanalysis databases) is providing more spatially explicit assessments (Fraga et al., 2015; Eccel et al., 2016; Moral et al., 2016; Mavromatis and Voulanas 2021).

3.2 Aims of the chapter

A number of studies have explored the climatic and hydrologic structure and their variations in Greece (e.g. Mavromatis, 2012). Overall, inverse temperature trends were identified in Greece between winter (cooling) and summer (warming) during 1955–2001 (Feidas et al., 2004). A more recent study by Mamara et al., (2015) also reported significantly warmer conditions in 52 weather stations during the summer (mainly June and July) over the period of records studied (i.e., 1960-2004). Moreover, extreme events such as annual tropical days (i.e. days with maximum temperatures above 30°C) increased during 1976–2000 (Nastos and Matzarakis, 2008) and are projected to increase thereafter (Nastos and Kapsomenakis, 2015). On the contrary, Mavromatis and Stathis (2011) showed significantly drier conditions (negative trends for precipitation totals), mostly in winter at a national scale. Despite the adequate number of published papers which thoroughly reflect the climatic and hydrologic variations in Greece (Feidas et al., 2007; Nastos and Zerefos, 2009; Mavromatis, 2012 among others) there is a lack of studies investigating countrywide climate relationships with grapevine phenology, productivity and wine quality (Koufos et al., 2014). Another study from Lazoglou et al. (2018) used reanalysis data as well as data from a regional climate model (i.e., RegCM version 3) in order to investigate the impacts of climate change in Greek viticulture by using nine widely used bioclimatic indices from the literature. However, the necessity for more accurate studies is critical as grape cultivation in Greece already takes place under warm and dry conditions and thus it is exposed to greater potential risk with regard to climate change. Furthermore, climate change investigations in warm to hot countries like Greece could allow the monitoring of vine performance at its upper temperature limits thereby providing cooler areas with valuable information for future adaptation strategies.

Considering the importance of viticulture in Greece and the fact that recent regional climate simulation studies (e.g. Tolika et al., 2012, Zanis et al., 2015, Politi et al., 2020 among others) show that future climatic changes in the Mediterranean basin could be significant, the aim of the this chapter is to study the spatiotemporal evolution of historical and future climate conditions for Greek viticulture. In particular the main goals of this Chapter are to: (1) to develop a comprehensive daily climatic database (database 1) from several sources for the main winegrape regions of Greece in order to investigate historical trends of the most important weather parameters (annually and seasonally) and viticultural bioclimatic indices, (2) to categorize the winegrape areas according to these indices and (3) to explore possible shifts in classification, and anticipate possible future threats to their suitability for viticulture using regional climate model simulations. Part of this chapter has been already published as a peer-reviewed article in the *International Journal of Climatology* in 2017 (Koufos et al. 2017).

3.3 Material and methods

To serve the above-mentioned purposes of this chapter, daily observations of maximum (TX), minimum (TN) air temperature (°C) and precipitation (PRCP) (mm), from 23 weather stations were obtained from the archive of the Hellenic National Meteorological Service (HNMS). Each weather station was close enough to each key viticultural areas in Greece (less than 30 km away, on average). The details regarding weather stations location, winegrape areas distribution and period of records are presented in figure 3.1 and Table 3.1, respectively. Overall, the database consists of eight island, 10 coastal and five mainland locations covering a period of 30 years for the majority of the stations (see Table 3.1). Even though in some stations the length of the historical period was less than 30 years long (i.e., Argostoli, Kavala, Paros and Velo weather stations with 25, 23 and 19 years, respectively) and the results might be not robust enough to depict trends for the selected climate parameters and indices, they enriched the analysis due to their importance in the Greek viticultural sector. While data from HNMS were quality controlled and complete until 2004, missing values were identified during the 2005–2010 period. To address this, a specific systematic procedure (see Sections 3.3.1 and 3.3.2 for details) was performed before data was used.

3.3.1 Daily climatic data preparation

First of all, the daily climate observations were organized by region on an annual base and the period that contained enough data to compute climate trends (i.e., 30 years or more) was identified (i.e., 1981-2010) and further analyzed on annual and seasonal [i.e., Winter (December-January-February, hereafter DJF), Spring (March-April-May, hereafter MAM), Summer (June-July-August, hereafter JJA) and Autumn (September-October-November, hereafter SON)] basis. Daily missing values from HNMS were filled from online data sources (www.ncdc.noaa.gov and www.meteo.gr). Before gap filling, correlation analysis between the primary source and the alternative source(s) was performed on daily basis with satisfactory results ($r > 0.95$, on average, for temperature and 0.75 for precipitation). More specifically: (i) every missing day (i.e., days that were not recorded) was automatically characterized as a missing value, (ii) all missing values were replaced from the alternative source(s) if available, (iii) if one or two consecutive missing values were not available even in the alternative source(s), then the missing gaps were calculated as the average of the two days before and after the missing value(s). Finally, due to elevation differences between the weather station and the vineyard areas, the internationally accepted reduction of 0.6℃/100m adjustment was used. Overall, the replaced (reconstructed) values were less than 6% (0.2%), on average, within the entire dataset.

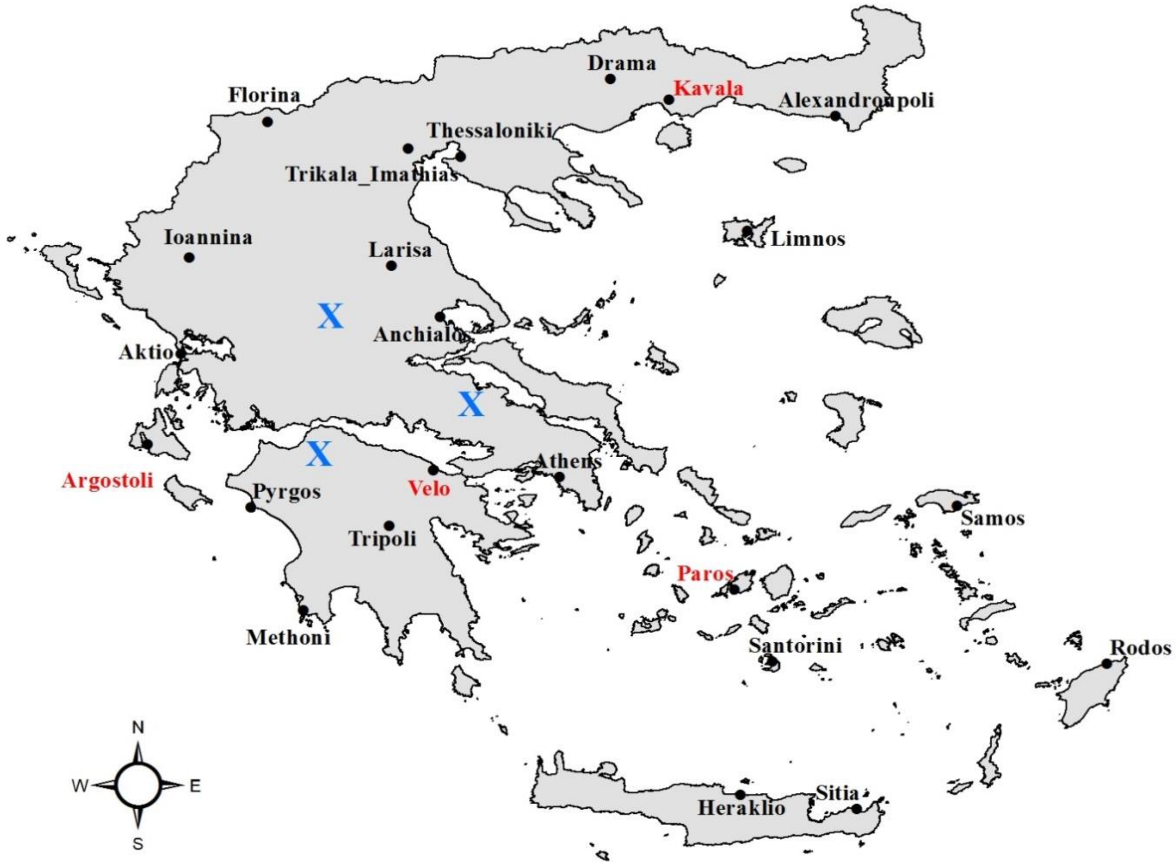

Figure 3.1. Map of the 23 studied areas in Greece. Black bold letters indicate that the weather station has 30 years of climate records (1981 - 2010) while red bold letters indicate shorter period of records. Blue bold X's represents additional key winegrape regions with no adequate climate data.

Table 3.1. Weather station details of the 23 studied areas (location details, latitude, longitude, elevation and period of record). Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**Latitude (decimal degrees)**	**Longitude (decimal degrees)**	**Elevation (m.a.s.l.)**	**Period of Record**
Aktio (Lefkada)[Cs]	38.91	20.75	4	1981 – 2010
Alexandroupoli (Maronia)[Cs]	40.85	25.93	2	1981 – 2010
Anchialos[Cs]	39.21	22.80	15	1981 – 2010
Athens (Spata)[Cs]	37.91	23.75	72	1981 – 2010
Argostoli (Kephalonia)[Is]	38.18	20.48	25	1992 – 2010
Drama[Mn]	41.15	24.15	104	1981 – 2010
Florina (Amyndeo)[Mn]	40.80	21.43	692	1981 – 2010
Heraklio (Peza)[Is]	35.33	25.18	39	1981 – 2010
Ioannina (Zitsa)[Mn]	39.70	20.81	483	1981 – 2010
Kavala (Podochori)[Cs]	40.98	24.61	5	1986 – 2010
Larisa (Tyrnavos)[Mn]	39.63	22.41	73	1981 – 2010
Limnos[Is]	39.91	25.23	3	1981 – 2010
Methoni (Triffilia)[Cs]	36.83	21.71	52	1981 – 2010
Paros[Is]	37.00	25.13	33	1992 – 2010
Pyrgos[Cs]	37.66	21.30	13	1981 – 2010
Rodos (Ebonas)[Is]	36.40	28.08	11	1981 – 2010

Samos[Is]	37.68	26.90	6	1981 – 2010
Santorini[Is]	36.41	25.43	37	1981 – 2010
Sitia (Zakros)[Is]	35.21	26.10	114	1981 – 2010
Thessaloniki (N. Messimvria)[Cs]	40.51	22.96	8	1981 – 2010
Trikala_Imathias (Naoussa)[Cs]	40.58	22.55	6	1981 – 2010
Tripoli (Mantinia)[Mn]	37.51	22.40	651	1981 – 2010
Velo (Nemea)[Cs]	37.96	22.75	19	1988 – 2010

3.3.2 Quality control and homogeneity

Data quality control (QC, hereafter) is it a very important procedure for indices calculation in order to detect climate change and climate extremes (Vincent *et al.*, 2005). QC of the database of this chapter was performed using the RClimDex software (Zhang and Yang, 2004), provided by the Expert Team on Climate Change Detection and Indices (ETCCDI, hereafter). RClimDex is a user-friendly software which can detect: (1) erroneous values (for instance, values of TX ≤ TN and negative values of precipitation - PRCP < 0mm); (2) suspicious values, lying outside a specific range of standard deviation (std) defined by the user and upper threshold of total precipitation (mm) in a single day. The range outside of which a value is characterized as an outlier was defined as the mean climatology of the day plus/minus n times the std of the day [mean ± n×std] (Zhang and Yang, 2004). In this chapter, n was set equal to 3.5 following previous climate studies (Aguilar et al., 2005; Alexander et al., 2006). The specific upper threshold to detect precipitation outliers (i.e., suspicious values) was set to 100 (in most of the studied areas) and 150mm (in the wettest areas such as Ioannina). Only a few cases (< 10 overall) with precipitation amounts greater than these thresholds were identified. Furthermore, the reliability of the results was closely checked using neighbor stations and the “new” values were either retained or set to missing. QC was also performed by visual inspection of the generated plots (as an additional way to check for erroneous or suspicious values). Overall, very few outliers (< 6 days, on average in each station) were identified with this procedure and were carefully handled.

Inhomogeneity in temperature time series is another important issue and can be caused by several issues. The most common issues originate from a stations' relocation, changes in weather instruments, changes in the environment the station is located in, etc. Each of these issues could lead to misleading climate change trends (Trewin, 2010). For this reason, highly reliable metadata is necessary in order to be sure if the shift was caused by a non-climatic reason or is a result of climate change (Vincent *et al*., 2005). However, very few weather stations have reliable metadata over a long period of time. Furthermore, long-term high quality temperature data of neighbor weather stations is required as a reference series to test an individual station for homogeneity (Vincent *et al*., 2005). In Greece, very few cases with adequate metadata exist to confirm or reject a shift. Since daily values tend to have much noise, homogeneity tests were performed on monthly TX and TN means, using the RHtestV4 (Wang and Feng, 2013a) program (accessible at: ETCCDI website, http://etccdi.pacificclimate.org/). This program is based on a two-phase regression model capable of identifying multiple changes in temperature series (Wang, 2003). The latter procedure was performed without using a reference series. PRCP data was checked with the RHtests_dlyPrcp programme (Wang and Feng, 2013b). TX (TN) and PRCP time series presented three (11) and seven cases (out of 23) with significant shifts respectively. Shifts were further checked visually through the generated plots and no potential causes were identified to explain that these were not climate related; thus, no further adjustments were applied to the original datasets.

Once data was carefully prepared and quality checked, RClimDex was used for climatic indices calculation. This software utilizes the input daily dataset to provide the exact formula for each one of 27 climatic core indices (16 temperature-based and 11 precipitation-based) recommended from ETCCDMI. For the purposes of this chapter, a set of 23 indices (15 temperature based and 8 precipitation) were selected and calculated (Table 3.2). Moreover, regarding the winegrape regions categorization, six principal bioclimatic indices was used (Table 3.3 and section 3.3.3 for more details).

Table 3.2. Definition of temperature- and precipitation- based indices (RClimDex software) used in this thesis.

Element	Index	Description	Definition	Unit
Temperature	TXmean	Annual maximum temperature	Annual mean of TX	°C
	TNmean	Annual minimum temperature	Annual mean of TN	°C
	TXx	Highest TX	Annual highest value of TX	°C
	TNx	Highest TN	Annual highest value of TN	°C
	TXn	Lowest TX	Annual lowest value of TX	°C
	TNn	Lowest TN	Annual lowest value of TN	°C
	ID0	Ice days	Annual count when TX < 0°C	Days
	SU25	Summer days	Annual count when TX > 25°C	Days
	SU30	Summer days	Annual count when TX > 30°C	Days

	SU35	Summer days	Annual count when TX > 35oC	Days
	TR20	Tropical nights	Annual count when TN > 20oC	Days
	FD0	Frost days	Annual count when TN < 0oC	Days
	FD-5	Frost days	Annual count when TN < -5oC	Days
	FD-10	Frost days	Annual count when TN < -10oC	Days
	DTR	Diurnal temperature range	Annual mean of difference between TX and TN	℃
Precipitation	R1	Number of days above 1mm	Annual count of days when PRCP≥1mm	Days
	R5	Number of days above 5mm	Annual count of days when PRCP≥5mm	Days
	R10	Number of days above 10mm	Annual count of days when PRCP≥10mm	Days
	R20	Number of days above 20mm	Annual count of days when PRCP≥20mm	Days

	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (PRCP≥ 1mm)	mm/days
	CDD	Consecutive dry days	Maximum number of consecutive dry days (PRCP≤ 1mm)	Days
	CWD	Consecutive wet days	Maximum number of consecutive wet days (PRCP≥ 1mm)	Days
	PRCPTOT	Total annual precipitation	Annual total precipitation	mm

3.3.3 Bioclimatic indices

Among all terroir components, climate is without any doubt, the aspect that has been related most to various vine operations from phenology and growth, berry synthesis and organoleptic properties to yield production and eventually, wine quality (van Leeuwen and Darriet 2016). It is well known that climate chiefly determines whether a region is climatically sufficient to cultivate specific varieties and produce quality grapes (Jones 2005).

Therefore, there have been created several bioclimatic indices that widely used, by the viticultural community: (i) for the characterization of mesoclimates of a viticultural area at a broader scale and the microclimatic conditions within a vineyard area, (ii) to establish the optimum range of winegrape varieties that can be grown inside a region, (iii) to determine the suitability of specific grapevine varieties for quality wine production within a given region (frequently related to the typicity of the produced wine) and (iv) for viticultural zoning, aiming to describe and compare different winegrape areas in recent and projected future periods, on a global scale (Mullins et al. 1992; Gladstones, 1992; Tonietto and Carboneau 2004; Jones 2006; Gladstones 2011). Most of them are accumulated metrics, based on heat summation units over the period of the vine's developmental cycle (typically referred as a 6 to 7-month period: April – October for the northern hemisphere and October – April for the nouthern hemisphere).

The most common index is the growing degree days (GDD, hereafter). GDD describe the heat energy received by the crop over the given time period and are calculated by determining the mean daily temperature [which is simply defined as maximum (TX) + minimum (TN) air temperature / 2] and subtracting the base temperature (Tbase, hereafter) from it. According to Winkler et al. 1974, the Tbase for grapevine physiological activities of photosynthesis and transpiration is considered to be 10°C. Amerine and Winkler (1944) collected a wide range of grapevine varieties cultivated in California and grouped them into five climatic regions according to their heat summations over the period April to October (Growing season, GS hereafter). Later, GDD classified into the Winkler Index (WI, hereafter) providing a valuable tool for predicting phenological stages, also giving an indication of ripening potential of numerous varieties and wine styles that can be produced (Winkler et al. 1974). It is also used as a guide for selecting the appropriate grape varieties in a region.

Another formulation based on GDD index is the Huglin Heliothermal Index (HI, hereafter) (Huglin 1978). This method with the inclusion of a coefficient of correction of the day length (k coefficient, varying from 1.02 to 1.06 at 40 to 50^{o}N), gives more weight to TX of a single day and is calculated for a six-month period, (i.e., April - September for the northern hemisphere and September – April for the southern hemisphere). This index has been widely utilized for viticulture suitability reflecting the potential quality of the produced wines (Huglin 1978).

In addition, Gladstones presented an index similar to GDD, but differentiated by imposing the upper temperature cap of 19°C, used a correction factor for latitude (same as in HI) and also a diurnal temperature range adjustment (Hall and Jones 2010).

Within the grape maturity context, Jones (2006) correlated the growing season average air temperature and phenology records for the most important winegrape varieties, principally cultivated in the most pronounce winegrape regions of the word. The results lead to climate-maturity groupings namely too cool (<13°C), cool (13 - 15°C), intermediate (15 - 17°C), warm (17 - 19°C), hot (19 - 21°C), very hot (21 - 24°C) and too hot (>24°C). The most economically important winegrape varieties of the world are cultivated within these narrow climatic *"niches"* leading to premium wine quality production. This index is a particularly useful tool for several reasons. For example, if a region has an average temperature of 17°C, is climatically sufficient for cultivating a specific number of winegrape varieties. However, if climate warms by 1°C, then the above-mentioned region may shift into another climate-maturity type (i.e., from intermediate to warm) which in turn may be characterized as climatically more conducive to cultivate an even larger number of winegrape varieties mainly due to the extension of the growing season length (i.e., total number of days with average air temperature above 10°C).

On the other hand, in a more holistic approach, the so-called Multicriteria climatic classification system (MCC, hereafter), Tonietto and Carbonneau (2004) had tried to describe the macroclimatic conditions of the viticulture regions of the world by combining 3 complementary viticultural indices: a dryness index (DI, hereafter), based on the potential water balance of soil of Riou's index (Riou et al. 1994), the HI (over the growing cycle) and the cool night index (CI, hereafter) during the maturation phase. The DI index classifies the hydrologic conditions of a given region, on a 6-month period (April – September for the northern hemisphere and September – April for the southern hemisphere) according to the initial useful water reserve (assumed to be 200mm for vineyards at the initial moment), precipitation, transpiration and direct evaporation from the soil. Moreover, the CI it is known that affects berry and wine quality attributes (e.g., anthocyanins concentration) (Tonietto and Carbonneau, 2004).

The index simply estimates the mean nighttime temperature of the ripening month on a given region (i.e., most commonly September month). The initial aim of this index was to investigate the relevant influence of nighttime conditions to the quality of the berries (e.g., aroma compounds) and eventually the resulting wine (Tonietto and Carboneau 2004). MCC classified 97 grape growing regions regarding their climatic conditions (both hydrologic and thermal) in 29 countries (Tonietto and Carboneau 2004).

Even though these indices had been criticized for being either too simple or only appropriate for a specific region, all considered valuable in the context of viticulture (Jones 2012). For example, the MCC system might consider as complex enough because the calculation of several parameters often requires additional knowledge and records that there are not readily available for the majority of the growers.

Table 3.3. The first two columns present the name and the respective source of the bioclimatic index as well as each respective equations and period of calculations. The third column contains details of class limits of each index for the viticultural areas. T_{mean}: mean daily temperature respectively; K: adjustment coefficient of latitude/day length (see Hall and Jones 2010 for more details); Wo: initial useful soil – water reserve, Tv: potential transpiration, Es: direct evaporation from the soil (see Tonietto and Carbonneau 2004 for more details).

Bioclimatic index/Source	**Equation/months**	**Class limits**
Average Growing Season Temperature (GST), Jones 2006	$\frac{\sum_{Apr}^{Oct}[TX + TN]/2}{n}$	Too cool < 13°C Cool 13 – 15°C Intermediate 15 – 17°C Warm 17 – 19°C Hot 19 – 21°C Very hot 21 – 24°C Too hot > 24°C
Growing Degree Days (GDD), Winkler et al. 1974; Anderson et al. 2012	$\sum_{Apr}^{Oct} \max[\frac{(TX + TN)}{2} - 10{,}0]$	Too cool < 850 (Region Ia) 850 – 1111 (Region Ib) 1111 – 1389 (Region II) 1389 – 1667 (Region III) 1667 – 1944 (Region IV) 1944 – 2222 (Region V) 2222 – 2700 Too hot > 2700

Huglin Index (HI), Huglin 1978	$\sum_{Apr}^{Sep}[(Tmean-10+TX-10)/2{,}0]K$	Too cool < 1200 Very cool 1200 – 1500 Cool 1500 - 1800 Temperate 1800 – 2100 Warm temperate 2100 – 2400 Warm 2400 – 2700 Very warm 2700 – 3000 Too hot > 3000
Biologically Effective Degrees Days (BEDD), Gladstones 1992	$\sum_{Apr}^{Oct}\min[max\left(\frac{[TX+TN]}{2}-10{,}0\right)K+DTRadj,9]$ DTRadj=$\begin{Bmatrix} 0.25[TX-TN-13],\ [TX-TN]>13 \\ 0{,}10<[TX-TN]<13 \\ 0.25[TX-TN-10],[TX-TN]<10 \end{Bmatrix}$	1. < 1000 2. 1000 – 1200 3. 1200 – 1400 4. 1400 – 1600 5. 1600 – 1800 6. 1800 – 2000 7. > 2000
Dryness Index (DI), Tonietto and Carbonneau 2004	$\sum_{Apr}^{Sep}(Wo+P-Tv-Es)$	Very dry ≤ -100 Moderate dry ≤ 50 > -100 Sub – Humid ≤ 150 > 50 Humid > 150
Night Cold Index (CI), Tonietto and	September average TN	Very cool nights ≤ 12 Cool nights > 12 ≤ 14

Carbonneau 2004		Temperate nights > 14 ≤ 18 Warm nights > 18

3.3.4 Climate simulations and scenarios

General circulation models (GCMs, hereafter) have been widely used to generate future projections to satisfy the growing interest for global climate change impacts. Regional climate models (RCMs, hereafter) on the other hand, were developed to enhance the regional information derived from GCMs at a local scale. They also provide more details for complex geographic features such as complex topography, coastlines, lakes and small islands (Zanis et al., 2015). For the purposes of the current chapter, regional climate analysis was performed using daily simulations from the International Centre for Theoretical Physics Regional Climate Model v4.3 (RegCM, hereafter). The RegCM enables a high horizontal resolution of 0.11° × 0.11° (http://www.euro-cordex.net/). The representative concentration pathway 8.5 (RCP8.5) was employed in order to assess the impacts of climate change for two different time windows [future period 1 (FP1, hereafter): 2021–2050 and future period 2 (FP2, hereafter): 2061–2090]. The RCP8.5 is characterized by a high increase in greenhouse gas emissions in the future. Numerical simulations have been carried out in Europe (EURO–CORDEX) and the results were generally consistent with the observed datasets (Giorgi et al., 2012). To investigate the RegCM's ability to reproduce the local climate conditions in Greece, the modelled mean monthly temperature and precipitation were compared with observed data from 19 HNMS weather stations over the period 1980–2004. The results are presented in Figures 3.2-3.4. The temperature scenarios for FP1 and FP2 were then constructed by adjusting the historical time series with the mean monthly changes (positive or negative) estimated between the control and FP1 and FP2 time series during the baseline period (BP, hereafter) 1981–2010. The respective mean monthly per cent changes (expressed as %) were used in the case of the precipitation scenarios for the two future periods FP1 and FP2.

3.4 Statistical analysis

The temporal evolution of the above-mentioned bioclimatic and RClimDex indices were initially explored using the basic regression equation (Y = a + bX) for each region. The ordinary least squares regression was used to fit the regression line. The trend of each variable and index was evaluated using the Pearson's correlation coefficient (r) while the statistical significance of the trend was assessed at the 5% level (p-value < 0.05). The results at 10% level were also presented (p-value < 0.1). All statistical analyses and computations were carried out using the R statistical software (R Core Team, 2014).

3.5 Results

This section is constructed as follow: first we present the results from the regional climate model evaluation. Next, we summarize the results of the trend analyses of the RClimDex core indices, and the seasonal climate overview. In the next section, we present the analysis regarding the main bioclimatic indices used for the studied areas. Lastly, the effects of historical and future climate conditions to climate-, viticulture-related indices and zoning are presented.

3.5.1 RegCM evaluation

The visual inspection of TX on monthly basis indicates consistent negative biases everywhere except for Rodos and Anchialos (Figure 3.2). Although positive biases for TN were predominant (11 cases, Figure 3.3) mainly in island (except for Heraklio), there is an underestimation (negative biases) in mainland locations (Drama, Florina and Ioannina). Finally, the results for PRCP showed a consistent monthly overestimation mainly in Northern (Thessaloniki, Drama and Alexandroupoli) and Western areas, with Western Greece (i.e., Ioannina, Aktio, Pyrgos and Methoni) being largely positively biased. Interestingly, a slight underestimation of summer months (e.g., July and August) in several cases was also identified (eight cases) (Figure 3.4).

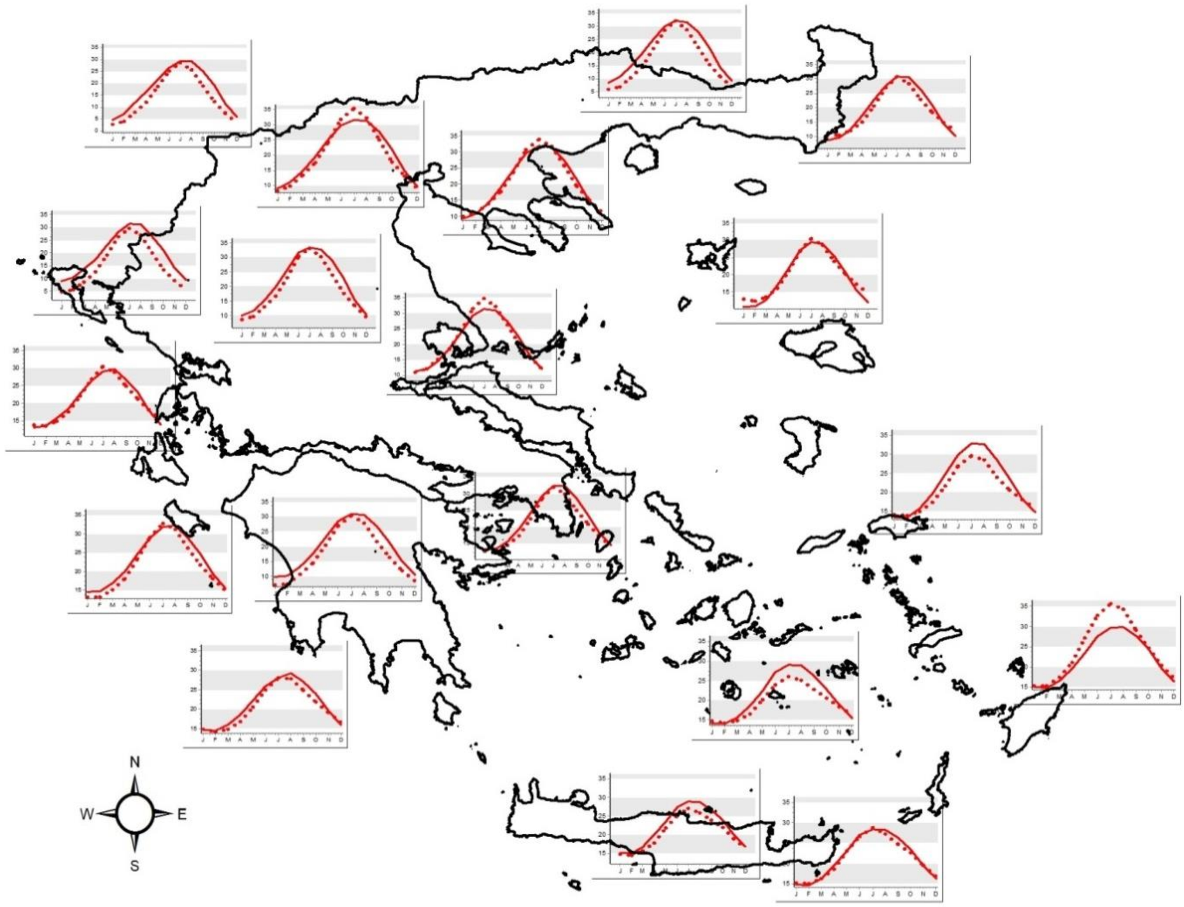

Figure 3.2. Comparison of mean monthly maximum air temperature (TX, °C) between observational data (solid lines) and the derived from the regional climate model (dashed lines) RegCM4 during 1980–2004. The vertical axes represent mean monthly maximum air temperature (TX), ranged from 2 to 36 ℃, while the horizontal axes show the months starting from January.

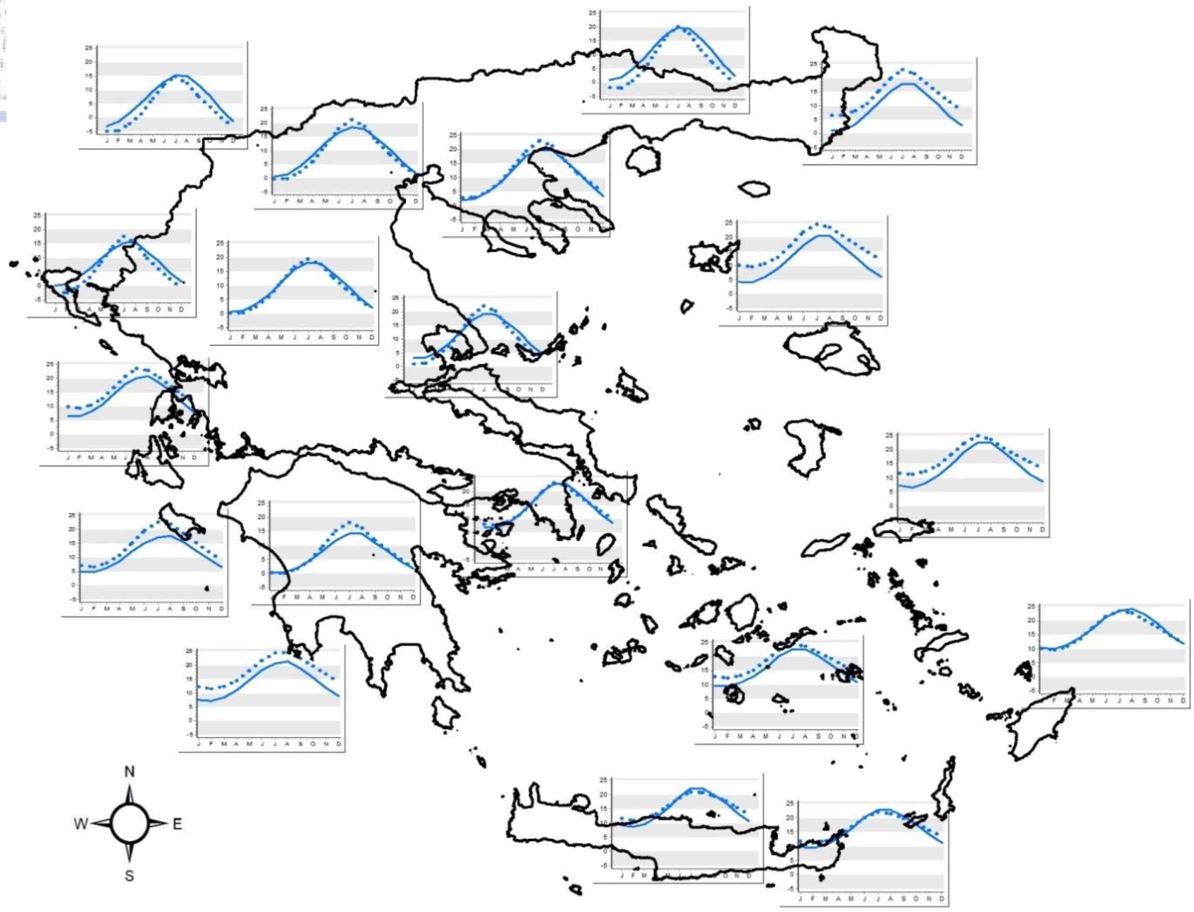

Figure 3.3. Comparison of mean monthly minimum air temperature (TN, °C) between observational data (solid lines) and the derived from the regional climate model (dashed lines) RegCM4 during 1980–2004. The vertical axes represent mean monthly minimum air temperature (TN), ranged from −5 to 25 ℃, while the horizontal axes show the months starting from January.

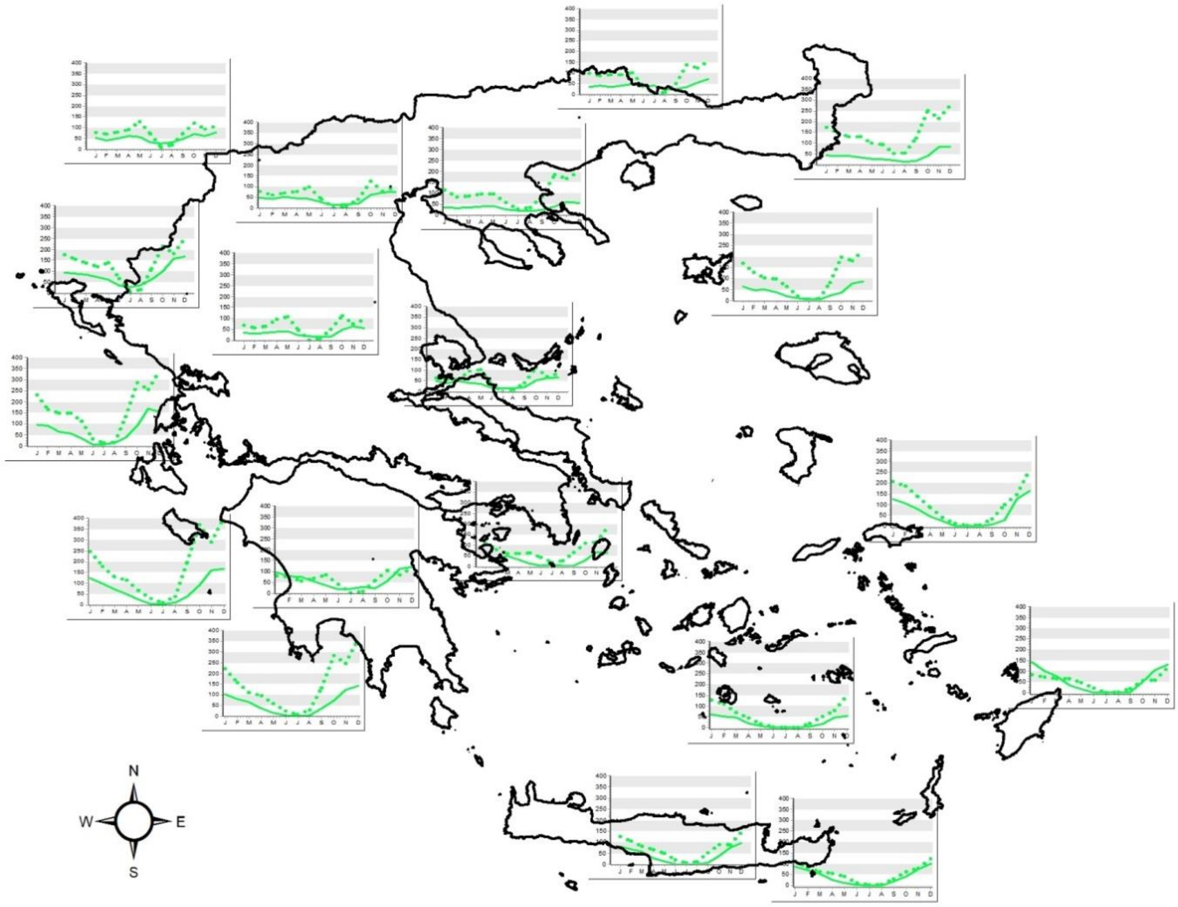

Figure 3.4. Comparison of mean monthly precipitation (PR) between observational data (solid lines) and the derived from the regional climate model (dashed lines) RegCM4 during 1980–2004. The vertical axes represent mean monthly precipitation (PR), ranged from 0 to 400 mm, while the horizontal axes show the months starting from January.

3.5.2 Annual analysis of the selected RClimDex core indices.

The results from the RClimDex core indices are summarized in tables 3.4 - 3.6. Regarding the temperature related indices, almost all of the studied areas experienced statistically significant upward trends in TX and TN means. The magnitude of trends is higher for the TN compared to the TX and this difference leads to a statistically significant decrease in DTR values. However, the absolute temperature indices (i.e., TXx, TXn and TNn) showed mixed changes mostly insignificant within the studied areas (Table 3.4). Contradictory, statistically significant increases of maximum daily minimum temperatures (TNx) were identified in the majority of the studied locations (15 out of 29 cases). The largest annual increase was reported in Drama and Florina (+4.5 and +4.2, respectively). As a result of warmer conditions (higher TX and TN), the annual number of warm night (TR20) was significantly increased (17 statistically significant cases). Similar results were reported for the summer days (SU30) as well, although of smaller magnitude (Table 3.5). In addition, frost days (i.e., FD0, FD-5 and FD-10) showed decreasing but mainly insignificant trends. Finally, for the period of records (1981-2010), the results showed mixed and insignificant trends in precipitation extremes, totals and indices (Table 3.6).

Table 3.4. Annual direction and slope (in the first row) for the temperature extreme indices for the baseline period 1981-2010 (30 years trend in parenthesis) in Greece [℃/yr for all variables]. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (i.e., p-value < 0.1). Underlined zeros indicate annual trend less than 0.01. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TXmean**	**TNmean**	**TXx**	**TXn**	**TNx**	**TNn**	**DTR**
Aktio (Lefkada)^{Cs}	***+ 0.02*** ***(+ 0.6)***	**+ 0.06** **(+ 1.8)**	**+ 0.07** **(+ 2.1)**	- 0.02 (- 0.6)	**+ 0.09** **(+ 2.7)**	+ 0.02 (+ 0.6)	**- 0.04** **(- 1.2)**
Alexandroupoli (Maronia)^{Cs}	**+ 0.05** **(+ 1.5)**	**+ 0.06** **(+ 1.8)**	**+ 0.10** **(+ 3.0)**	+ 0.01 (+ 0.3)	+ 0.03 (+ 0.9)	+ 0.03 (+ 0.9)	- 0.02 (- 0.6)
Anchialos^{Cs}	**+ 0.04** **(+ 1.2)**	**+ 0.04** **(+ 1.2)**	- 0.03 (- 0.9)	- 0.01 (- 0.3)	+ 0.04 (+ 1.2)	+ 0.01 (+ 0.3)	- 0 (0)
Athens (Spata)^{Cs}	**+ 0.05** **(+ 1.5)**	**+ 0.04** **(+ 1.2)**	**+ 0.11** **(+ 3.3)**	- 0.02 (- 0.6)	**+ 0.10** **(+ 3.0)**	- 0.03 (- 0.9)	+ 0.01 (+ 0.12)
Drama^{Mn}	***+ 0.03*** ***(+ 0.9)***	**+ 0.13** **(+ 3.9)**	+ 0.01 (+ 0.3)	+ 0.01 (+ 0.3)	**+ 0.15** **(+ 4.5)**	**+ 0.14** **(+ 4.2)**	**- 0.11** **(- 3.3)**
Florina (Amyndeo)^{Mn}	+ 0.01 (+ 0.3)	**+ 0.06** **(+ 1.8)**	+ 0.04 (+ 1.2)	- 0.06 (- 1.8)	**+ 0.14** **(+ 4.2)**	- 0.04 (- 1.2)	**- 0.05** **(- 1.5)**

Heraklio (Peza)[Is]	**+ 0.05** (**+ 1.5**)	**+ 0.03** (**+ 0.9**)	+ 0.07 (+ 2.1)	+ 0.01 (+ 0.3)	**+ 0.06** (**+ 1.8**)	+ 0.02 (+ 0.6)	**+ 0.02** (**+ 0.6**)
Ioannina (Zitsa)[Mn]	+ 0 (0)	**+ 0.04** (**+ 1.2**)	+ 0.02 (+ 0.6)	+ 0.01 (+ 0.3)	+ 0.01 (+ 0.3)	+ 0 (0)	**- 0.04** (**- 1.2**)
Larisa (Tyrnavos)[Mn]	**+ 0.04** (**+ 1.2**)	**+ 0.06** (**+ 1.8**)	+ 0.01 (+ 0.3)	- 0.03 (- 0.9)	**+ 0.09** (**+ 2.7**)	+ 0 (0)	- 0.03 (- 0.9)
Limnos[Is]	**+ 0.04** (**+ 1.2**)	**+ 0.05** (**+ 1.5**)	+ 0.05 (+ 1.5)	- 0.06 (- 1.8)	**+ 0.10** (**+ 3.0**)	- 0.01 (- 0.3)	**- 0.02** (**- 0.6**)
Methoni (Triffilia)[Cs]	**+ 0.03** (**+ 0.9**)	**+ 0.03** (**+ 0.9**)	- 0.01 (- 0.3)	+ 0 (0)	**+ 0.07** (**+ 2.1**)	- 0.01 (- 0.3)	+ 0 (0)
Pyrgos[Cs]	**+ 0.04** (**+ 1.2**)	**+ 0.09** (**+ 2.7**)	***+ 0.08*** (***+ 2.4***)	+ 0.02 (+ 0.6)	**+ 0.09** (**+ 2.7**)	+ 0.02 (+ 0.6)	**- 0.05** (**- 1.5**)
Rodos (Ebonas)[Is]	**+ 0.03** (**+ 0.9**)	**+ 0.05** (**+ 1.5**)	+ 0.03 (+ 0.9)	- 0.01 (- 0.3)	**+ 0.05** (**+ 1.5**)	0 (0)	**- 0.02** (**- 0.6**)
Samos[Is]	**+ 0.04** (**+ 1.2**)	**+ 0.09** (**+ 2.7**)	**+ 0.07** (**+ 2.1**)	- 0.01 (- 0.3)	**+ 0.09** (**+ 2.7**)	+ 0.02 (+ 0.6)	**- 0.05** (**- 1.5**)
Santorini[Is]	**+ 0.02** (**+ 0.6**)	**+ 0.07** (**+ 2.1**)	- 0.01 (- 0.3)	- 0.01 (- 0.3)	**+ 0.08** (**+ 2.4**)	+ 0.02 (+ 0.6)	**- 0.05** (**- 1.5**)

Sitia (Zakros)[Is]	0 (0)	**+ 0.07 (+ 2.1)**	+ 0.04 (+ 1.2)	- 0.01 (- 0.3)	**+ 0.10 (+ 3.0)**	+ 0.03 (+ 0.9)	**- 0.07 (- 2.1)**
Thessaloniki (N. Messimvria)[Cs]	**+ 0.03 (+ 0.9)**	**+ 0.07 (+ 2.1)**	+ 0.08 (+ 2.4)	- 0.01 (- 0.3)	**+ 0.10 (+ 3.0)**	+ 0.08 (+ 2.4)	**- 0.04 (- 1.2)**
Trikala_Imathias (Naoussa)[Cs]	**+ 0.05 (+ 1.5)**	**+ 0.05 (+ 1.5)**	+ 0.07 (+ 2.1)	- 0.01 (- 0.3)	**+ 0.09 (+ 2.7)**	+ 0.01 (+ 0.3)	0 (0)
Tripoli (Mantinia)[Mn]	+ 0.02 (+ 0.6)	+ 0.02 (+ 0.6)	0 (0)	- 0.03 (- 0.9)	+ 0.08 (+ 2.4)	+ 0.05 (+ 1.5)	0 (0)
Overall *Negative* *Nonsignificant* *Positive*	 *0* *6* *13*	 *0* *1* *18*	 *0* *15* *4*	 *0* *19* *0*	 *0* *4* *15*	 *0* *18* *1*	 *11* *7* *1*

Table 3.5. Annual direction and slope (in the first row) for the temperature extreme indices for the baseline period 1981-2010 (30 years trend in parenthesis) in Greece [days/yr for all variables]. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). Underlined zeros indicate annual trend less than 0.01. Empty cells indicate that no days with temperature below the specific threshold was recorded. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**ID0**	**SU25**	**SU30**	**SU35**	**TR20**	**FD0**	**FD-5**	**FD-10**
Aktio (Lefkada)[Cs]	0 (0)	+ 0.4 (+ 12.0)	**+ 0.3 (+ 9.0)**	0 (0)	**+ 1.1 (+ 33.0)**	- 0.1 (- 3.0)		
Alexandroupoli (Maronia)[Cs]	- 0.04 (- 1.2)	**+ 0.4 (+ 12.0)**	**+ 0.9 (+ 27.0)**	**+ 0.3 (+ 9.0)**	**+ 0.9 (+ 27.0)**	- 0.3 (- 9.0)	- 0.1 (- 3.0)	0 (0)
Anchialos[Cs]	0 (0)	- 0.2 (- 6.0)	**+ 0.8 (+ 24.0)**	+ 0.1 (+ 3.0)	**+ 0.9 (+ 27.0)**	- 0.2 (- 6.0)	0 (0)	0 (0)
Athens (Spata)[Cs]		+ 0.3 (+ 9.0)	**+ 1.3 (+ 39.0)**	**+ 0.5 (+ 15.0)**	**+ 1.0 (+ 30.0)**	- 0.02 (- 0.6)		
Drama[Mn]	0 (0)	- 0.2 (- 6.0)	+ 0.3 (+ 9.0)	+ 0.1 (+ 3.0)	**+ 1.9 (+ 57.0)**	**- 1.4 (- 42.0)**	**- 0.3 (- 9.0)**	0 (0)
Florina (Amyndeo)[Mn]	+ 0.1	- 0.1	+ 0.4	+ 0.1	**+ 0.1**	- 1.0	***- 0.4***	0

	(+ 3.0)	(- 3.0)	(+ 12.0)	(+ 3.0)	**(+ 3.0)**	(- 30.0)	***(- 12.0)***	(0)
Heraklio (Peza)^{Is}		**+ 1.2** **(+ 36.0)**	+ 0.2 (+ 6.0)	***+ 0.1*** ***(+ 3.0)***	**+ 0.7** **(+ 21.0)**	0 (0)		
Ioannina (Zitsa)^{Mn}	0 (0)	***- 0.5*** ***(- 15.0)***	+ 0.1 (+ 3.0)	+ 0.04 (+ 1.2)	0 (0)	***- 0.4*** ***(- 12.0)***	- 0.1 (- 3.0)	0 (0)
Larisa (Tyrnavos)^{Mn}	- 0.02 (- 0.6)	- 0.1 (- 3.0)	***+ 0.5*** ***(+ 15.0)***	**+ 0.4** **(+ 12.0)**	**+ 0.6** **(+ 18.0)**	**- 0.7** **(- 21)**	- 0.1 (- 3.0)	0 (0)
Limnos^{Is}	+ 0.02 (+ 0.6)	0 (0)	**+ 1.0** **(+ 30.0)**	+ 0.01 (+ 0.3)	**+ 0.9** **(+ 27.0)**	- 0.1 (- 3.0)	0 (0)	
Methoni (Triffilia)^{Cs}		**+ 0.9** **(+ 27.0)**	0 (0)	0 (0)	**+ 0.5** **(+ 15.0)**	0 (0)	0 (0)	
Pyrgos^{Cs}		+ 0.1 (+ 3.0)	**+ 0.7** **(+ 21.0)**	**+ 0.4** **(+ 12.0)**	**+ 1.2** **(+ 36.0)**	**- 0.4** **(- 12.0)**	0 (0)	
Rodos (Ebonas)^{Is}		**+ 0.5** **(+ 15.0)**	***+ 0.1*** ***(+ 3.0)***	0 (0)	**+ 1.4** **(+ 42.0)**	0 (0)		
Samos^{Is}	0 (0)	+ 0.03 (+ 0.9)	**+ 1.0** **(+ 30.0)**	***+ 0.1*** ***(+ 3.0)***	**+ 1.3** **(+ 39.0)**	***- 0.3*** ***(- 9.0)***	0 (0)	
Santorini^{Is}		0	**+ 0.5**	0	**+ 1.8**	0		

		(0)	**(+ 15.0)**	(0)	**(+ 54.0)**	(0)		
Sitia (Zakros)[Is]		- 0.3 (- 9.0)	+ 0.1 (+ 3.0)	+ 0.03 (+ 0.9)	**+ 1.4** **(+ 42.0)**			
Thessaloniki (N. Messimvria)[Cs]	0 (0)	- 0.3 (- 9.0)	**+ 0.6** **(+ 18.0)**	**+ 0.3** **(+ 9.0)**	**+ 1.9** **(+ 57.0)**	***- 0.3*** ***(- 9.0)***	***- 0.1*** ***(- 3.0)***	0 (0)
Trikala_Imathias (Naoussa)[Cs]	- 0.04 (- 1.2)	+ 0.2 (+ 6.0)	**+ 1.0** **(+ 30.0)**	**+ 0.2** **(+ 6.0)**	**+ 0.6** **(+ 18.0)**	- 0.4 (- 12.0)	- 0.04 (- 1.2)	- 0.02 (- 0.6)
Tripoli (Mantinia)[Mn]	0 (0)	- 0.1 (- 3.0)	+ 0.5 (+ 15.0)	+ 0.1 (+ 3.0)	+ 0.1 (+ 3.0)	+ 0.1 (+ 3.0)	+ 0.1 (+ 3.0)	0 (0)
Overall *Negative* *Nonsignificant* *Positive*	 0 12 0	 0 15 4	 0 9 10	 0 12 6	 0 2 17	 3 15 0	 1 12 0	 0 9 0

Table 3.6. Annual direction and slope (in the first row) for the precipitation extreme indices for the baseline period 1981-2010 (30 years trend in parenthesis) in Greece [mm/yr for SDII and PRCPTOT while R1, R5, R10, R20 and CDD, CWD days/yr]. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). Underlined zeros indicate annual trend less than 0.01. Empty cells indicate that no days with temperature below the specific threshold was recorded. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**R1**	**R5**	**R10**	**R20**	**SDII**	**CDD**	**CWD**	**PRCPTOT**
Aktio (Lefkada)[Cs]	+ 0.2 (+ 6.0)	+ 0.2 (+ 6.0)	+ 0.2 (+ 6.0)	+ 0.1 (+ 3.0)	<u>0</u> <u>(0)</u>	- 0.1 (- 3.0)	+ 0.1 (+ 3.0)	+ 2.9 (+ 87.0)
Alexandroupoli (Maronia)[Cs]	+ 0.2 (+ 6.0)	+ 0.2 (+ 6.0)	+ 0.1 (+ 3.0)	***+ 0.1*** ***(+ 3.0)***	+ 0.1 (+ 3.0)	+ 0.1 (+ 3.0)	<u>0</u> <u>(0)</u>	+ 4.5 (+ 135.0)
Anchialos[Cs]	- 0.05 (- 1.5)	<u>0</u> <u>(0)</u>	+ 0.1 (+ 3.0)	<u>0</u> <u>(0)</u>	<u>0</u> <u>(0)</u>	- 0.6 (- 18.0)	<u>0</u> <u>(0)</u>	+ 0.2 (+ 6.0)
Athens (Spata)[Cs]	+ 0.04 (+ 1.2)	- 0.02 (- 0.6)	- 0.03 (- 0.9)	- 0.03 (- 0.9)	<u>0</u> <u>(0)</u>	- 0.4 (- 12.0)	+ 0.03 (+ 0.9)	- 0.2 (- 6.0)
Drama[Mn]	**+ 0.6** **(+ 18.0)**	***+ 0.3*** ***(+ 12.0)***	+ 0.2 (+ 6.0)	**+ 0.2** **(+ 6.0)**	+ 0.03 (+ 0.9)	***- 0.5*** ***(- 1.5)***	- 0.02 (- 0.6)	**+ 8.1** **(+ 243.0)**

Florina (Amyndeo)[Mn]	- 0.1 (- 3.0)	- 0.2 (- 6.0)	- 0.1 (- 3.0)	- 0.02 (- 0.6)	- 0.02 (- 0.6)	- 0.1 (- 3.0)	0 (0)	- 1.6 (- 48.0)
Heraklio (Peza)[Is]	+ 0.1 (+ 2.7)	- 0.04 (- 1.2)	- 0.1 (- 3.0)	0 (0)	0 (0)	- 0.4 (- 12.0)	0 (0)	+ 0.1 (+ 3.0)
Ioannina (Zitsa)[Mn]	+ 0.3 (+ 9.0)	***+ 0.4 (+ 12.0)***	***+ 0.3 (+ 9.0)***	***+ 0.2 (+ 6.0)***	***+ 0.1 (+ 3.0)***	- 0.5 (- 15.0)	- 0.04 (- 1.2)	***+ 8.5 (+ 255.0)***
Larisa (Tyrnavos)[Mn]	+ 0.1 (+ 3.0)	0 (0)	+ 0.1 (+ 3.0)	- 0.04 (- 1.2)	0 (0)	- 0.2 (- 6.0)	0 (0)	0 (0)
Limnos[Is]	+ 0.2 (+ 6.0)	**+ 0.3 (+ 9.0)**	***+ 0.2 (+ 6.0)***	***+ 0.1 (+ 3.0)***	**+ 0.1 (+ 3.0)**	+ 0.5 (+ 15.0)	**+ 0.1 (+ 3.0)**	**+ 7.1 (+ 213.0)**
Methoni (Triffilia)[Cs]	- 0.2 (- 6.0)	- 0.1 (- 3.0)	***- 0.2 (- 6.0)***	- 0.1 (- 3.0)	- 0.02 (- 0.6)	+ 0.2 (+ 6.0)	- 0.1 (- 3.0)	- 3.5 (- 108)
Pyrgos[Cs]	+ 0.1 (+ 3.0)	0 (0)	- 0.1 (- 3.0)	- 0.04 (- 1.2)	**- 0.07 (- 2.1)**	- 0.1 (- 3.0)	+ 0.1 (+ 3.0)	- 3.6 (- 105.0)
Rodos (Ebonas)[Is]	- 0.1 (- 3.0)	- 0.1 (- 3.0)	- 0.1 (- 3.0)	- 0.02 (- 0.6)	- 0.05 (- 1.5)	- 0.1 (- 3.0)	**- 0.1 (- 3.0)**	- 3.6 (- 108.0)
Samos[Is]	- 0.1	- 0.2	- 0.2	- 0.1	- 0.04	- 0.1	- 0.02	- 3.0

	(- 3.0)	(- 6.0)	(- 6.0)	(- 3.0)	(- 1.2)	(- 3.0)	(- 0.6)	(- 90.0)
Santorini[Is]	+ 0.2 (+ 6.0)	+ 0.2 (+ 6.0)	+ 0.04 (+ 1.2)	0 (0)	0 (0)	**- 2.1** **(- 63.0)**	0 (0)	+ 1.1 (+ 33.0)
Sitia (Zakros)[Is]	0 (0)	- 0.2 (- 6.0)	- 0.1 (- 3.0)	**- 0.1** **(- 3.0)**	**- 0.1** **(- 3.0)**	+ 0.7 (+ 21.0)	+ 0.05 (+1.5)	***- 4.5*** ***(- 135.0)***
Thessaloniki (N. Messimvria)[Cs]	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	- 0.04 (- 1.2)	+ 0.2 (+ 6.0)
Trikala_Imathias (Naoussa)[Cs]	+ 0.1 (+ 3.0)	- 0.1 (- 3.0)	+ 0.04 (+ 1.2)	+ 0.1 (+ 3.0)	+ 0.03 (+ 0.9)	- 0.2 (- 6.0)	+ 0.01 (+ 0.3)	+ 3.2 (+ 96.0)
Tripoli (Mantinia)[Mn]	- 0.02 (- 0.6)	- 0.1 (- 3.0)	- 0.1 (- 3.0)	- 0.1 (- 3.0)	- 0.03 (- 0.9)	- 0.4 (- 12.0)	0 (0)	- 1.4 (- 42.0)
Overall *Negative* *Nonsignificant* *Positive*	 *0* *18* *1*	 *0* *18* *1*	 *0* *19* *0*	 *1* *17* *1*	 *2* *16* *1*	 *1* *18* *0*	 *1* *17* *1*	 *0* *17* *2*

3.5.3 Seasonal overview of air TX, TN, DTR and PRCP (averages and trends)

Mean TX during the DJF ranged from 6.1 (Florina) to 15.3°C (Sitia) with island locations generally exhibiting warmer conditions (13.2°C, on average) than the respective coastal and mainland ones (11.7 and 8.8°C, on average respectively) (Table 3.7). The highest TN means were identified mainly at island locations compared to the coastal and mainland (7.7, 3.9, 0.2°C, on average, respectively). DTR values were lower at island (5.5°C, on average) than at coastal and mainland locations

(7.7 and 8.6°C, on average respectively). Finally, total PRCP ranged from 120 mm (Larisa) to 383 mm (Samos). The highest values were observed mostly on islands which experienced wetter winter conditions (268 mm, on average). On the other hand, Aktio, Ioannina and Pyrgos received the highest values of total precipitation among coastal and mainland locations (Table 3.7).

The direction and magnitude of trends in each variable along with the statistical significance are also shown in Table 3.7. Overall, the analysis of the DJF revealed positive trends for both TX and TN (7 and 11 statistically significant cases for TX and TN, respectively) in every case except for TN in Tripoli (Table 3.7). With regards to the average magnitude of trends, across all locations, the TN warming rate was +0.9°C higher than the TX rate (1.5 *vs* 0.6°C/30 year, on average). Specifically, trends in TN were more pronounced than TX in most cases (13 *vs* 2), four locations experienced equal temperature trends and in only two locations (Heraklio and Trikala Imathias), TX trends were higher than TN (Table 3.7). Drama, Pyrgos and Samos exhibited the highest rates of change in TN (0.14 and 0.07°C year^{-1}, respectively), Athens, Heraklio and Methoni displayed the lowest (0.02°C year^{-1}) while Tripoli exhibited no trend. In contrast, moderate TX trends were identified in most of the cases (the trend of 0.02°C year^{-1} appeared 7 times) while Drama and Trikala Imathias presented the highest trends (0.06 and 0.05°C year^{-1}). Because of the higher increases in TN, statistically significant negative trends in DTR were identified in most cases (12 cases in total, 7 statistically significant). Significant positive trend was observed only in Heraklio along with several other locations with non-significant trends. Finally, PRCP showed mixed results (12 positive trends *vs* 7 negative). However, none of these cases was statistically (Table 3.7).

Table 3.7 Descriptive statistics for air temperature variables (i.e., TX and TN), DTR and precipitation during the DJF (DJF: December–January-February) [first row of each location (station) corresponds to mean value and standard deviation in parenthesis, while 30 years trends and Pearson *r* are presented in the second row, respectively] for the main winegrape areas in Greece during the baseline period (1981–2010). The total number of statistically significant cases are summarized in the final row of the table. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). The nonsignificant cases of each variable are also presented. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TX - avg/sd, °C (trend yr^{-1}/pearson r)**	**TN - avg/sd, °C (trend yr^{-1}/pearson r)**	**DTR - avg/sd, °C (trend yr^{-1}/pearson r)**	**PRCP - avg/sd, mm (trend yr^{-1}/pearson r)**
Aktio (Lefkada)^{Cs}	11.8 / 0.6 (0.01 / 0.08)	**5.3 / 0.9** **(0.06 / 0.55)**	**6.6 / 0.7** **(-0.05 / -0.64)**	111.7 / 6.6 (1.86 / 0.15)
Alexandroupoli (Maronia)^{Cs}	9.2 / 0.7 (0.02 / 0.29)	1.5 / 1.1 (0.03 / 0.24)	7.7 / 0.9 (-0.00 / -0.05)	79.7 / 7.7 (2.52 / 0.28)
Anchialos^{Cs}	12.0 / 0.9 (0.03 / 0.28)	3.7 / 0.9 (0.03 / 0.27)	8.2 / 0.8 (-0.00 / -0.01)	65.2 / 8.2 (0.70 / 0.09)
Athens (Spata)^{Cs}	13.3 / 0.8 (0.01 / 0.11)	6.8 / 0.9 (0.02 / 0.23)	6.5 / 0.5 (-0.01 / -0.22)	70.3 / 6.5 (-0.70 / -0.09)
Drama^{Mn}	**9.0 / 0.9** **(0.06 / 0.57)**	**1.6 / 1.5** **(0.14 / 0.81)**	**7.4 / 1.0** **(-0.08 / -0.71)**	93.1 / 7.4 (2.71 /0.26)
Florina (Amyndeo)^{Mn}	6.1 / 1.2 (0.01 / 0.04)	**-1.7 / 1.3** **(0.06 / 0.40)**	**7.8 / 0.8** **(-0.05 / -0.62)**	55.7 / 7.8 (-0.55 / -0.09)
Heraklio (Peza)^{Is}	**14.0 / 0.9** **(0.04 / 0.38)**	7.8 / 0.7 (0.02 / 0.28)	**6.2 / 0.4** **(0.02 / 0.36)**	88.8 / 6.2 (1.65 / 0.16)
Ioannina (Zitsa)^{Mn}	8.5 / 0.8	-0.3 / 1.2	8.9 / 1.2	125.0 / 8.9

	(0.02 / 0.25)	(0.04 / 0.28)	(-0.02 / -0.12)	(2.43 / 0.17)
Larisa (Tyrnavos)Mn	**10.2 / 1.0** **(0.04 / 0.37)**	***0.7 / 1.2*** ***(0.04 / 0.31)***	9.5 / 1.3 (0.00 / -0.01)	45.3 / 9.5 (0.53 / 0.10)
LimnosIs	11.3 / 0.8 (0.02 / 0.17)	***5.1 / 1.1*** ***(0.04 / 0.31)***	6.2 / 0.7 (-0.02 / -0.28)	88.2 / 6.2 (2.84 / 0.28)
Methoni (Triffilia)Cs	***12.8 / 0.6*** ***(0.02 / 0.31)***	5.6 / 0.8 (0.02 / 0.23)	7.2 / 0.4 (-0.00 / -0.01)	99.4 / 7.2 (-0.90 / -0.08)
PyrgosCs	**15.1 / 0.6** **(0.03 / 0.44)**	**5.7 / 1.3** **(0.07 / 0.47)**	***9.4 / 1.1*** ***(-0.04 / -0.33)***	114.3 / 9.4 (-1.52 / -0.12)
Rodos (Ebonas)Is	**12.8 / 0.7** **(0.03 / 0.36)**	**8.1 / 0.8** **(0.04 / 0.42)**	4.7 / 0.4 (-0.01 / -0.18)	135.4 / 4.7 (0.66 / 0.04)
SamosIs	11.2 / 0.8 (0.02 / 0.26)	**5.0 / 1.1** **(0.07 / 0.54)**	**6.2 / 0.6** **(-0.04 / -0.63)**	152.3 / 6.3 (-3.26 / -0.19)
SantoriniIs	14.6 / 0.8 (0.02 / 0.27)	**10.1 / 0.9** **(0.05 / 0.56)**	**4.5 / 0.6** **(-0.03 / -0.49)**	83.6 / 4.5 (1.27 / 0.13)
Sitia (Zakros)Is	15.3 / 1.0 (0.00 / 0.01)	**10.3 / 0.8** **(0.06 / 0.63)**	**5.0 / 0.9** **(-0.06 / -0.57)**	98.0 / 5.0 (-0.18 / -0.02)
Thessaloniki (N. Messimvria)Cs	10.3 / 0.7 (0.02 / 0.21)	**2.7 / 1.0** **(0.04 / 0.37)**	7.6 / 0.9 (-0.03 / -0.25)	61.2 / 7.6 (1.37 / 0.20)
Trikala_Imathias (Naoussa)Cs	**9.0 / 1.0** **(0.05 / 0.44)**	0.2 / 1.1 (0.03 / 0.27)	8.7 / 1.3 (0.02 / 0.13)	(82.2 / 8.7) 2.12 / 0.23
Tripoli (Mantinia)Mn	10.3 / 1.1 (0.00 / 0.02)	1.0 / 1.4 (0.00 / -0.01)	9.3 / 1.2 (0.00 / 0.03)	132.8 / 9.3 (-1.02 / -0.07)

Overall				
Negative (sig)	*0*	*0*	*7*	*0*
Nonsignificant	*12*	*8*	*11*	*19*
Positive (sig)	*7*	*11*	*1*	*0*
Is (avg/sd)	*13.2 / 0.8*	*7.7 /0.9*	*5.5 /0.6*	*268.2 / 107.7*
Cs (avg/sd)	*11.7 / 0.7*	*3.9 /1.0*	*7.7 / 0.8*	*224.9 / 85.5*
Mn (avg/sd)	*8.8 / 1.0*	*0.2 / 1.3*	*8.6 / 1.1*	*223.2 / 90.4*

Mean TX during the JJA ranged from 25.5 (Methoni) to 32.0°C (Larisa) with mainland and coastal locations exhibiting slightly warmer conditions (30.0 and 29.4 *vs* 27.9°C, on average respectively) (Table 3.8). On the contrary, the highest TN means were identified mainly at island locations compared to the coastal and mainland (20.5 *vs* 18.3 and 15.5°C, on average, respectively). DTR values were significantly lower at island (7.5°C, on average) compared to coastal but mainly mainland locations (11.1 and 14.5°C, on average respectively). Finally, total PRCP ranged from 1 mm (Santorini) to 110 mm (Drama). The highest values were observed mostly on mainland locations which experienced wetter summer conditions (84 mm, on average).

The direction and magnitude of trends in each variable along with the statistical significance are also shown in Table 3.8. Overall, the analysis of the JJA revealed statistically significant positive trends for both TX and TN (16 and 19 out of 19 cases for TX and TN, respectively) almost everywhere (Table 3.8). With regards to the average magnitude of trends, across all locations, the TN warming rate was +0.9°C (calculated from Table 3.8) higher than the TX rate (2.4 *vs* 1.5°C/30 year, on average). Specifically, trends in TN were more pronounced than TX in almost every case (16 *vs* 2) while only Methoni exhibited similar temperature trends (Table 3.8). Drama was the area with the highest rate of change in TN (0.16°C year^{-1}) while Heraklio and Tripoli displayed the lowest (0.04 and 0.05°C year^{-1} respectively). With regards to mean TX trends, Athens presented the highest trend (0.11°C) with the high elevated areas of Tripoli, Ioannina and Florina presenting the lowest (0.04°C, Table 3.8). As a result of the higher increases in TN, statistically significant negative trends in DTR were identified in the vast majority of the cases (16 cases in total, 11 statistically significant). Positive trends were observed in Methoni (statistically (insignificant), Athens and Heraklio (statistically significant)). Finally, PRCP showed the least number of significant cases (1 significant negative trend in Rodos island).

Table 3.8 Descriptive statistics for air temperature variables (i.e., TX and TN), DTR and precipitation during the JJA (JJA: June-July-August) [first row of each location (station) corresponds to mean value and standard deviation in parenthesis, while 30 years trends and Pearson *r* are presented in the second row, respectively] for the main winegrape areas in Greece during the baseline period (1981–2010). The total number of statistically significant negative and positive trends along with the averages are summarized in the final row of the table. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). The nonsignificant cases of each variable are also presented. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TX - avg/sd, °C (trend yr⁻¹/pearson r)**	**TN - avg/sd, °C (trend yr⁻¹/pearson r)**	**DTR - avg/sd, °C (trend yr⁻¹/pearson r)**	**PRCP - avg/sd, mm (trend yr⁻¹/pearson r)**
Aktio (Lefkada)[Cs]	**26.8 / 0.8** **(0.05 / 0.49)**	**18.2 / 0.9** **(0.08 / 0.73)**	**8.7 / 0.6** **(-0.03 / -0.42)**	30.5 / 30.0 (0.50 / 0.15)
Alexandroupoli (Maronia)[Cs]	**29.5 / 1.1** **(0.09 / 0.71)**	**17.1 / 1.2** **(0.11 / 0.83)**	***12.4 / 0.7*** ***(-0.02 / -0.32)***	63.8 / 44.0 (0.14 / 0.03)
Anchialos[Cs]	**30.7 / 0.8** **(0.05 / 0.63)**	**18.7 / 0.8** **(0.07 / 0.77)**	12.0 / 0.6 (-0.02 / -0.28)	55.0 / 34.4 (0.51 / 0.13)
Athens (Spata)[Cs]	**31.0 / 1.2** **(0.11 / 0.79)**	**21.6 / 1.0** **(0.08 / 0.74)**	**9.4 / 0.6** **(0.03 / 0.40)**	18.2 / 14.7 (-0.22 / -0.13)
Drama[Mn]	***30.6 / 1.1*** ***(0.04 / 0.32)***	**18.7 / 1.7** **(0.16 / 0.83)**	**11.9 / 1.4** **(-0.12 / -0.73)**	110.0 / 70.3 (1.80 / 0.22)
Florina (Amyndeo)[Mn]	28.5 / 1.2	**14.6 / 0.8**	13.9 / 1.0	86.4 / 41.6

	(0.04 / 0.29)	**(0.06 / 0.69)**	(-0.02 / -0.22)	(-0.48 / -0.10)
Heraklio (Peza)Is	**26.6 / 0.7** **(0.06 / 0.73)**	**19.5 / 0.6** **(0.04 / 0.61)**	**7.1 / 0.3** **(0.01 / 0.42)**	5.1 / 10.4 (-0.32 / -0.27)
Ioannina (Zitsa)Mn	28.9 / 1.0 (0.01 / 0.10)	**13.5 / 0.8** **(0.06 / 0.65)**	**15.3 / 1.1** **(-0.05 / -0.41)**	98.8 / 55.8 (0.21 / 0.03)
Larisa (Tyrnavos)Mn	**32.0 / 0.9** **(0.05 / 0.46)**	**17.0 / 1.0** **(0.10 / 0.85)**	**15.1 / 0.8** **(-0.05 / -0.41)**	57.6 / 36.9 (-0.61 / -0.15)
LimnosIs	**28.8 / 0.9** **(0.07 / 0.68)**	**19.6 / 0.9** **(0.08 / 0.72)**	9.2 / 0.6 (-0.01 / -0.14)	27.0 / 22.4 (0.41 / 0.16)
Methoni (Triffilia)Cs	**25.5 / 0.8** **(0.05 / 0.59)**	**17.9 / 0.7** **(0.05 / 0.62)**	7.6 / 0.3 (0.01 / 0.14)	10.6 / 15.0 (0.04 / 0.02)
PyrgosCs	**31.2 / 1.0** **(0.07 / 0.59)**	**17.1 / 1.2** **(0.11 / 0.80)**	**14.0 / 0.9** **(-0.04 / -0.38)**	18.6 / 26.8 (-0.36 / -0.12)
Rodos (Ebonas)Is	**26.4 / 0.6** **(0.04 / 0.60)**	**20.4 / 0.7** **(0.06 / 0.78)**	**6.0 / 0.4** **(-0.02 / -0.49)**	***1.2 / 2.5*** ***(-0.09 / -0.34)***
SamosIs	**29.3 / 0.6** **(0.07 / 0.65)**	**19.1 / 1.1** **(0.11 / 0.87)**	**10.2 / 0.6** **(-0.04 / -0.67)**	2.7 / 4.6 (-0.14 / 0.16)
SantoriniIs	**28.6 / 0.7** **(0.04 / 0.49)**	**22.0 / 1.0** **(0.10 / 0.81)**	**6.6 / 0.9** **(-0.06 / -0.61)**	1.1 / 2.0 (-0.01 / -0.04)
Sitia (Zakros)Is	27.8 / 0.5 (0.00 / 0.04)	**22.0 / 1.0** **(0.08 / 0.70)**	**5.7 / 1.0** **(-0.08 / -0.70)**	3.4 / 6.0 (-0.20 / -0.29)
Thessaloniki (N. Messimvria)Cs	**31.0 / 0.9** **(0.06 / 0.53)**	**19.4 / 1.1** **(0.11 / 0.88)**	**11.6 / 0.8** **(-0.06 / -0.61)**	68.6 / 35.7 (-0.04 / -0.01)
Trikala_Imathias (Naoussa)Cs	**29.9 / 0.9** **(0.07 / 0.69)**	**16.6 / 1.0** **(0.09 / 0.74)**	13.3 / 0.9 (-0.01 / -0.13)	64.6 / 41.1 (-0.00 / -0.01)
Tripoli (Mantinia)Mn	***30.1 / 1.1***	***13.7 / 1.3***	16.4 / 1.1	68.0 / 45.5

	(0.04 / 0.32)	*(0.05 / 0.35)*	(-0.01 / -0.09)	(-0.39 / -0.07)
Overall				
Negative (sig)	*0*	*0*	*11*	*1*
Nonsignificant	*3*	*0*	*6*	*18*
Positive (sig)	*16*	*19*	*2*	*0*
Is (avg/sd)	*27.9 / 0.7*	*20.5 / 0.9*	*7.5 / 0.6*	*6.7 / 8.0*
Cs (avg/sd)	*29.4 / 0.9*	*18.3 / 1.0*	*11.1 / 0.7*	*41.3 / 30.2*
Mn (avg/sd)	*30.0 / 1.1*	*15.5 / 1.1*	*14.5 / 1.1*	*84.2 / 50.0*

Mean TX during the MAM ranged from 16.7 (Methoni) to 20.7°C (Pyrgos). Coastal, mainland and island locations exhibited almost the same conditions (18.6, 18.3 and 18.2°C, on average, respectively) (Table 3.9). On the contrary, the highest TN means were identified mainly at island locations compared to the coastal and mainland (11.9 *vs* 8.9 and 6.3°C, on average, respectively). DTR values were significantly lower at island (7.0°C, on average), intermediate at coastal (9.7°C, on average) and high at mainland locations (12.0°C, on average). Finally, total PRCP ranged from 68 mm (Santorini) to 217 mm (Ioannina) showing that mainland and coastal locations received more rainfall during spring than the island ones.

Overall, the analysis of the MAM revealed statistically significant positive trends for both TX and TN everywhere (Table 3.9). With regards to the average magnitude of trends, across all locations, the TN warming rate was +0.6°C higher than the TX rate (1.5 *vs* 0.9°C/30 year, on average). Specifically, trends in TN were more pronounced than TX in most cases (12 *vs* 7). Drama was the area with the highest rate of change in TN (0.13°C $year^{-1}$) while Heraklio and Trikala Imathias those areas with the lowest (0.02°C $year^{-1}$ respectively). With regards to mean TX trends, Trikala Imathias (0.07°C $year^{-1}$), Athens and Larisa (0.06 $year^{-1}$ respectively) presented the highest trends. Consequently, DTR values significantly decreased in most cases (7 out of 11 statistically significant cases). Significant positive trends were observed only in Athens and Trikala Imathias. Finally, PRCP showed only two statistically significant negative cases (Pyrgos and Sitia).

Table 3.9 Descriptive statistics for air temperature variables (i.e., TX and TN), DTR and precipitation during the MAM (MAM: March-April-May) [first row of each location (station) corresponds to mean value and standard deviation in parenthesis, while 30 years trends and Pearson *r* are presented in the second row, respectively] for the main winegrape areas in Greece during the baseline period (1981–2010). The total number of statistically significant negative and positive trends along with the averages are summarized in the final row of the table. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). The nonsignificant cases of each variable are also presented. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TX - avg/sd, °C (trend yr^{-1}/pearson r)**	**TN - avg/sd, °C (trend yr^{-1}/pearson r)**	**DTR - avg/sd, °C (trend yr^{-1}/pearson r)**	**PRCP - avg/sd, mm (trend yr^{-1}/pearson r)**
Aktio (Lefkada)^{Cs}	17.3 / 0.8 (0.02 / 0.20)	**9.5 / 0.9** **(0.06 / 0.64)**	**7.8 / 0.6** **(-0.05 / -0.65)**	156.0 / 65.7 (-0.67 / -0.09)
Alexandroupoli (Maronia)^{Cs}	**17.3 / 1.1** **(0.05 / 0.41)**	**7.1 / 0.9** **(0.06 / 0.57)**	10.2 / 0.8 (0.00 / -0.05)	102.7 / 47.2 (-0.33 / -0.06)
Anchialos^{Cs}	**19.3 / 1.2** **(0.05 / 0.37)**	**8.8 / 0.8** **(0.05 / 0.51)**	10.4 / 0.7 (0.00 / 0.03)	116.7 / 64.3 (-1.61 / -0.22)
Athens (Spata)^{Cs}	**19.5 / 1.1** **(0.06 / 0.49)**	**11.2 / 0.8** **(0.04 / 0.42)**	***8.3 / 0.5*** ***(0.02 / 0.34)***	92.6 / 56.1 (-1.80 / -0.28)
Drama^{Mn}	19.3 / 1.3 (0.04 / 0.30)	**8.7 / 1.4** **(0.13 / 0.80)**	**10.5 / 1.3** **(-0.09 / -0.58)**	123.5 / 42.4 (0.89 / 0.18)
Florina (Amyndeo)^{Mn}	16.9 / 1.3 (0.00 / 0.02)	**5.8 / 1.0** **(0.05 / 0.45)**	**11.1 / 1.0** **(-0.05 / -0.45)**	154.3 / 71.4 (-1.88 / -0.23)
Heraklio (Peza)^{Is}	***18.4 / 1.0*** ***(0.03 / 0.31)***	10.6 / 0.7 (0.02 / 0.25)	7.8 / 0.5 (0.01 / 0.25)	91.4 / 55.0 (-1.34 / -0.21)
Ioannina (Zitsa)^{Mn}	17.1 / 1.2	**5.1 / 0.7**	12.0 / 0.9	217.0 / 70.8

	(0.01 / 0.04)	**(0.03 / 0.40)**	(-0.03 / -0.26)	(0.39 / 0.05)
Larisa (Tyrnavos)[Mn]	**19.9 / 1.5** **(0.06 / 0.36)**	**6.7 / 0.9** **(0.06 / 0.59)**	13.2 / 1.3 (0.00 / 0.02)	109.8 / 53.4 (-1.16 / -0.19)
Limnos[Is]	17.4 / 1.0 (0.03 / 0.29)	**9.4 / 0.9** **(0.05 / 0.46)**	8.0 / 0.6 (-0.01 / -0.21)	109.9 / 43.6 (1.13 / 0.23)
Methoni (Triffilia)[Cs]	**16.7 / 0.8** **(0.04 / 0.42)**	***9.1 / 0.8*** ***(0.03 / 0.33)***	7.6 / 0.4 (0.01 / 0.20)	112.3 / 47.9 (-1.41 / -0.26)
Pyrgos[Cs]	**20.7 / 1.0** **(0.05 / 0.43)**	**9.3 / 1.0** **(0.07 / 0.58)**	11.4 / 0.8 (-0.02 / -0.21)	**136.6 / 47.6** **(-1.98 / -0.37)**
Rodos (Ebonas)[Is]	17.3 / 0.9 (0.02 / 0.21)	**11.7 / 0.8** **(0.04 / 0.43)**	**5.7 / 0.4** **(-0.02 / -0.43)**	115.4 / 71.3 (-1.42 / -0.18)
Samos[Is]	17.5 / 1.0 (0.03 / 0.28)	**8.8 / 1.1** **(0.09 / 0.71)**	**8.7 / 0.7** **(-0.06 / -0.71)**	138.4 / 62.7 (-1.46 / -0.20)
Santorini[Is]	19.1 / 0.9 (0.01 / 0.15)	**13.4 / 0.8** **(0.05 / 0.60)**	**5.7 / 0.7** **(-0.04 / -0.50)**	68.1 / 52.2 (-0.89 / -0.15)
Sitia (Zakros)[Is]	19.6 / 0.9 (-0.00 / -0.04)	**13.3 / 0.9** **(0.06 / 0.63)**	**6.3 / 0.9** **(-0.07 / -0.66)**	**79.6 / 51.2** **(-2.25 / -0.39)**
Thessaloniki (N. Messimvria)[Cs]	19.3 / 1.2 (0.03 / 0.23)	**9.0 / 0.9** **(0.05 / 0.54)**	10.4 / 0.9 (-0.02 / -0.23)	109.4 / 37.0 (-0.66 / -0.16)
Trikala_Imathias (Naoussa)[Cs]	**18.9 / 1.3** **(0.07 / 0.43)**	7.5 / 0.8 (0.02 / 0.18)	***11.4 / 1.2*** ***(0.05 / 0.35)***	143.9 / 59.4 (-0.11 / -0.02)
Tripoli (Mantinia)[Mn]	18.3 / 1.4 (0.04 / 0.26)	5.2 / 1.2 (0.03 / 0.24)	13.1 / 1.1 (0.01 / 0.06)	165.4 / 57.3 (-0.19 / -0.03)
Overall *Negative (sig)* *Nonsignificant*	 *0* *11*	 *0* *3*	 *7* *10*	 *2* *17*

Positive (sig)	*8*	*16*	*2*	*0*
Is (avg/sd)	*18.2 / 0.9*	*11.2 / 0.9*	*7.0 / 0.6*	*100.4 / 56.0*
Cs (avg/sd)	*18.6 / 1.1*	*8.9 / 0.9*	*9.7. / 0.7*	*121.3 / 53.2*
Mn (avg/sd)	*18.3 / 1.4*	*6.3 / 1.1*	*12.0 / 1.1*	*154.0 / 59.1*

Finally, mean TX during the SON ranged from 18.4 (Florina) to 24.3°C (Pyrgos) during SON period. Island and coastal locations exhibited warmer TX compared to mainland (21.6, 21.5 and 20.1°C, on average, respectively) (Table 3.10). On the contrary, island faced significantly higher values of TN compared to the coastal and mainland (15.2 *vs* 12.2 and 8.6°C, on average, respectively). DTR values were significantly lower at island (6.4°C, on average) than in any other location (coastal - 9.4°C and mainland – 11.5°C on average respectively). Total PRCP values ranged from 70 mm (Santorini) to 328 mm (Ioannina). Coastal and mainland exhibited wetter conditions that island locations (Table 3.10).

Overall, the analysis of the SON revealed statistically significant positive trends for TN everywhere (Table 3.10). On the other hand, TX revealed only one statistically significant negative and positive trend across all locations (Table 3.10). In addition, trends in TN were more pronounced than TX everywhere except for Heraklio. Drama and Pyrgos were the cases with the highest rates of change in TN (0.13 and 0.10°C year^{-1}, respectively) while Tripoli indicated no trend. DTR values significantly decreased everywhere except for Heraklio (Table 3.10). Finally, PRCP showed only three statistically significant positive cases (Athens, Drama and Ioannina).

Table 3.10 Descriptive statistics for air temperature variables (i.e., TX and TN), DTR and precipitation during the SON (SON: September-October-November) [first row of each location (station) corresponds to mean value and standard deviation in parenthesis, while 30 years trends and Pearson *r* are presented in the second row, respectively] for the main winegrape areas in Greece during the baseline period (1981–2010). The total number of statistically significant negative and positive trends along with the averages are summarized in the final row of the table. Red bold letters indicate statistical significance at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). The nonsignificant cases of each variable are also presented. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TX - avg/sd, °C (trend yr-1/pearson r)**	**TN - avg/sd, °C (trend yr-1/pearson r)**	**DTR - avg/sd, °C (trend yr-1/pearson r)**	**PRCP - avg/sd, mm (trend yr-1/pearson r)**
Aktio (Lefkada)[Cs]	20.8 / 0.7 (-0.00 / -0.06)	**13.3 / 0.8** **(0.04 / 0.44)**	**7.5 / 0.6** **(-0.04 / -0.66)**	310.5 / 106.9 (1.29 / 0.11)
Alexandroupoli (Maronia)[Cs]	20.1 / 0.9 (0.02 / 0.17)	**10.0 / 1.0** **(0.06 / 0.49)**	**10.1 / 0.7** **(-0.04 / -0.48)**	154.1 / 73.7 (2.19 / 0.26)
Anchialos[Cs]	21.9 / 0.8 (0.01 / 0.11)	12.2 / 0.7 (0.02 / 0.22)	9.7 / 0.6 (-0.01 / -0.10)	144.4 / 59.4 (0.61 / 0.09)
Athens (Spata)[Cs]	22.8 / 0.8 (0.02 / 0.19)	**15.1 / 0.7** **(0.03 / 0.36)**	7.7 / 0.5 (-0.01 / -0.18)	**111.1 / 54.5** **(2.55 / 0.41)**
Drama[Mn]	20.5 / 1.0 (0.00 / -0.02)	**10.8 / 1.6** **(0.13 / 0.74)**	**9.7 / 1.4** **(-0.13 / -0.82)**	**126.3 / 57.9** **(2.90 / 0.44)**
Florina (Amyndeo)[Mn]	18.4 / 1.2 (-0.01 / -0.04)	**7.4 / 1.1** **(0.06 / 0.45)**	**11.0 / 1.0** **(-0.06 / -0.51)**	170.3 / 83.1 (1.29 / 0.14)
Heraklio (Peza)[Is]	**21.7 / 0.9** **(0.06 / 0.54)**	**15.0 / 0.7** **(0.04 / 0.48)**	**6.8 / 0.4** **(0.02 / 0.38)**	126.1 / 71.0 (0.07 / 0.01)
Ioannina (Zitsa)[Mn]	***19.2 / 0.9***	**7.3 / 0.8**	**11.8 / 1.0**	**328.0 / 133.7**

	(-0.03 / -0.33)	**(0.04 / 0.42)**	**(-0.07 / -0.62)**	**(5.47 / 0.36)**
Larisa (Tyrnavos)Mn	21.6 / 1.0 (0.00 / 0.03)	**9.6 / 0.9** **(0.06 / 0.40)**	***11.9 / 1.0*** ***(-0.04 / -0.34)***	137.9 / 60.4 (1.23 / 0.18)
LimnosIs	20.5 / 0.9 (0.03 / 0.26)	**13.0 / 0.8** **(0.04 / 0.44)**	7.5 / 0.5 (-0.02 / -0.30)	147.1 / 101.8 (2.82 / 0.24)
Methoni (Triffilia)Cs	21.1 / 0.6 (0.01 / 0.20)	***13.1 / 0.6*** ***(0.02 / 0.32)***	8.0 / 0.4 (-0.01 / -0.23)	227.2 / 84.5 (-1.35 / -0.14)
PyrgosCs	24.3 / 0.7 (0.00 / 0.02)	**12.8 / 1.2** **(0.10 / 0.70)**	**11.6 / 1.2** **(-0.09 / -0.70)**	285.3 / 82.6 (0.33 / 0.04)
Rodos (Ebonas)Is	21.2 / 0.7 (0.02 / 0.28)	**15.9 / 0.70** **(0.04 / 0.58)**	**5.3 / 0.5** **(-0.02 / -0.41)**	154.9 / 103.7 (-2.75 / -0.23)
SamosIs	20.8 / 0.8 (0.02 / 0.23)	**12.7 / 1.0** **(0.08 / 0.67)**	**8.1 / 0.7** **(-0.06 / -0.68)**	169.8 / 106.7 (1.97 / 0.16)
SantoriniIs	22.6 / 0.9 (0.01 / 0.12)	**17.1 / 1.0** **(0.06 / 0.55)**	**5.5 / 0.7** **(-0.05 / -0.60)**	70.2 / 45.4 (0.74 / 0.14)
Sitia (Zakros)Is	22.9 / 0.8 (0.01 / 0.11)	**17.5 / 1.0** **(0.08 / 0.71)**	**5.4 / 1.0** **(-0.07 / -0.64)**	132.4 / 87.6 (-1.90 / -0.19)
Thessaloniki (N. Messimvria)Cs	21.1 / 0.9 (0.00 / 0.01)	**11.9 / 1.0** **(0.07 / 0.57)**	**9.2 / 0.8** **(-0.06 / -0.72)**	117.8 / 47.0 (-0.54 / -0.10)
Trikala_Imathias (Naoussa)Cs	20.2 / 1.0 (0.02 / 0.22)	**9.0 / 1.1** **(0.04 / 0.37)**	11.3 / 0.9 (-0.02 / -0.21)	158.7 / 65.6 (1.27 / 0.17)
Tripoli (Mantinia)Mn	21.0 / 1.2 (-0.01 / -0.09)	7.8 / 1.4 (0.00 / 0.01)	13.2 / 1.1 (-0.01 / -0.12)	194.3 / 59.6 (0.08 / 0.01)
Overall *Negative (sig)* *Nonsignificant*	 *1* *17*	 *0* *2*	 *12* *6*	 *0* *16*

Positive (sig)	*1*	*17*	*1*	*3*
Is (avg/sd)	*21.6 / 0.8*	*15.2 / 0.9*	*6.4 / 0.6*	*133.4 / 86.0*
Cs (avg/sd)	*21.5 / 0.8*	*12.2 / 0.9*	*9.4 / 0.7*	*188.6 / 71.8*
Mn (avg/sd)	*21.0 / 0.9*	*10.8 / 1.0*	*10.2 / 0.9*	*189.7 / 74.5*

3.6.3 Historical climate overview for the BP (averages and trends)

Mean TX during the GS ranged from 22.7 (Methoni) to 27.4°C (Pyrgos) with mainland and coastal locations generally exhibiting warmer conditions (25.5 and 25.4°C, on average, respectively) than the respective island ones (24.6°C, on average) (Table 3.11). However, the highest TN means were identified mainly at island and coastal compared to mainland locations (17.1°C, 14.7°C *vs* 12.0°C, on average, respectively), presenting a general coherence. DTR values were significantly lower at island (7.4°C, on average), intermediate at coastal (10.6°C, on average) and higher in inland locations (13.4°C, on average), with some exceptions. Finally, total PRCP ranged from 56 mm (Santorini) to 391 mm (Ioannina). The highest values were observed in western and northern Greece (approximately 250 mm, on average), while most islands experienced drier conditions (<120 mm, on average). However, Limnos and Drama were the only locations with consistent and significantly increasing trends on annual PRCP indices (Table 3.11).

Table 3.11 Descriptive statistics for climate variables during the growing season (GS; April–October) [first row of each location (station) corresponds to mean value and standard deviation in parenthesis, while 30 years trends are presented in the second row, respectively] for the main winegrape areas in Greece during the baseline period (1981–2010) obtained and calculated from the nearest weather station location. The internationally accepted reduction of 0.6 °C per 100 m adjustment was used to better simulate the climatic conditions of the respective winegrape areas. Red bold letters indicate statistically significant trends at p-value < 0.05, while italicized blue bold letters indicate lower statistical significance (p-value < 0.1). Empty rows indicate no trend. Superscript letters [a](1992–2010), [b](1986–2010) and [c](1988–2010) indicate shorter period of records and therefore, trends were not calculated. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	**TX mean (°C)**	**TN mean (°C)**	**DTR (°C)**	**SU30 (days)**	**TR20 (days)**	**PRCP (mm)**
Aktio (Lefkada)[Cs]	23.5 (0.6) (+0.6)	15.3 (0.7) **(+1.8)**	8.2 (0.5) **(−1.2)**	15 (7) **(+9.0)**	23 (16) **(+33.0)**	265 (97) (+87.0)
Alexandroupoli (Maronia)[Cs]	24.9 (0.7) **(+1.5)**	13.4 (0.9) **(+1.8)**	11.5 (0.6) (−0.6)	47 (13) **(+27.0)**	16 (11) **(+27.0)**	198 (76) (+135.0)
Anchialos[Cs]	26.3 (0.6) **(+1.2)**	15.2 (0.6) **(+1.2)**	11.2 (0.4)	66 (13) **(+24.0)**	32 (15) **(+27.0)**	208 (89) (+60.0)
Argostoli[a] (Kephalonia)[Is]	23.5 (0.7)	15.0 (0.6)	8.5 (0.9)	18 (9)	22 (10)	229 (103)
Athens (Spata)[Cs]	26.7 (0.8) **(+1.5)**	17.8 (0.7) **(+1.2)**	8.9 (0.4) (+0.3)	69 (17) **(+39.0)**	80 (15) **(+30.0)**	108 (46) (−60.0)
Drama[Mn]	26.2 (0.8) ***(+0.9)***	14.9 (1.4) **(+3.9)**	11.3 (1.4) **(−3.3)**	66 (15) (+9.0)	35 (22) **(+57.0)**	265 (98) **(+243.0)**
Florina (Amyndeo)[Mn]	24.0 (0.9) (+0.3)	11.3 (0.7) **(+1.8)**	12.7 (0.9) **(−1.5)**	42 (15) (+12.0)	3 (3) **(+3.0)**	302 (131) (−48.0)

Heraklio (Peza)[Is]	23.9 (0.6) (+1.5)	16.5 (0.5) (+0.9)	7.3 (0.2) (+0.6)	12 (5) (+6.0)	50 (10) (+21.0)	98 (60) (+3.0)
Ioannina (Zitsa)[Mn]	24.2 (0.8)	10.4 (0.6) (+1.2)	13.8 (1.0) (−1.2)	41 (13) (+3.0)	2 (3)	391 (141) *(+255.0)*
Kavala[b] (Podochori)[Cs]	23.7 (0.6)	13.8 (0.8)	9.9 (0.6)	22 (10)	13 (10)	165 (114)
Larisa (Tyrnavos)[Mn]	27.3 (0.8) (+1.2)	13.1 (0.8) (+1.8)	14.1 (0.8) (−0.9)	84 (14) (+15.0)	12 (8) (+18.0)	210 (78)
Limnos[Is]	24.5 (0.6) (+1.2)	15.9 (0.7) (+1.5)	8.7 (0.5) (−0.6)	33 (13) (+30.0)	54 (14) (+27.0)	156 (87) (+213.0)
Methoni (Triffilia)[Cs]	22.7 (0.5) (+0.9)	14.9 (0.5) (+0.9)	7.8 (0.2)	4 (3)	21 (9) (+15.0)	168 (73) (+105.0)
Paros[aIs]	26.0 (0.7)	18.6 (0.6)	7.4 (0.7)	45 (12)	98 (13)	77 (54)
Pyrgos[Cs]	27.4 (0.7) (+1.2)	14.5 (1.0) (+2.7)	12.9 (0.8) (−1.5)	74 (13) (+21.0)	17 (16) (+36.0)	219 (72) (−108.0)
Rodos (Ebonas)[Is]	23.4 (0.5) (+0.9)	17.6 (0.6) (+1.5)	5.8 (0.4) (−0.6)	7 (4) (+3.0)	72 (17) (+42.0)	105 (86) (−108.0)
Samos[Is]	24.9 (0.6) (+1.2)	15.4 (1.0) (+2.7)	9.5 (0.7) (−1.5)	42 (14) (+30.0)	43 (15) (+39.0)	112 (57) (−90.0)
Santorini[Is]	25.2 (0.5) (+0.6)	19.0 (0.9) (+2.1)	6.2 (0.7) (−1.5)	29 (11) (+15.0)	101 (18) (+54.0)	56 (45) (+33.0)
Sitia (Zakros)[Is]	25.1 (0.5)	19.1 (0.9) (+2.1)	5.9 (1.0) (−2.1)	19 (6) (+3.0)	107 (20) (+42.0)	98 (78) (−135.0)
Thessaloniki (N. Messimvria)[Cs]	26.4 (0.7) (+0.9)	15.5 (0.8) (+2.1)	10.9 (0.7) (−1.2)	69 (14) (+18.0)	44 (20) (+57.0)	208 (65) (+60.0)

Trikala_Imathias (Naoussa)[Cs]	25.6 (0.7) **(+1.5)**	13.1 (0.7) **(+1.5)**	12.6 (0.7)	52 (15) **(+30.0)**	8 (9) **(+18.0)**	247 (89) (+96.0)
Tripoli (Mantinia)[Mn]	25.7 (0.9) (+0.6)	10.5 (1.2) (+0.6)	15.1 (1.0)	60 (15) (+15.0)	4 (3) (+3.0)	239 (83) (−42.0)
Velo[c] (Nemea)[Cs]	26.0 (0.7)	13.9 (0.9)	12.1 (0.8)	60 (14)	15 (15)	137 0)

The GST index reveals "Hot" and "Very hot" conditions for viticulture in Greece (mainly islands and coastal locations, 18 cases), with only a few "warm" locations (Table 3.12). GST values ranged from a 17.3 (Ioannina) to 22.3°C (Paros and Athens). With regards to GDD, 18 locations were classified as "Regions IV and V", four (Tripoli, Methoni, Kavala and Florina) as "Regions III" and only one as "Region II" (Ioannina). 18 locations were characterized as "Warm temperate" and "Warm", according to HI, four as "Very warm" and only Methoni as "Temperate". Regarding BEDD, 21 locations were classified from temperate to warm and only Florina and Ioannina were in the lower-class interval (1200–1400). For CI, a wide range of nocturnal ripening temperatures, from a low 10.9°C (Ioannina) to a high 20.8°C (Sitia), covering all four potential classes, was identified. In particular, 13 locations experienced "Warm temperate nights" and five "Warm nights". Five locations belong to the coolest classes, Larisa and Trikala_Imathias showing values between 12.0 and 14.0°C ("Cool nights") while Florina, Tripoli and Ioannina were placed in the lower class with night-time temperatures averaging 11.3°C ("Very cool nights"). Finally, with regards to DI, 21 locations were classified as "Moderate dry" while only Florina and Ioannina were considered as "Sub-humid".

Table 3.12 Mean value, trends (in parenthesis year^{-1}) and classification [second row of each location (station)] for six bioclimatic indices for the main winegrape areas in Greece during the baseline period (1981–2010) obtained and calculated from the nearest weather station location. The internationally accepted reduction of 0.6°C/100 m adjustment was used to better simulate the climatic conditions of the respective winegrape areas. Full description of the classes and the period of calculations are described in Table 3.3. Red bold letters indicate statistically significant trends at p-value < 0.05. Superscript letters [a](1992–2010), [b](1986–2010) and [c](1988–2010) indicate shorter period of records and therefore, trends were not calculated. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

Locations (winegrape areas)	GST (°C)	GDD (°C units)	HI (°C units)	BEDD (°C units)	DI (mm)	CI (°C)
Aktio (Lefkada)[Cs]	**19.4 (0.04) (Hot)**	**2010 (8.3) (Region IV)**	**2197 (6.8) (Warm Temperate)**	1550 (2.2) (4)	15.0 (0.01) (Moderate dry)	16.7 (0.02) (Temperate nights)
Alexandroupoli (Maronia)[Cs]	**19.2 (0.06) (Hot)**	**1981 (13.6) (Region IV)**	**2399 (11.8) (Warm Temperate)**	**1499 (3.3) (4)**	-1.0 (0.08) (Moderate dry)	**14.1 (0.05) (Temperate nights)**
Anchialos[Cs]	**20.7 (0.04) (Hot)**	**2303 (7.8) (Region V)**	**2643 (6.9) (Warm)**	1632 (1.9) (5)	-23.0 (-0.07) (Moderate dry)	16.1 (0.01) (Temperate nights)
Argostoli[a] (Kephalonia)[Is]	19.2 (Hot)	1981 (Region IV)	2173 (Warm Temperate)	1528 (4)	14.0 (Moderate dry)	16.6 (Temperate nights)
Athens (Spata)[Cs]	**22.3 (0.06)**	**2624 (12.0)**	**2795 (12.3)**	**1713 (2.5)**	**-96.0 (-1.3)**	19.0 (0.01)

	(Very Hot)	**(Region V)**	**(Very Warm)**	**(5)**	**(Moderate dry)**	(Warm nights)
Drama[Mn]	**20.6 (0.07) (Hot)**	**2271 (14.0) (Region V)**	**2674 (7.5) (Warm)**	1604 (2.1) (5)	4.0 (-0.01) (Moderate dry)	**15.5 (0.09) (Temperate nights)**
Florina (Amyndeo)[Mn]	17.6 (0.03) (Warm)	1680 (5.1) (Region III)	2185 (2.8) (Warm Temperate)	1369 (-1.1) (3)	60.0 (-0.8) (Sub – Humid)	11.8 (0.02) (Very cool nights)
Heraklio (Peza)[Is]	**20.2 (0.04) (Hot)**	**2185 (8.0) (Region IV)**	**2272 (7.3) (Warm Temperate)**	**1624 (2.3) (5)**	**-41.0 (-1.0) (Moderate dry)**	**18.0 (0.03) (Temperate nights)**
Ioannina (Zitsa)[Mn]	17.3 (0.02) (Warm)	1601 (2.8) (Region II)	2150 (0.7) (Warm Temperate)	1365 (-1.7) (3)	97.0 (0.5) (Sub – Humid)	10.9 (0.02) (Very cool nights)
Kavala[b] (Podochori)[Cs]	18.7 (Warm)	1882 (Region III)	2234 (Warm Temperate)	1456 (4)	-8.0 (Moderate dry)	14.1 (Temperate nights)
Larisa (Tyrnavos)[Mn]	**20.2 (0.05) (Hot)**	**2190 (10.5) (Region IV)**	**2711 (8.0) (Very Warm)**	1596 (2.1) (4)	-19.0 (-0.5) (Moderate dry)	**13.8 (0.05) (Cool nights)**
Limnos[Is]	**20.2 (0.05)**	**2184 (9.4)**	**2423 (7.9)**	1562 (1.9)	-35.0 (0.4)	16.9 (0.03)

	(Hot)	**(Region IV)**	**(Warm)**	(4)	(Moderate dry)	(Temperate nights)
Methoni (Triffilia)[Cs]	**18.8 (0.03) (Warm)**	**1895 (6.8) (Region III)**	**2039 (6.9) (Temperate)**	**1509 (2.7) (4)**	-3.0 (-0.5) (Moderate dry)	16.6 (0.01) (Temperate nights)
Paros[aIs]	22.3 (Very Hot)	2640 (Region V)	2699 (Warm)	1746 (5)	-94.0 (Moderate dry)	20.1 (Warm nights)
Pyrgos[Cs]	**21.0 (0.06) (Hot)**	**2349 (13.6) (Region V)**	**2711 (10.3) (Very Warm)**	**1716 (3.1) (5)**	-27.0 (-0.5) (Moderate dry)	**15.8 (0.1) (Temperate nights)**
Rodos (Ebonas)[Is]	**20.5 (0.03) (Hot)**	**2251 (6.9) (Region V)**	**2261 (5.3) (Warm Temperate)**	1619 (1.4) (5)	-56.0 (-0.8) (Moderate dry)	**19.6 (0.03) (Warm nights)**
Samos[Is]	**20.1 (0.06) (Hot)**	**2176 (13.2) (Region IV)**	**2434 (9.4) (Warm)**	**1556 (3.4) (4)**	-60.0 (-1.0) (Moderate dry)	**16.6 (0.05) (Temperate nights)**
Santorini[Is]	**22.1 (0.05) (Very Hot)**	**2585 (10.0) (Region V)**	**2588 (6.3) (Warm)**	1726 (1.4) (5)	**-88.0 (-1.0) (Moderate dry)**	**20.3 (0.08) (Warm nights)**
Sitia (Zakros)[Is]	**22.1 (0.04)**	**2588 (7.6)**	2553 (2.6) (Warm)	1741 (0.6)	-71.0 (-1.3)	**20.8 (0.07)**

	(Very Hot)	(Region V)		(5)	(Moderate dry)	(Warm nights)
Thessaloniki (N. Messimvria)[Cs]	21.0 (0.05) (Hot)	2350 (11.0) (Region V)	2712 (7.7) (Very Warm)	1630 (1.3) (5)	-29.0 (-0.9) (Moderate dry)	16.2 (0.06) (Temperate nights)
Trikala_Imathias (Naoussa)[Cs]	19.4 (0.05) (Hot)	2016 (9.7) (Region IV)	2493 (9.1) (Warm)	1549 (1.9) (4)	-22.0 (0.08) (Moderate dry)	13.1 (0.02) (Cool nights)
Tripoli (Mantinia)[Mn]	18.1 (0.02) (Warm)	1760 (4.7) (Region III)	2331 (4.1) (Warm Temperate)	1464 (0.3) (4)	31.0 (-0.4) (Moderate dry)	11.1 (-0.01) (Very cool nights)
Velo[c] (Nemea)[Cs]	19.9 (Hot)	2133 (Region IV)	2521 (Warm)	1592 (4)	-31.0 (Moderate dry)	15.2 (Temperate nights)

The direction and magnitude of trends in each temperature-related indicator along with the statistical significance are also shown in Table 3.11. Overall, the analysis of the BP revealed statistically significant positive trends for both TX and TN (in 13 and 18 out of 19 locations, respectively) in the majority of the cases. With regards to the average magnitude of trends, across all locations, the TN warming rate was +0.8°C higher than the TX rate (1.7 *vs* 0.9°C/30 year, on average). Specifically, trends in TN were more pronounced than TX in most cases (13 *vs* 2), four locations experienced equal temperature trends and in only two locations (Athens and Heraklio), TX trends were higher than TN (Figure 3.5). Samos, Pyrgos and Drama exhibited the highest rates of change in TN (0.09 and 0.13°C year^{-1}, respectively) while Heraklio and Methoni displayed the lowest (0.03°C year^{-1}). In contrast, moderate TX trends (0.05°C year^{-1})

were identified in Alexandroupoli, Athens, Heraklio and Trikala_Imathias. Because of the higher increases in TN, statistically significant negative trends in DTR were identified in most cases. Positive trends were observed only in Heraklio (significant) and Athens (nonsignificant). Finally, threshold index analyses showed a larger number of statistically significant trends for SU30 and TR20 across all locations (Figures 3.6 and 3.7). More specifically, annual tropical nights showed significant increases except for the high-altitude areas of Ioannina and Tripoli (Figure 3.6). The annual summer days (SU30) also showed significant upward trends but to a lesser degree (10 out of 19 cases).

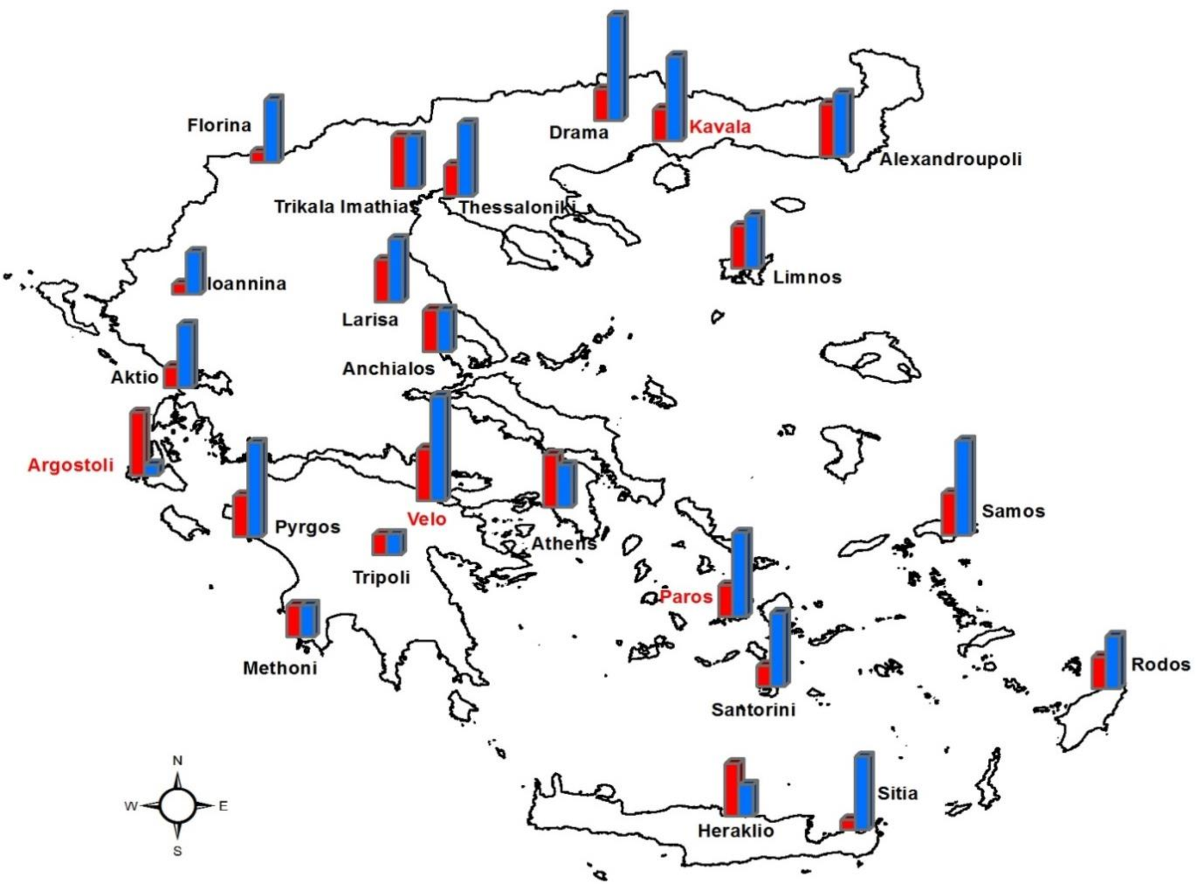

Figure 3.5. Magnitude of trends of mean maximum (TX, grey bars) and minimum air temperature (TN, black bars) during the baseline period (1981–2010). Underlined bold letters indicate shorter period of records (see Table 3.1).

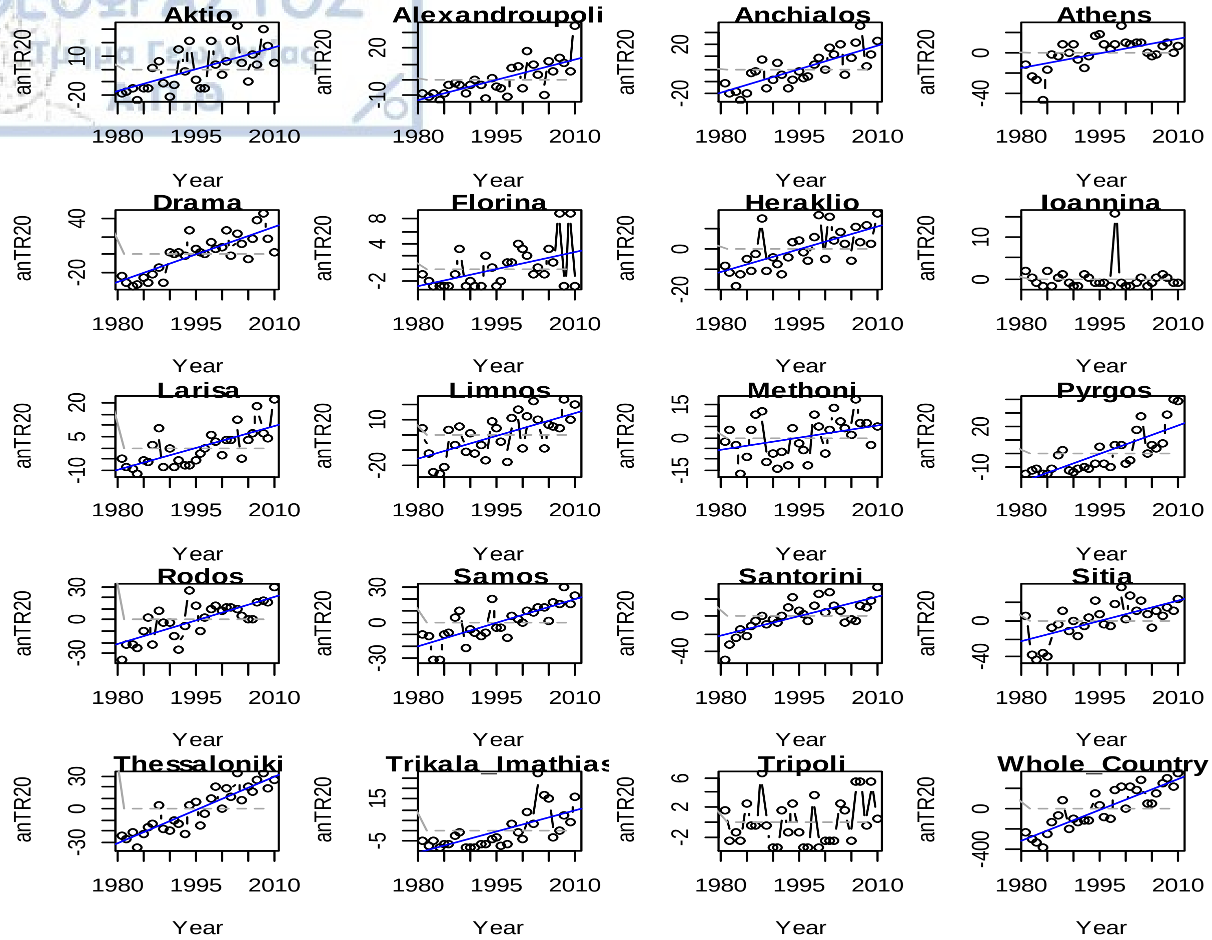

Figure 3.6. Time series of tropical nights anomaly (anTR20) at the studied locations and country average [bottom right "Whole_Country"]. Blue solid lines indicate statistically significant trends ($p < 0.05$) while no-line indicates non-significant trends. The zero x – axis horizontal (dark grey dotted line) are also presented.

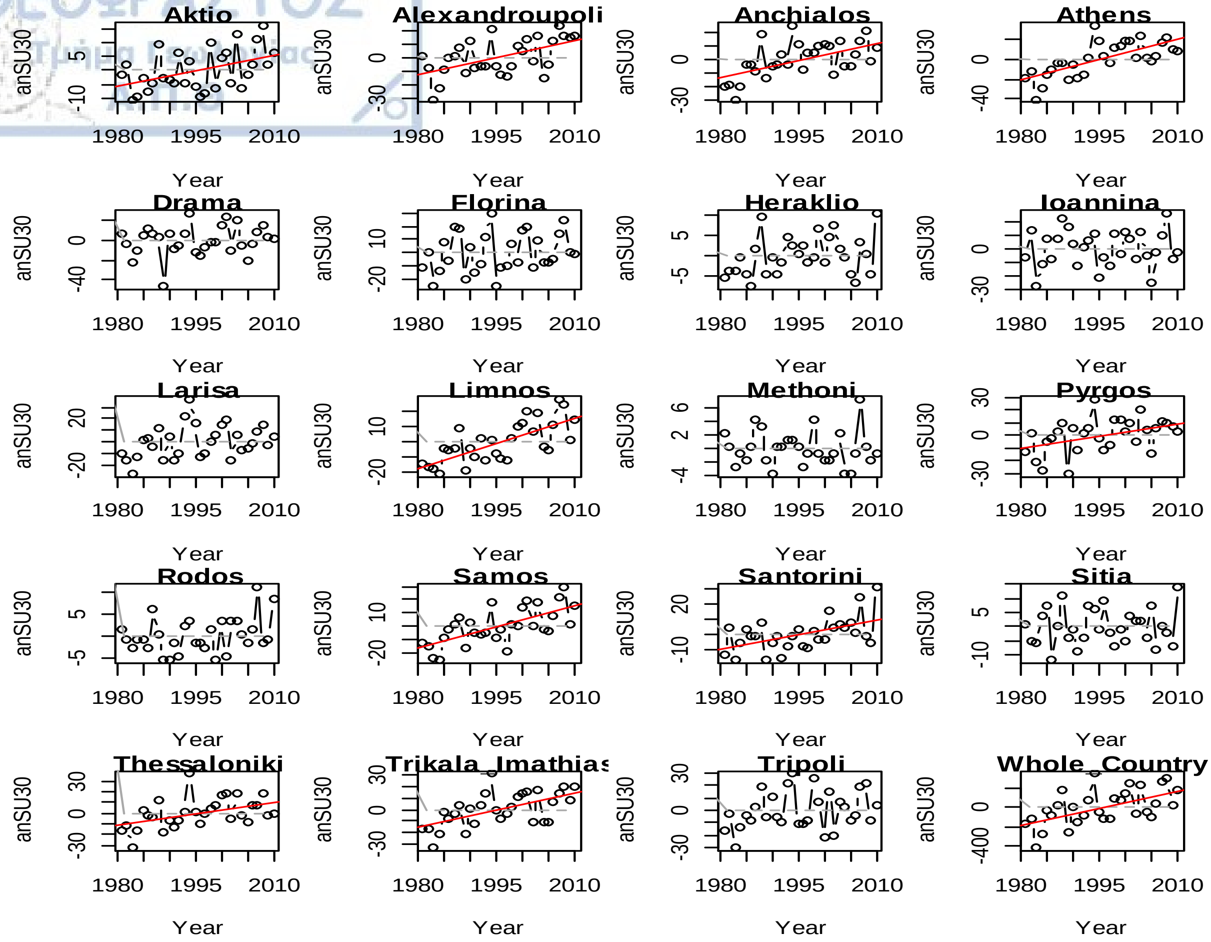

Figure 3.7. Time series of summer days anomaly (anSU30) at the studied locations and country average [bottom right "Whole_Country"]. Red solid lines indicate statistically significant trends ($p < 0.05$) while no-line indicates non-significant trends. The zero x – axis horizontal (dark grey dotted line) are also presented.

Regarding the trends in the bioclimatic indices (Table 3.12), the GST index showed the largest number of statistically significant increasing trends (16 of 19) ranging from 0.02 (Tripoli and Ioannina) to 0.07°C year^{-1} (Drama). The overall trend, averaged across all locations was +1.3°C. GDD showed similar trends. The respective overall trend for the BP was +276 GDD. The directions of HI trends were similar to those of GST and GDD indices but the overall trend across all locations was lower (+211 HI units). The BEDD index presented the least number of statistically significant trends (6 cases). The CI showed positive changes almost everywhere with 10 locations showing statistically significant trends, ranging from 0.05 to 0.1°C year^{-1}, over the BP. The DI showed five positive and 14 negative trends. All but one island (Limnos) encountered increasingly drier conditions, with Heraklio and Santorini being statistically significant (1.0 mm year^{-1} in both cases, Table 3.12).

3.6 Effects of historical and future climates on viticulture-related climatic indices and zoning

3.6.1 Regional future climate overview

The annual and GS averages of TX, TN and PRCP for the future periods (FP1 and FP2), along with the respective differences between BP and each future period, are summarized in Table 3.13. Average warming across all locations during the FP1 time period was +1.9°C, with TN warming being marginally higher (+0.1°C) than the warming of TX in the majority of the locations (10 vs four cases). Five cases showed same trends. Warming for the FP2 time period was +4.5°C across locations, with TX and TN ranging from 3.9°C (Heraklio) to 5.2°C (Tripoli) and from 3.8°C (Heraklio) to 4.9°C (Anchialos), respectively, increasing northward. In general, the islands experienced cooler conditions in both time periods (-0.6 and -0.3°C, on average) than the respective mainland and coastal locations. PRCP amounts were reduced almost everywhere (15 cases) under the FP1 time period with the only exception being the northern locations of Alexandroupoli, Florina, Thessaloniki and Heraklio (Table 3.13). PRCP reductions expanded everywhere and consistently during the FP2 time period. The values ranged from 44 (Santorini) to 285 (Ioannina) mm. During the GS, islands are projected to face much drier conditions than coastal and mainland locations (87mm vs. 166 and 214mm, on average, respectively).

Table 3.13 Mean values of annual TX, TN and Pr (GS average in the parenthesis) for the FP1 (FP2) are presented in the first (second) column on each region. Upward (↑) – downward (↓) trends are presented in the second row of each location while the percentage of changes (on annual base) between the FP1 and FP2 for the selected climate parameters are presented in the third row respectively. Each location has superscript letters indicating coastal (Cs), Island (Is) and mainland (Mn) locations.

	TX (℃)		**TN (℃)**		**PRCP (mm)**	
Locations (winegrape areas)	**FP1**	**FP2**	**FP1**	**FP2**	**FP1**	**FP2**
Aktio (Lefkada)^{Cs}	21.1 (25.5)	23.3 (28.2)	13.4 (17.2)	15.6 (19.8)	894 (259)	784 (211)
	↑2.0	↑4.7	↑1.9	↑4.5	↓6.0	↓54.0
	+10.4%		+16.4%		-12.3%	
Alexandroupoli (Maronia)^{Cs}	21.0 (27.0)	23.1 (29.4)	10.9 (15.5)	12.8 (17.7)	549 (201)	512 (179)
	↑2.0	↑4.7	↑2.1	↑4.3	↑2.0	↓19.0
	+10%		+17.4%		-6.7%	
Anchialos^{Cs}	22.8 (28.4)	25.2 (31.3)	12.8 (17.2)	15.0 (20.0)	471 (187)	441 (173)
	↑2.0	↑4.9	↑2.1	↑4.9	↓21.0	↓35.0
	+10.5%		+17.2%		-6.4%	
Athens (Spata)^{Cs}	23.5 (28.6)	25.6 (31.1)	15.5 (19.8)	17.5 (22.2)	377 (106)	331 (94)
	↑1.9	↑4.4	↑2.0	↑4.4	↓3.0	↓15.0
	+8.9%		+12.9%		-12.2%	
Drama^{Mn}	21.6 (28.1)	24.0 (30.9)	11.8 (16.9)	13.9 (19.4)	547 (260)	457 (195)
	↑1.9	↑4.7	↑2.0	↑4.5	↓5.0	↓70.0
	+11.1%		+17.8%		+1.8%	
	19.3 (25.9)	21.7 (28.6)	8.4 (13.3)	10.6 (15.8)	584 (303)	500 (249)

Florina (Amyndeo)[Mn]	↑1.9	↑4.6	↑2.0	↑4.5	↑1.0	↓53.0
	+12.4%		+26.2%		-14.4%	
Heraklio (Peza)[Is]	22.0 (25.7) ↑1.8	23.8 (27.8) ↑3.9	15.0 (18.3) ↑1.8	16.8 (20.3) ↑3.8	475 (108) ↑8.0	434 (94) ↓6.0
	+8.2%		+12.0%		-8.6%	
Ioannina (Zitsa)[Mn]	20.2 (26.1) ↑1.9	22.7 (29.0) ↑4.8	8.3 (12.5) ↑2.1	10.5 (15.0) ↑4.6	1010 (359) ↓32.0	857 (285) ↓106.0
	+12.4%		+26.5%		-15.1%	
Larisa (Tyrnavos)[Mn]	22.7 (29.2) ↑1.9	25.0 (31.8) ↑4.5	10.3 (15.1) ↑2.0	12.4 (17.6) ↑4.5	401 (195) ↓15.0	356 (171) ↓39.0
	+10.1%		+20.4%		-11.2%	
Limnos[Is]	21.4 (26.5) ↑2.0	23.5 (28.9) ↑4.4	13.7 (17.9) ↑2.0	15.8 (20.3) ↑4.4	517 (141) ↓15.0	505 (130) ↓26.0
	+9.8%		+15.3%		-2.3%	
Methoni (Triffilia)[Cs]	20.9 (24.6) ↑1.9	23.0 (27.1) ↑4.4	13.3 (16.8) ↑1.8	15.3 (19.1) ↑4.1	676 (148) ↓20.0	601 (120) ↓48.0
	+10.0%		+15.0%		-11.1%	
Pyrgos[Cs]	24.7 (29.4) ↑2.0	26.8 (31.7) ↑4.3	13.1 (16.4) ↑1.9	15.1 (18.7) ↑4.2	844 (200) ↓19.0	742 (160) ↓59.0
	+8.5%		+15.3%		-12.1%	
Rodos (Ebonas)[Is]	23.3 (25.4) ↑2.0	25.1 (28.0) ↑4.6	17.6 (19.7) ↑2.1	19.5 (22.1) ↑4.5	474 (101) ↓4.0	412 (86) ↓19.0
	+7.7%		+10.8%		-13.1%	
Samos[Is]	21.4 (26.8) ↑1.9	23.6 (29.3) ↑4.4	16.0 (17.3) ↑1.9	18.1 (19.6) ↑4.2	686 (105) ↓7.0	601 (90) ↓22.0
	+10.3%		+13.1%		-12.4%	

Santorini[Is]	21.6 (27.0) ↑1.8	23.7 (29.2) ↑4.0	13.3 (20.9) ↑1.9	15.3 (23.0) ↑4.0	759 (52) ↓4.0	693 (44) ↓19.0
	+9.7%		+15.0%		-8.7%	
Sitia (Zakros)[Is]	23.1 (27.0) ↑1.9	25.0 (29.1) ↑4.0	17.5 (21.0) ↑1.9	19.4 (23.1) ↑4.0	324 (96) ↓2.0	296 (78) ↓20.0
	+8.2%		+10.9%		-8.6%	
Thessaloniki (N. Messimvria)[Cs]	22.3 (28.5) ↑2.1	24.6 (31.2) ↑4.8	12.6 (17.5) ↑2.0	14.8 (20.3) ↑4.8	471 (231) ↑23.0	402 (197) -11.0
	+10.3%		+17.5%		-14.6%	
Trikala_Imathias (Naoussa)[Cs]	21.3 (27.5) ↑1.8	23.8 (30.7) ↑5.0	10.1 (15.0) ↑1.9	12.4 (17.8) ↑4.7	550 (242) ↓5.0	453 (194) ↓53.0
	+11.7%		+22.8%		-17.6%	
Tripoli (Mantinia)[Mn]	21.9 (27.7) ↑2.0	24.5 (30.9) ↑5.2	8.8 (12.5) ↑2.0	10.9 (15.1) ↑4.6	712 (219) ↓20.0	578 (170) ↓69.0
	+11.9%		+23.9%		-18.8%	
Islands	22.1 ↑1.9	24.1 ↑4.2	15.5 ↑1.9	17.5 ↑4.2	539 ↓4	490 ↓19
	+9.0%		+12.7%		-9.1%	
Mainland	21.1 ↑1.9	23.6 ↑4.8	9.5 ↑2.0	11.7 ↑4.5	651 ↓14	570 ↓67
	+11.5%		+22.5%		-12.5%	
Coastal	22.2 ↑2.0	24.4 ↑4.7	12.7 ↑2.0	14.8 ↑4.5	651 ↓6	570 ↓37
	+10.0%		+16.5%		-11.7%	

The regional classification according to bioclimatic indices for the BP and the FP1 and FP2 periods is presented in Figures 3.8-3.10 and Table 3.14. For the GST, 12 locations fall into the "Hot" class, over the BP, with four locations being classed as "Warm" and three cases exhibiting "Very hot" conditions (Figure 3.8). For the FP1 period, the number of "Very hot" locations markedly increased (from 3 to 14) (Figure 3.8), while under further warming (FP2 period) only six locations remain within the range of being climatically suitable for viticulture (Figure 3.8).

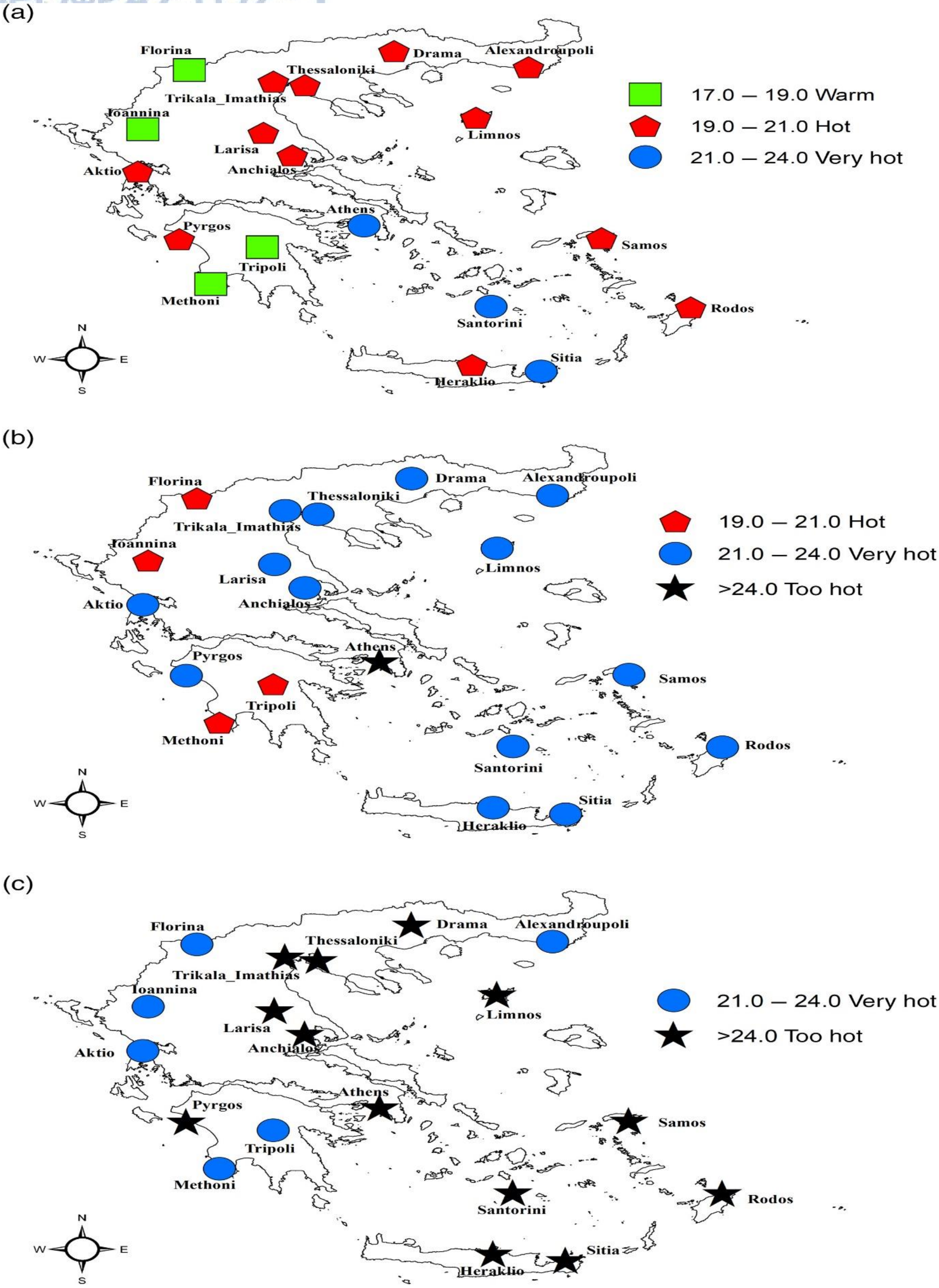

Figure 3.8. Direct impacts of climate trends on GST classification for (a) BP, (b) FP1 and (c) FP2 period.

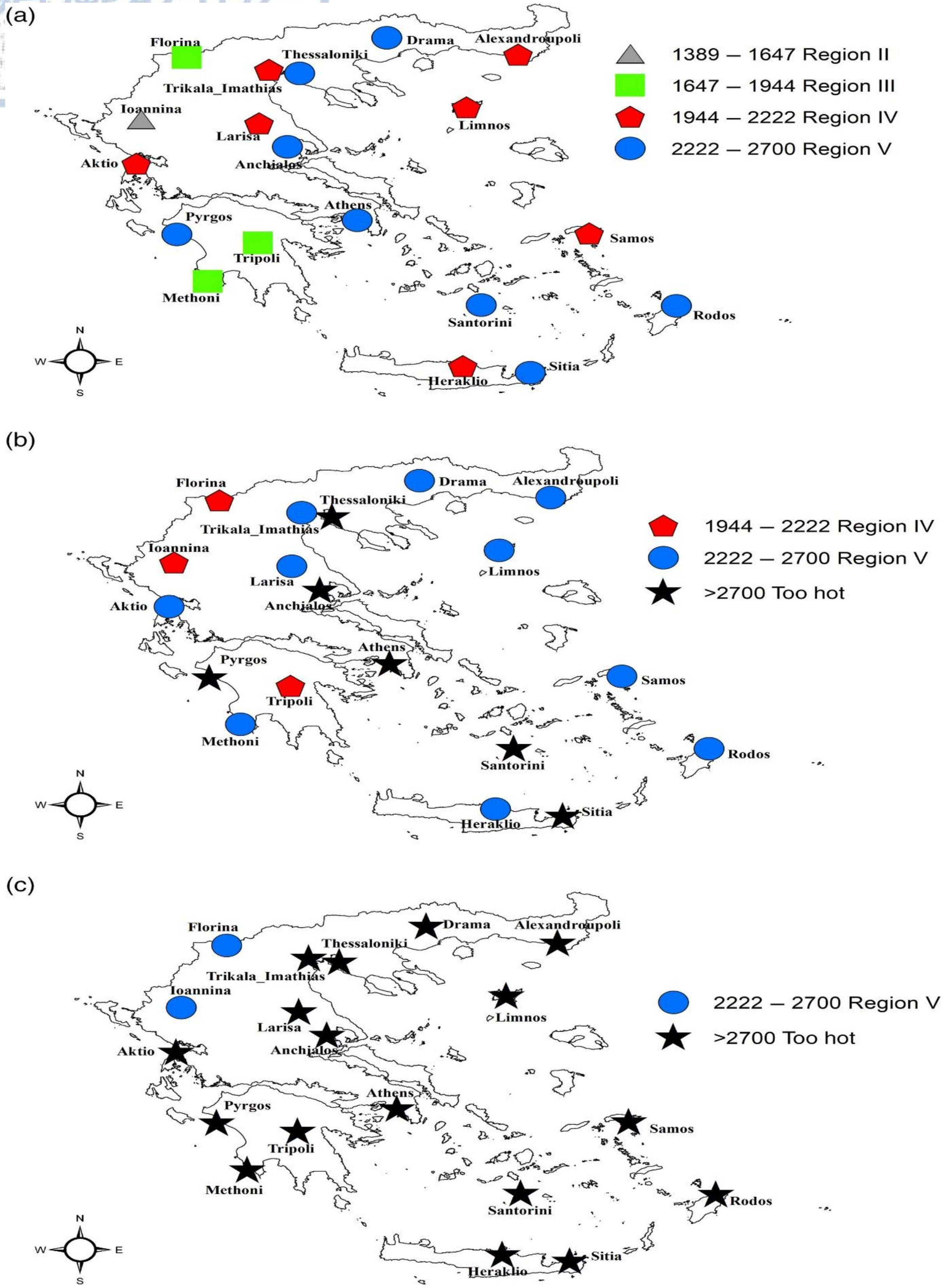

Figure 3.9. Direct impacts of climate trends on GDD classification for (a) BP, (b) FP1 and (c) FP2 period.

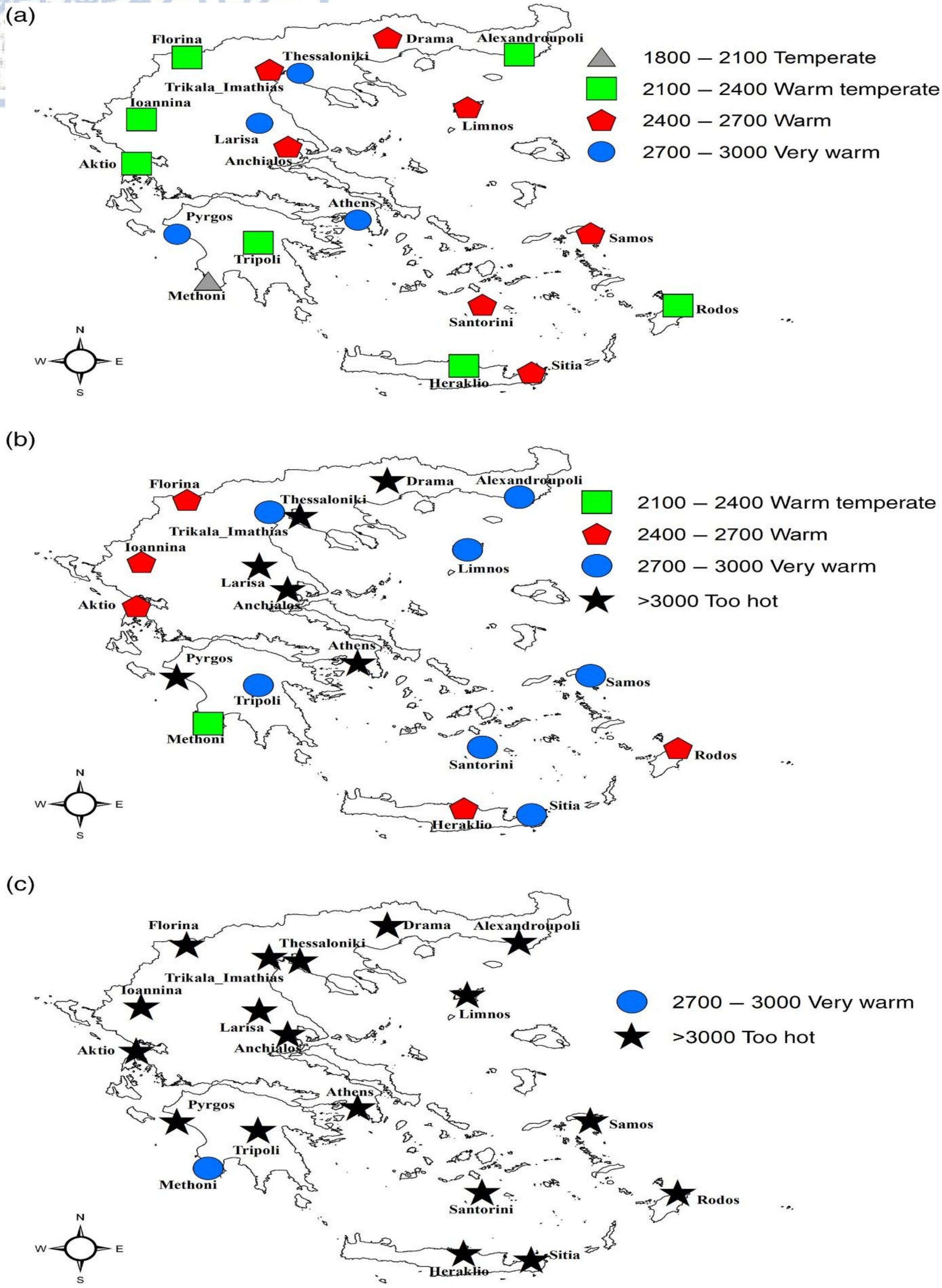

Figure 3.10. Direct impacts of climate trends on HI classification for (a) BP, (b) FP1 and (c) FP2 period.

Table 3.14. Bioclimatic indices, class ranges and frequency of the main winegrape areas in Greece for the baseline (1981–2010), and two future periods, FP1 (2021–2050) and FP2 (2061–2090) according to RCP 8.5 scenario.

		1981-2010		**2021-2050**		**2061-2090**	
Index	**Classes**	**Total number**	**Frequency (%)**	**Total number**	**Frequency (%)**	**Total number**	**Frequency (%)**
GST (°C)	Warm	4	21.1	0	0	0	0
	Hot	12	63.1	4	21.1	0	0
	Very hot	3	15.8	14	73.6	6	31.6
	Too hot	0	0	1	5.3	13	68.4
GDD (°C units)	Region II	1	5.3	0	0	0	0
	Region III	3	15.8	0	0	0	0
	Region IV	7	36.8	3	15.8	0	0
	Region V	8	42.1	10	52.6	2	10.5
	Too hot	0	0	6	31.6	17	89.5
HI (°C units)	Temperate	1	5.3	0	0	0	0
	Warm temperate	7	36.8	1	5.3	0	0
	Warm	7	36.8	5	26.3	0	0
	Very warm	4	21.1	7	36.8	1	5.3
	Too hot	0	0	6	31.6	18	94.7
BEDD (°C units)	3	2	10.5	0	0	0	0
	4	8	42.1	2	10.5	0	0
	5	9	47.4	13	68.4	7	36.8

	6	0	0	4	21.1	12	63.1
DI (mm)	Very dry	0	0	4	21.5	17	89.5
	Moderate dry	17	89.5	14	73.2	2	10.5
	Sub-Humid	2	10.5	1	5.3	0	0
CI (°C)	Very cool nights	3	15.8	0	0	0	0
	Cool nights	2	10.5	3	15.8	0	0
	Temperate nights	10	52.6	4	21.1	3	15.8
	Warm nights	4	21.1	12	63.1	16	84.2

The estimated GDD for the FP1 also led to noticeable shifts. The relatively cooler classes (i.e., "Regions III and IV") were reduced (Figure 3.9) with respect to the BP (Figure 3.9), while the warmest class "Region V" became more common. In FP2, the locations with suitable thermal conditions for quality viticulture were limited to the higher elevation areas only (Florina and Ioannina) (Figure 3.9). Regarding the HI, eight locations were characterized as "Temperate" and "Warm temperate" over the BP (Figure 3.10). A growing number of cases are projected to fall into warmer classes (i.e., "Very warm" and "Too hot") in FP1 and only one location is projected to remain "Warm temperate" (i.e., Methoni) during the FP2 period (Figure 3.10). All locations, except for Methoni, are projected to be unsuitable for viticulture according to HI in the FP2 period (Figure 3.10). For the BEDD index, most of the locations currently fall within 1400–1600 (eight cases) and 1600–1800 intervals (nine cases). Over the FP1 period, the latter class is projected to become more common (13 cases) (Table 3.14). An increase in the number of locations placed in 1800–2000 BEDD class was identified under additional warming (FP2).

A full range of CI classes was identified across locations under historical climate conditions, notably with five cases falling into the coolest classes ("Cool nights" and "Very cool nights"). "Warmer nights" are likely to become more pronounced during

FP1, while an increasing rate was apparent thereafter (FP2). Moderate dry conditions, according to the DI index, were identified in 17 locations with only two cases experiencing more humid conditions during the BP. Within the FP1, four locations were characterized as insufficient ("Very dry") of meeting the hydrologic requirements for viticulture (Table 3.14). Under FP2, 13 more locations are projected to show unfavorable water availability conditions for viticulture.

The results from the analysis of the threshold indices are presented in Table 3.15. The analysis for the first period (FP1) showed an increase in both SU30 and TR20 across all locations. However, this increase will not affect every location in the same way. During FP2 the percentage of total days with extremes during GS further rises.

Table 3.15. Mean values of SU30 and TR20 (see table 3.1 for more details) for the baseline and two future periods are presented in the first row on each region. The percentage of the total number of days during the growing season (April – October, 214 days) for each period and region are presented in the parenthesis while the percentage in the second row shows the increase during the studied future periods.

Locations (winegrape areas)	**BS**		**FP1**		**FP2**	
	SU30	TR20	SU30	TR20	SU30	TR20
Aktio (Lefkada)[Cs]	15 (7%)	23 (11%)	40 (19%) +167%	66 (31%) +187%	90 (43%) +500%	113 (53%) +391%
Alexandroupoli (Maronia)[Cs]	47 (22%)	16 (8%)	76 (36%) +62%	46 (22%) +188%	108 (51%) +130%	82 (38%) +413%
Anchialos[Cs]	66 (31%)	32 (15%)	97 (45%) +47%	74 (35%) +131%	132 (62%) +100%	118 (55%) +269%
Athens (Spata)[Cs]	69 (32%)	80 (37%)	96 (45%) +39%	111 (52%) +39%	128 (60%) +86%	140 (65%) +75%
Drama[Mn]	66 (31%)	35 (16%)	94 (44%) +42%	67 (31%) +91%	128 (60%) +94%	107 (50%) +205%
Florina (Amyndeo)[Mn]	42 (20%)	3 (1%)	64 (30%) +52%	13 (6%) +333%	100 (47%) +138%	54 (25%) +1700%

Heraklio (Peza)[Is]	12 (6%)	50 (23%)	29 (14%) +142%	84 (39%) +68%	79 (37%) +558%	120 (56%) +140%
Ioannina (Zitsa)[Mn]	41 (19%)	2 (1%)	67 (31%) +63%	6 (3%) +200%	103 (48%) +151%	38 (18%) +1800%
Larisa (Tyrnavos)[Mn]	84 (39%)	12 (6%)	109 (51%) +30%	40 (19%) +233%	135 (63%) +61%	84 (39%) +600%
Limnos[Is]	33 (15%)	54 (25.2)	67 (31%) +103%	84 (39%) +56%	104 (49%) +215%	116 (54%) +115%
Methoni (Triffilia)[Cs]	4 (2%)	21 (10%)	17 (8%) +325%	58 (27%) +176%	68 (32%) +1600	103 (48%) +391%
Pyrgos[Cs]	74 (35%)	18 (8%)	103 (48%) +39%	48 (22%) +182%	136 (64%) +84%	95 (44%) +459%
Rodos (Ebonas)[Is]	7 (3%)	72 (34%)	29 (14%) +314%	115 (54%) +55%	83 (39%) +1086%	145 (68%) +96%
Samos[Is]	42 (20%)	43 (20%)	72 (34%) +71%	73 (34%) +70%	105 (49%) +150%	105 (49%) +144%
Santorini[Is]	29 (14%)	101 (47%)	64 (30%) +121%	130 (61%) +28%	106 (50%) +266%	155 (72%) +54%

Sitia (Zakros)[Is]	19 (9%)	107 (50%)	55 (26%) +190%	132 (62%) +23%	105 (49%) +453%	159 (74%) +49%
Thessaloniki (N. Messimvria)[Cs]	69 (32%)	44 (21%)	96 (45%) +39%	80 (37%) +82%	130 (61%) +88%	119 (56%) +171%
Trikala_Imathias (Naoussa)[Cs]	52 (24%)	8 (4%)	86 (40%) +65%	34 (16%) +325%	128 (60%) +146%	84 (39%) +950%
Tripoli (Mantinia)[Mn]	60 (28%)	4 (2%)	88 (41%) +47%	10 (5%) +150%	127 (59%) +112%	37 (17%) +825%

3.7 Discussion

The climatic overview of the BP clearly depicts an island (coastal)/mainland contrast throughout the Greek wine areas. In particular, islands were characterized by drier conditions (lower PRCP) and moderate TX, and thereby lower DTR and SU30 values. However, higher values of TN in the island locations were responsible for higher nocturnal heating (CI, TR20). Both island and coastal locations were generally warmer (higher GDD and HI) while cooler (lower GDD and HI) and milder night temperatures (lower CI and TR20) with more humid conditions (higher DI and PRCP) were confined in the mainland locations of Florina, Ioannina and Tripoli as a result of their higher elevation [ranged from 483 (Ioannina) to 651 and 692 m.a.s.l. (Tripoli and Florina, respectively)] and complex orography with a wider variety of terroir aspects (i.e., slope, inclination). The lower elevation mainland locations of Larisa and Drama (73 and 104 m.a.s.l., respectively) also depict the same contrast between island (coastal) and mainland locations but with smaller ranges.

The trend analysis over the BP during the GS showed that the statistically significant increasing trends of TN were higher than the respective TX in the majority of the cases.

No differences were identified for TN trends between island, coastal and mainland locations (0.06°C year^{-1}, on average). For TX, however, coastal and island locations are experiencing higher increasing trends than the mainland locations (0.04, 0.03 and 0.02 °C year^{-1}, on average, respectively). Thus, decreasing DTR trends were identified almost everywhere (17 cases) with mainland locations experiencing significantly lower DTR trends (−0.05°C year^{-1}, on average). On the other hand, temperature extremes are increasingly frequent with TR20 more pronounced than the respective SU30 (17 vs 10 cases). Regarding PRCP, mainland areas showed a trend towards wetter conditions (+2.7 mm year^{-1}, on average) as compared to island and coastal locations (−0.5 and +0.7 mm year^{-1}, on average, respectively). The more pronounced trends in TN versus TX, responsible for significant decreases in DTR values, were also identified in many regions globally (Easterling et al., 1997). On the other hand, opposite trends (higher TX trends) were found in some countries such as Spain (e.g., Ramos et al., 2008), highlighting climate's spatial inhomogeneity in trends (Jones et al., 2005). Regarding seasonal analysis, the results showed that summer months experienced significantly warmer conditions than spring, autumn and winter.

Increasing temperatures are highly correlated with earlier phenological events in the grapevine annual cycle. Budburst, flowering and véraison have trended almost 2 and 3 weeks earlier over 1965–2003 in Alsace, respectively (Duchêne and Schneider, 2005) and harvest dates advanced about 13 days over 1952–1997 in Bordeaux (Jones and Davis, 2000). Warmer conditions are also responsible for the earlier harvest dates in the majority of the studied winegrape areas in Greece (Koufos et al., 2014). Accordingly, as grape maturity takes place earlier during the hottest part of the vegetative cycle (summer months), wine quality may be impaired from unbalanced sugar and acid levels and lacking in aromatic expression, especially for early ripening varieties (Van Leeuwen et al., 2008).

The majority of the winegrape areas in Greece are currently experiencing warm to very warm conditions. Important shifts in regional classifications resulting in warmer and drier climate types, particularly during the FP2 period across all the locations, were identified. Significant changes in the mean thermal conditions during the GS (higher GDD and HI) and ripening period (CI) with additional changes to drier conditions (lower DI) leading to substantial shifts in traditional winegrape areas were also found in the Italian Alps (Eccel et al., 2016). Temperature increases also resulted in higher WI units in Vilafranca del Penedès, Cabacès and Lleida winegrape areas in north-east Spain (Ramos et al. 2008). In particular, increased WI by more than 400 units in Vilafranca del Penedès moved the area from the region II class (higher end) to IV (lower end). Similar results were reported for the HI in Cabacès and Lleida areas. Heat accumulation trends moved these areas from warm temperate climate type to warm and from warm to very warm, respectively. However, degree summation indices, like WI, may display substantial spatial variability between plots within a winegrape region due to elevation differences and different vineyard exposure (Laure de Rességuier et al. 2020). White et al. (2006), using a high-resolution RCM for winegrape producing areas in the USA, showed that production could be reduced by 81% in the 21st century, while extreme heat (>35°C) could eliminate entire areas. Similar results were found in Australia where one third of the currently cultivated areas could face shifts into warmer and possibly unsuitable conditions for high quality wines (Hall and Jones, 2008).

The potential climatic shifts could be a major problem, primarily for areas currently cultivated with early maturing varieties. For example, grapes of white varieties Chardonnay and Sauvignon blanc and those of red varieties of Syrah and Merlot, mainly cultivated in the "Hot" northern Greece winegrape areas of Maronia (weather station, Alexandroupoli) and Drama are currently (last decade) harvested earlier than the climatically favorable period (between 10 September and 10 October for optimal varietal expression) for the Northern Hemisphere (Van Leeuwen and Seguin, 2006). Specifically, harvest of the Chardonnay cultivar in Drama usually occurs around mid to late August (G. C. Koufos, 2015; personal communication). Over the last decade (2001–2010), during July and August, when the principal processes of sugar accumulation and acid degradation take place, GST consistently exceeded 26.0°C leading to earlier ripening (20 August, on average) under more extreme temperatures (average TX and TN for July and August: 32.0 and 21.0°C, respectively). Assuming that no action will be taken for delaying grape ripening, harvest is projected to take place a month earlier (Table 3.12, future budburst dates were estimated using a simple model adopted by Jones and Davis, 2000) which would likely result in unbalanced wines due to higher sugar and lower acid concentration in the grape must. Moreover, the higher nocturnal temperatures of July/August (as compared to September/October) would likely further impair aromatic expression of the final wines (Tonietto and Carbonneau, 2004). In such cases, specific adjustments should be made to preserve some of the characteristics of these varieties in long-term. Intensive monitoring of the heat resilience (upper threshold) of the currently cultivated varieties in these winegrape areas should be a compulsory task in order to identify long-term modifications to be adopted to delay ripeness. These include, but are not limited to (1) adjustments in vine training and canopy architecture, (2) modification of viticultural practices (e.g., irrigation and soil management), (3) moving the cultivation to new areas at higher elevations and to north-facing slopes, or (4) changing wine style preferences (i.e., red or sweet wines instead of whites). However, a long-term action to future environmental conditions could be the substitution of earlier-ripening varieties to later-ripening varieties, in order to allow ripening to occur within the optimum "window" for berry ripening.

Table 3.16 Phenological response of an early- (cv. Chardonnay) and late- ripening variety (cv. Xinomavro) over and two future periods, FP1 (2021-2050) and FP2 (2061-2090) according to RCP 8.5 scenario. Budburst dates were calculated following the formulae used in Jones and Davis (2000). Harvest dates assumed to take place when GDD reached the specific variety optimum.

Variety/ Winegrape area	**Current Period**	**FP1**	**FP2**
cv. Chardonnay (cultivated in Drama)			
mean Budburst (2005-2010)	28 – March	21 – March	8 – March
mean Harvest (2005-2010) (GDD = 1760)	25 – August	16 – August	27 – July
cv. Xinomavro [cultivated in Naoussa (weather station Trikala_Imathias)]			
mean Budburst (2007-2013)	31 – March	24 – March	14 – March
mean Harvest (2007-2013) (GDD = 2170)	26 – September	27 – September	23 – August

On the other hand, climate trends in Greece were found to exert a moderate or no effect on harvest dates of late ripening varieties cultivated in mainland wine areas like Xinomavro [cultivated in Amyndeon (Florina weather station) and in Naoussa (Trikala_Imathias weather station)], Agiorgitiko [cultivated in Nemea (Velo weather station)] and Moschofilero [cultivated in Mantinia (Tripoli weather station)] (Koufos et al., 2014). Although, projections in future warming hints that these areas will likely become marginally suitable for grapevine cultivation, it is likely that earlier maturation will more consistently allow optimal sugar concentration and better aromatic and phenolic maturation, possibly leading to more balanced fruit. For example, Xinomavro which is currently harvested in late September to mid-October in Naousa (Trikala_Imathias weather station) and Amyndeon (Florina weather station) (on average, G. C. Koufos, 2015; personal communication), warmer future conditions may allow the producers to meet the desired maturity index (sugar/acid ratio) more often than currently experienced. This is likely enhanced by the projection that harvest dates do not seem to be affected as much over the next 30 year (harvest is projected to be delayed by 1 day, on average, in the FP1) (Table 3.12).

However, further warming will likely result in a significantly earlier harvest (about a month earlier than today under FP2) and actions should be taken to preserve the variety's flavor uniqueness. Moreover, the current growing season period (i.e., April - October), which seems to be the case for the late ripening variety of Xinomavro in the recent past (i.e., 2007-2013), will probably be shorter (from 180 days to 163) and moved forward (from April – October to March - September) during the FP2. Similarly, the late varieties in the Veneto wine producing area (Italy) were found to exhibit lower reactions to climate changes than the mid ripening and early ripening varieties (Tomasi et al., 2011). Interestingly, higher wine quality rankings for both red and white varieties have reported to be significantly associated with higher average growing season temperatures in Burgundy in France (Jones et al., 2005), although potential thresholds to these relationships have been proposed.

Chapter 4: Adaptive capacity of winegrape varieties cultivated in Greece to climate change: Current trends and future projections.

4.1 Introduction

Atmospheric temperature increases due to climate change have been shown to affect both grape composition and yield formation (Jones and Davis, 2000). Furthermore, air temperature rises and changes in solar radiation (increase in UV-B levels) are expected to play an important role to grapevines' growth cycle, phenology and the synthesis of secondary metabolites in final wines (Schultz 2000). Additional warming of about 1.0-5.7 °C projected, on average, by the end of the century (IPCC, 2021) would substantially alter the current grapevine geographical distribution, possibly placing areas at low latitudes at danger (Fraga et al., 2016). Especially in regions like Greece (which is located in the warmer part of the Mediterranean basin) vineyards might need to migrate to higher elevations depending on the rate and magnitude of warming in the future (Koufos et al., 2017).

Wine production has a strong economic and social importance in many countries worldwide and thus, the studies investigating the possible future climate threats on viticulture have increased recently (e.g., Teslić et al., 2018). A major part of the research in this area focuses on the effects of climate change on grapevine phenology (growth cycle duration and precocity) reporting significant earlier occurrence of grapevine developmental stages due to warming growing season temperatures thereby placing ripening during a warmer period of the year. Once Jones et al. (2005) reported that phenology trended significantly earlier in Europe under warmer growing season conditions, a large number of relative studies around the world showed similar results thereafter (e.g., Webb et al. 2007, Ramos et al. 2008, Bock et al.

2011, Tomasi et al. 2011, Webb et al. 2011, Koufos et al. 2014, Ruml et al. 2016). The resulting higher temperatures during the maturation phase are very likely to contribute to an increase in sugar levels and a decrease in acid concentrations of grape composition at harvest (Neethling et al., 2012). Moreover, higher night-time temperatures seem to impair synthesis and favor breakdown of secondary metabolites (aroma and color compounds) in berries (Kliewer, 1973; Gaiotti et al., 2018). Furthermore, while vines are resilient to drought and in some cases wine quality may benefited from dry conditions (Van Leeuwen and Darriet 2016), extreme water deficit could have serious implications on berry formation and wine phenolics (Koundouras et al. 2006) as well as lower yields (Fraga et al. 2016).

The viticultural community has recently focused on investigating the adaptive capacity of the most economically important winegrape varieties to climate change (Wolkovich et al., 2018). Several studies attempted to assess grapevines' specific thermal requirements and explored their level of resilience to climate change signals, in well-known winegrape regions of the world (e.g., Parker et al. 2013, Van Leeuwen et al. 2008). These studies also highlighted the necessity for a more complex indicator, than the traditional agro-climatic indices, capable of incorporating: (i) the potential contribution of other crucial factors (i.e., solar radiation and water) and (ii) varietal adaptive capacity to the upcoming climate changes. To successfully adapt grapevine varieties to the changing thermal conditions, phenology which is mainly driven by temperature has been the key parameter examined (García de Cortázar-Atauri et al., 2017). Therefore, the identification of the specific thermal requirements per variety to reach full berry ripeness could provide a valuable tool for grape growers to plan mitigation strategies to adjust to future climate change (Parker et al., 2013; van Leeuwen et al., 2008).

Greece has played an important role in the development of viticulture and wine production and continues today with a great tradition in winemaking from the ancient times. Later, in the second half of the 20th century, many international varieties were introduced to Greece and are now widely cultivated. Chapter 3 analyzed the characteristics and trends of climate parameters as well as their relationship with viticulture, for the most important winegrape areas and local varieties in Greece. The results showed that: (I) island locations faced proportionally more extreme temperatures and drier conditions compared to mainland and coastal areas, (II) minimum air temperatures increased at a higher rate than maximum temperatures in the majority of winegrape areas, and (III) harvest in the future is projected to occur significantly earlier for most of the areas and varieties.

4.2 Aims of the chapter

The majority of the studies investigating the potential impacts of climate change on viticulture, focused either on traditional winegrape areas (e.g., Webb et al. 2007; Hall et al. 2016) or varieties (e.g., Fraga et al. 2016). Complementary to the objectives of the above-mentioned studies, this chapter investigates how the most important international varieties reacted in comparison to the native ones throughout the Greek territory.

This chapter also further adds to this knowledge by reporting data on an extended number of winegrape varieties (both indigenous and international) and locations across the Greek territory, in order to: (1) investigate the relationships of air temperature calculated over different periods with grape harvest dates and chemical composition [i.e., Potential alcohol (%) and acidity (g/L) levels], (2) calculate heat requirements (GDD) from 1st of April to harvest and group the most important winegrape varieties according to their heat requirements, and (3) estimate future harvest dates based upon these heat requirements under different representative emission pathways (i.e., RCP4.5 and RCP8.5) in two future time periods (2041-2065 and 2071-2095), using an ensemble projection from 10 regional climate models.

The determination of the upper temperature threshold of the lesser-known indigenous varieties in a hot winegrape area such as Greece, where the cultivation of particular varieties it is often regulated by law, is of outmost importance. The identification of heat demands and consequently, the projection of its phenological stages could provide new insights and constitute a valuable tool for grape growers in order to plan their mitigation strategies to adjust in future cultivar responses (Van Leeuwen et al. 2008).

The significance of the present chapter lies in incorporating 14 wine producing regions covering roughly 90% of the country's grapevine acreage and production, over a time period of approximately 20 years (from 2000 to 2017, on average) with the aim to predict how climate change may transform Greek grape producing regions and variety distributions in the future. These observations are very important since Greece is one of the warmest winegrape regions in the world (see Chapter 3) and as such could be considered as a useful model for other viticultural regions that may face similar conditions in the near future. Moreover, Greek varieties (indigenous) make up an important genetic pool for the adaptation of wine sector to future climate because of their high suitability to local (semiarid) ecological conditions. Establishing their heat requirements would also increase the knowledge of and potential utilization of the varieties grown in Greece by the international viticultural community. Part of this chapter has been already published as a peer-reviewed article in the *Oeno One* in 2020.

4.3 Materials and methods

4.3.1 Climate data

Daily observations of maximum (TX) and minimum (TN) air temperature (°C) were obtained from the HNMS in order to investigate the relationships between air temperature and harvest dates and berry composition, for the regions studied. The 14 weather stations were previously checked for errors and used for climate trend analysis and winegrape region classifications as they appeared to reflect the general structure for climatic conditions of the wine producing areas in Greece (see Chapter 3). The distance of the weather stations ranged from 50 km (the Kavala region) to less than 10 km (in 6 cases). An average lapse rate (0.6°C/100 m) adjustment, similar to the procedure described in the previous chapter, was performed (Table 4.1).

Table 4.1. Geographical coordinates and altitude of the 12 weather stations used in this thesis for heat requirements estimation. Adjustments to stations were done to account for differences between station and vineyard elevations. HNMS is the Hellenic National Meteorological Service.

Weather station (winegrape region)	**Latitude (decimal degrees)**	**Longitude (decimal degrees)**	**Elevation (m.a.s.l.)**	**Adjustments (± 0.6/100 m)**	**Origin**
Alexandroupoli (Maronia)	40.85	25.93	2	no adjustments	HNMS
Drama (Adriani)	41.15	24.15	104	no adjustments	Weather station inside the vineyard
Heraklio (Peza)	35.33	25.18	39	adjustments made	HNMS
Kavala (Kokkinochori)	40.98	24.61	5	no adjustments	HNMS
Limnos	39.91	25.23	3	no adjustments	HNMS
Pyrgos	37.66	21.30	13	no adjustments	HNMS
Rodos (Ebonas)	36.40	28.08	11	adjustments made	HNMS
Samos	37.68	26.90	6	adjustments made	HNMS

Thessaloniki (Chalkidiki)	40.51	22.96	8	adjustments made	HNMS
Trikala_Imathias (Naoussa)	40.58	22.55	6	adjustments made	HNMS
Tripoli (Mantinia)	37.51	22.40	651	no adjustments	HNMS
Nemea	37.80	22.70	290	no adjustments	Meteo

4.3.2 Viticulture data

Initially, in order to examine the second research question of this thesis (i.e., to investigate how does recent and future projected warming influence Greek indigenous varieties compared to international ones?), we had to create a sufficient viticultural database (database 2). For this reason, viticultural data consisted of harvest dates and berry composition (potential alcohol levels/must Baumé degrees and acid concentrations) measurements were collected from representative wineries across Greece (Figure 4.1). The above-mentioned dataset was used to : (i) investigate the temporal evolution of the main phenological events in Greece, (ii) explore the relevant influence of climate (mainly air temperature) on grape phenology, composition and yield, (iii) to calculate the heat demands for the currently cultivated varieties in Greece, (iv) to compare the standard growing season (i.e., April to October) with the actual growing season in Greece (i.e., March - September) and (v) to predict future harvest dates in two future periods according to different RCPs (i.e., RCP4.5 and RCP8.5) using an ensemble dataset derived from 10 RCM (Table 4.2).

More specifically, the harvest date dataset consisted of 29 varieties (16 indigenous and 13 international) that were either cultivated in a specific area, or in various plots within the same area or in different areas, creating a total number of 49 study cases (Table 4.3). Harvest date as defined by the producers, is the time-point at which, after a number of consecutive measurements by company representatives, no further change in sugar accumulation is observed. Similar definitions of harvest and maturity dates have been used before (e.g., Tomasi et al., 2011). Berry composition data (potential alcohol and acidity of the must) was recorded at harvest after the picking of the grapes. The harvest dates and berry composition dataset details are presented in Tables 4.3-4.5. The database described above, was provided from each producer separately based upon maintaining anonymity, is not freely available. The majority of the studied areas are under protected designation of origin (PDO) cultivated with local varieties while the rest are protected geographical indications (PGI). Overall, the areas studied adequately represent the spatial distribution of wine production in Greece, covering areas with multiple "terroir" aspects considering the varieties, the complex topography (e.g., a wide range of elevation, slope, and orientation in the vineyards), geology (e.g., type of soil, inclination, and proximity to water bodies), legislation (e.g., restrictions in irrigation) and cultivation methods. There are also important winegrape areas mainly in central and eastern Greece such as Ioannina (winegrape area of Zitsa) and Larisa (winegrape area of Tirnavos and Rapsani) were not concluded in this thesis due to short time series and or data discontinuity

Figure 4.1. Map of Greek Protected Designation of Origin and Geographical Indication winegrape areas used in this thesis.

To estimate heat requirements (GDD), 29 winegrape varieties with sufficient data, currently grown in 12 out of 14 regions, were selected. For these locations, the HNMS provided sufficient daily data for 10 out of 12 regions. In addition, a commercial website (i.e., www.meteo.gr) that distributes high quality daily observations was used for shorter climate series in the case of Nemea due to the proximity to the vineyards (3 km vs. 18 km) while a weather station network located inside the vineyard area was used for the Drama region. Initially these two data sources (HNMS and Meteo) were combined to account for gaps in the Drama and Nemea timeseries, which works reasonably well with temperatures, however to avoid over or under-estimations in GDD summations we used data from a single station for these sites (Matese et al., 2014; Fourment et al., 2017).

To consider future climates, the DEAR-Clima database was used (http://meteo3.geo.auth.gr:3838/). DEAR-Clima is a reliable, user friendly open access online data source with future climate data from high resolution (0.11° x 0.11°) regional climate models from the Coordinated Regional Downscaling Experiment (CORDEX) research program. In this thesis, future harvest projection analysis was performed using daily simulations of TX and TN from 10 RCMs (Table 4.2).

Table 4.2. Summary of Global Climate / Regional Climate Model chains (GCM / RCM) used in this thesis over the 2041 – 2065 (future period 1: FP1) and 2071 – 2095 (future period 2: FP2) future periods.

GCM	**RCM**	**RCP (future period)**
CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN53	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
ICHEC-EC-EARTH	KNMI-RACMO22E	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
IPSL-IPSL-CM5A-MR	IPSL-INERIS-WRF331F	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
IPSL-IPSL-CM5A-MR	SMHI-RCA4	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
MOHC-HadGEM2-ES	SMHI-RCA4	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	historical (1981 – 2005) rcp45 (2041 – 2065) rcp85 (2071 – 2095)
MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	historical (1981 – 2005) rcp45 (2041 – 2065)

		rcp85 (2071 – 2095)

GCM: Global Climate Model, RCM: Regional Climate Model, RCP: Representative Concentration Pathway

The representative emission pathways 4.5 (RCP4.5) and 8.5 (RCP8.5) were employed in order to project harvest dates in two different time windows [future period 1 (FP1): 2041-2065 and future period 2 (FP2): 2071-2095]. The TX and TN scenarios for FP1 and FP2 were then constructed by adjusting the historical time series with the mean monthly changes (positive or negative) estimated between the baseline period (BP) and FP1 and FP2 time series during the period 1981–2005 (see Chapter 3 for more details).

4.3.3 Period definitions and variable selection

In order to investigate the relationships between harvest time, grape potential alcohol and acidity with air temperature, a preliminary analysis examining relationships between maximum (TX) and minimum (TN) temperatures over numerous time periods (e.g., March-September, April-September, March-July, June-July, ripening period, etc.) found that March-July, June-July, and the ripening period were the most important. As such TX and TN were used to compute the following variables:

For harvest time dependence on temperature, TX and TN were calculated for March-July (i.e., TXMarchJuly, TNMarchJuly) and also for the RP (i.e., TXRP, TNRP) (Conde et al. 2007). With regard to the sugar content of grapes at harvest (potential alcohol), TX and TN were calculated for the RP (TXRP, TNRP) since sugar accumulation in berries takes places entirely during this phase (Davies and Robinson, 1996). Finally, regarding the acid concentration of grapes at harvest, TX and TN were computed for June to July (i.e., TXJuneJuly, TNJuneJuly), corresponding on average to the first period of berry development where tartaric acid synthesis takes place (Iland and Coombe, 1988).

A preliminary analysis examining relationships between maximum (TX) and minimum (TN) with harvest, grape potential alcohol, and acidity found that maximum temperatures (TX) during TXMarchJuly, TXJuneJuly, and TXRP were most important. For this reason, all temperature analyses, thereafter, were executed only for the abovementioned periods.

4.3.4 Variety heat requirements

For assessing each varieties' heat requirements, growing degree-days (GDD, Winkler et al., 1974) were calculated using the standard formula:

$$GDD = \sum [\frac{TX + TN}{2}] - Tbase, \qquad \left\{ \begin{matrix} Tbase = 10°C \\ if\ \frac{TX + TN}{2} - Tbase\ \leq 0, 0 \end{matrix} \right\}$$

Then we calculated the heat requirements for each variety as the growing degree-days accumulated over the period 1st of April to the date that harvest was observed for each variety. The date of harvest was determined to be the day when, after a number of consecutive measurements, no further change in sugar accumulation occurred (Tomasi et al., 2011). Although the onset of the developmental cycle of the grapevine (i.e., budbreak) may occur slightly earlier or later (e.g., in mid-March or mid-April) depending on the variety, pruning date and region, a fixed starting point (i.e., 1st of April) for all varieties was selected. In order to calculate the GDD units of the studied varieties in Greece we used harvest dates records for the last 14 consecutive years for the majority of cases (except for the winegrape regions of Crete, with 11 years on average and the regions of Drama and Nemea, with 9 years).

4.3.5 Statistical analysis

Initially, to evaluate the consistency of varietal classification according to heat units, a K-mean clustering analysis was performed on the GDD series for each variety (Hartigan and Wong, 1979; Fraga et al., 2015). Three clusters were chosen to group the varieties studied into typical maturity grapevine classes (i.e., early, mid-season, and late ripening varieties).

A generalized linear model procedure was performed to investigate the relative influence of maximum temperature (TX) averaged over different periods (TXMarchJuly and TXRP) on harvest dates considering the three maturity groups

(Tomasi et al., 2011). The comparison was based on the AIC criterion. The temporal evolution of climatic and viticultural parameters (i.e., harvest dates and berry composition) as well as the relationships between each parameter and the selected temperature variable and period (i.e., TXMarchJuly, TXJuneJuly, and TXRP) were explored using the basic linear regression model (Y = a + bX). Statistical significance was evaluated at p-value < 0.05 and < 0.10.

In order to investigate the potential different harvest date responses to maximum air temperature variation among the varieties, the Z-Score was calculated for each variety by subtracting the mean harvest date shift considering all varieties [i.e., a negative value (for example -5) denotes earlier appearance by five days] and time series from harvest date shift of each variety and then dividing the difference by the standard deviation of the overall mean (i.e., 3.20) using the following formula:

$$z = \frac{x - \bar{x}}{S}$$

where $\bar{x}$ and S are the sample mean the standard deviation, respectively.

Mean harvest date shift (i.e., -5.26) was calculated as the summation of harvest date response (i.e., slope b from the linear regression models) to maximum air temperature of each variety over the period of records divided by the total number of varieties studied (i.e., 29). The harvest date shift of each variety is simply the slope of the linear regression model between harvest dates and maximum air temperature. As an example, the Z-Score for Xinomavro (mean harvest shift -2.7) is calculated as follows:

-2.7 - (-5.26) / 3.20 = 0.80

Therefore, the Z-Score of 0.80 for the Xinomavro variety indicates that the harvest response for the specific variety is above the mean harvest response with all varieties considered by 0.80 standard deviations.

Future harvest dates were estimated by accumulating GDD from 1st of April until the specific optimum heat requirement for each variety is reached. All computations, statistical analysis, and figures were performed and created using the R statistical software and R packages (R Core Team, 2014).

4.4 Results

4.4.1 Harvest dates and berry composition

The analysis showed an average harvest date in Greece by 4 September (± 8 days) across the regions and varieties (Table 4.3). White varieties are harvested on average by 29 August (ranging from 5 August to 23 September, ± 7 days) while red varieties are harvested on average 11 September (ranging from 6 September to 2 October, ± 9 days). The earliest variety to harvest is on average Muscat blanc in Samos (5 August) while the latest variety to harvest is on average Moschofilero in Tripoli (2 October). By groups, the early maturing varieties average 24 August (± 7 days) while mid and late maturing varieties average 3 September (± 8 days) and 19 September (± 9 days), respectively.

For those regions and varieties with potential alcohol data at harvest, the average across all varieties and regions was 13.4 % (± 0.5 %) with Moschofilero in Tripoli having the lowest values (11.4 %) and Merlot in Drama having the highest values (15.2 %) (Table 4.4). White varieties averaged slightly lower potential alcohol at harvest than do red varieties (12.7 % vs. 13.9 %). Similarly, early maturing varieties (12.8 %) averaged lower potential alcohol than mid or late maturing varieties (13.4 % and 13.7 %, respectively).

For acid concentrations at harvest, the average was 4.6 g/L varying ± 0.4 g/L across all regions and varieties (Table 4.5). The lowest acid concentration at harvest was observed with Syrah and Chardonnay in the Kavala region (3.5 g/L) while the highest acid concentration was observed with Chardonnay in the Maronia region (7.3 g/L). White varieties tend to have higher average acidity (5.0 g/L) compared to red varieties (4.4 g/L). Early maturing varieties averaged 5.0 g/L at harvest, while mid maturing varieties had lower average acidity at harvest (3.9 g/L) compared to later maturing varieties (4.9 g/L).

Table 4.3. Harvest date and air temperature details for the 29 Vitis Vinifera winegrape varieties used in this thesis (16 indigenous and 13 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for harvest dates are given in column 3. Trend direction (- or +) and slope (b coefficient) for harvest dates given in column 4. The relationships between harvest dates and TXMarchJuly [for the early (E) ripening varieties] and TXRP [for mid (M) and late (L) ripening varieties] are given in column 5 with the values representing days per 1 °C. The period of record for harvest dates is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

				Harvest Date/ TXmarchJuly and TXRP	
Region	**Average (Standard Deviation)**	**Harvest Date Trends**	**Region**	**Slope**	**Period of Record**
Muscat blanc ^{E,W,b}	Samos	5 August (5.8)	**-0.35**	**-5.43**	1985-2017
Sylvaner ^{E,W,b}	Crete	18 August (9.8)	**-1.76**	**-11.97**	2003-2013
Sauvignon blanc ^{E,W,b}	Drama	16 August (6.0)	**-1.07**	**-5.87**	2004-2017
	Kavala	20 August (4.2)	-0.15	**-3.59**	2001-2017

	Maronia	19 August (3.0)	*-0.41*	**-2.55**	2005-2017
	Crete	17 August (10.2)	**-2.05**	**-12.26**	2003-2013
Chardonnay [E,W,b]	Drama	22 August (7.7)	**-1.15**	**-7.19**	2004-2017
	Kavala	29 August (5.3)	-0.30	**-4.82**	2002-2017
	Tripoli	9 September (7.3)	-0.43	**-4.79**	2001-2017
	Maronia	15 August (3.8)	-0.32	**-2.78**	2005-2017
	Crete	14 August (9.4)	**-1.88**	**-11.81**	2003-2013
Malagouzia [E,W,a]	Chalkidiki	19 August (4.2)	**-0.48**	**-3.13**	2001-2017
Traminer [E,W,b]	Tripoli	15 September (7.4)	-0.29	**-4.58**	2001-2017
Liatiko [E,R,a]	Crete	26 August (9.5)	-0.92	**-11.09**	2003-2011
Malvasía Aromática [E,W,b]	Crete	25 August (11.7)	*-1.84*	**-13.66**	2003-2013
Riesling [E,W,b]	Tripoli	20 September (8.7)	*-0.71*	-2.24	2001-2017

Muscat of Alexandria M,W,b	Limnos	4 September (9.3)	**-0.56**	**-4.46**	1974-2017
Vilana M,W,a	Crete	31 August (8.8)	***-1.02***	-5.70	2003-2016
Merlot M,R,b	Drama	1 September (5.0)	-0.19	**-2.65**	2004-2017
	Kavala	29 August (6.1)	**-0.66**	**-3.70**	2001-2017
	Naousa	27 August (7.5)	-0.21	**-2.81**	1991-2017
	Maronia	26 August (6.3)	-0.40	-2.07	2005-2017
Athiri M,W,a	Rodos	23 August (4.8)	**0.36**	**2.36**	1990-2017
Moschofilero M,W,a	Tripoli	2 October (6.5)	***-0.55***	**-2.11**	2001-2017
Plyto M,W,a	Crete	2 September (5.1)	-0.72	***-4.38***	2006-2016
Sangiovese M,R,b	Drama	8 September (12.2)	-1.18	**-4.94**	2004-2017
Vidiano M,W,a	Crete	4 September (12.0)	-0.23	-6.61	2008-2016

Assyrtiko [M,W,a]	Santorini	10 August (5.2)	-0.41	-2.08	1993-2017
	Drama	8 September (8.0)	-0.50	-4.27	2004-2017
	Kavala	18 September (7.2)	-1.14	-3.75	2002-2017
	Chalkidiki	25 August (5.5)	-0.21	-2.11	2001-2017
Syrah [M,R,b]	Kavala	10 September (7.8)	-1.23	-4.17	2002-2017
	Naousa	8 September (10.3)	-0.48	-4.68	1991-2017
	Nemea	10 September (9.9)	-1.82	-5.28	2004-2017
	Crete	4 September (10.6)	-1.11	-8.94	2003-2013
CabernetSauvignon [L,R,b]	Drama	18 September (6.5)	-0.79	-3.13	2004-2017
	Kavala	10 September (8.3)	-1.42	-4.41	2002-2017

Kotsifali [L,R,a]	Crete	15 September (8.3)	0.12	**-8.97**	2003-2013
Agiorgitiko [L,R,a]	Drama	23 September (9.8)	-1.20	**-3.70**	2005-2016
	Kavala	17 September (6.8)	**-1.07**	**-3.54**	2002-2017
	Nemea	17 September (9.5)	**-1.76**	**-4.29**	2004-2017
Limnio [L,R,a]	Maronia	10 September (9.9)	-0.12	**-4.88**	2005-2017
Mandilari [L,R,a]	Crete	17 September (8.5)	***-0.98***	**-8.01**	2003-2016
Nebbiolo [L,R,b]	Drama	20 September (12.7)	**-1.69**	**-4.44**	2004-2017
Roditis [L,R,a]	Nemea	19 September (9.4)	-0.61	**-3.55**	1998-2016
	Aigialia	1 October (8.1)	-0.45	**-3.56**	2005-2017

Daphni [L,W,a]	Crete	23 September (6.7)	-0.02	-5.70	2006-2015
Mavrodaphni [L,R,a]	Pyrgos	16 September (9.7)	-0.75	-4.48	1989-2017
Xinomavro [L,R,a]	Naousa	23 September (6.3)	*-0.17*	-2.75	1980-2017
Summary	Early	24 August (7.1)	-0.88	-6.73	
	Mid	3 September (7.8)	-0.64	-3.81	
	Late	19 September (8.6)	-0.78	-4.67	
	Red	11 September (8.6)	-0.83	-4.78	
	White	29 August (7.1)	-0.70	-5.21	
	International	30 August	-0.90	-5.53	
	Indigenous	10 September	-0.58	-4.38	
	Overall	4 September (7.8)	-0.76	-5.01	

Table 4.4. Potential alcohol and air temperature details for the 12 Vitis vinifera winegrape varieties used in this thesis (7 indigenous and 5 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for potential alcohol are given in column 3. Trend direction (- or +) and slope (b coefficient) for potential alcohol given in column 4. The relationships between potential alcohol and TXRP are given in column 5 with the values representing % per 1 °C. The period of record for potential alcohol is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

Variety	Region	Average (Standard Deviation)	Potential Alcohol Trends (%)	Potential Alcohol/TXRP Slope	Period of Record
Sauvignon blanc ^{E,W,b}	Kavala	13.3 (0.5)	**0.06**	**0.32**	2002-2017
Chardonnay ^{E,W,b}	Kavala	13.5 (0.2)	0.02	**0.11**	2002-2017
	Maronia	12.1 (0.7)	0.05	0.26	2005-2017
Malagouzia ^{E,W,a}	Chalkidiki	12.5 (1.1)	**0.13**	0.14	2001-2017
Merlot ^{M,R,b}	Drama	15.2 (0.6)	0.07	**0.32**	2005-2016
	Kavala	14.4 (0.4)	**0.05**	**0.27**	2002-2017
Moschofilero ^{M,W,a}	Tripoli	11.4 (0.4)	**0.05**	**0.16**	2003-2017
Vidiano ^{M,W,a}	Crete	12.9 (0.6)	0.05	0.10	2008-2016
Assyrtiko ^{M,W,a}	Kavala	13.3 (0.4)	0.02	0.09	2002-2017
	Chalkidiki	12.9 (0.8)	**0.07**	**0.35**	2001-2017
Syrah ^{M,R,b}	Kavala	13.0 (0.6)	**0.07**	**0.26**	2002-2017

	Nemea	14.0 (0.7)	**0.09**	***0.23***	2004-2017
Cabernet Sauvignon [L,R,b]	Drama	14.7 (0.4)	0.02	**0.14**	2005-2016
	Kavala	14.2 (0.5)	**0.07**	**0.23**	2002-2017
Agiorgitiko [L,R,a]	Drama	14.4 (0.7)	0.08	***0.17***	2005-2016
	Kavala	13.7 (0.5)	**0.06**	**0.21**	2002-2017
	Nemea	13.6 (0.5)	**0.09**	**0.20**	2004-2017
Mavrodaphni [L,R,a]	Pyrgos	12.4 (0.4)	**0.03**	**0.09**	1989-2017
Xinomavro [L,R,a]	Naousa	13.1 (0.4)	**0.03**	0.04	1993-2017
Summary	Early	12.8 (0.6)	0.07	0.21	
	Mid	13.4 (0.5)	0.06	0.22	
	Late	13.7 (0.5)	0.05	0.15	
	Red	13.9 (0.5)	0.06	0.20	
	White	12.7 (0.6)	0.06	0.19	
	International	13.8 (0.5)	0.06	0.24	
	Indigenous	13.2 (0.6)	0.06	0.15	
	Overall	13.4 (0.5)	0.06	0.19	

Table 4.5. Acidity and air temperature details for the seven Vitis vinifera winegrape varieties used in this thesis (2 indigenous and 5 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Averages and standard deviation (in parenthesis) for acidity levels are given in column 3. Trend direction (- or +) and slope (b coefficient) for acidity levels given in column 4. The relationships between acidity levels and TXJuneJuly are given in column 5 with the values representing g/L per 1 °C. The period of record for acidity levels is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

Variety	**Region**	**Average (Standard Deviation)**	**Acid Trends (g/L)**	**Acid/TXJune-July Slope**	**Period of Record**
Sauvignon blanc [E,W,b]	Kavala	4.2 (0.3)	-0.02	-0.09	2002-2017
Chardonnay [E,W,b]	Kavala	3.5 (0.3)	-0.01	-0.07	2002-2017
	Maronia	7.3 (0.9)	-0.10	-0.31	2005-2017
Merlot [M,R,b]	Drama	4.4 (0.7)	***-0.09***	-0.09	2005-2016
	Kavala	3.8 (0.3)	**-0.04**	***-0.16***	2002-2017
Syrah [M,R,b]	Kavala	3.5 (0.3)	-0.01	**-0.21**	2002-2017
CabernetSauvignon [L,R,b]	Kavala	3.9 (0.3)	-0.02	-0.05	2002-2017

Agiorgitiko [L,R,a]	Kavala	3.7 (0.3)	**-0.04**	**-0.23**	2002-2017
Xinomavro [L,R,a]	Naousa	7.0 (0.4)	***-0.03***	-0.11	1993-2017
Summary	Early	5.0 (0.5)	-0.04	-0.16	
	Mid	3.9 (0.4)	-0.05	-0.15	
	Late	4.9 (0.3)	-0.03	-0.13	
	Red	4.4 (0.4)	-0.04	-0.14	
	White	5.0 (0.5)	-0.04	-0.16	
	International	4.4 (0.4)	-0.04	-0.14	
	Indigenous	5.4 (0.3)	-0.04	-0.17	
	Overall	4.6 (0.4)	-0.04	-0.15	

4.4.2 Variety heat requirements and clustering

The 29 varieties averaged 1750 GDD from the 1st of April until the time-point at which, after a number of consecutive measurements, no further change in sugar accumulation occurred and the fruit was harvested (Tomasi et al., 2011). There was a range in 644 GDD for the lowest required to harvest for Muscat blanc (1425) to the highest required to harvest for Xinomavro (2069) (Figure 4.2, Table 4.6).

Table 4.6. Growing degree days (GDD) variety-mean, maximum and minimum values for the 29 varieties studied. GDD calculated with a base temperature of 10°C (see text for further details). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

Variety	meanGDD	maxGDD	minGDD
Muscat blanc ^{E,W,b}	1425	1526	1240
Sylvaner ^{E,W,b}	1489	1643	1376
Sauvignon blanc ^{E,W,b}	1524	1726	1331
Chardonnay ^{E,W,b}	1538	1850	1331
Malagouzia ^{E,W,a}	1541	1656	1468
Traminer ^{E,W,b}	1583	1719	1460
Liatiko ^{E,R,a}	1590	1734	1481
Malvasía Aromática ^{E,W,b}	1592	1773	1465
Riesling ^{E,W,b}	1617	1772	1472
Muscat of Alexandria ^{M,W,b}	1680	1813	1568
Vilana M,W,a	1695	1877	1528
Merlot M,R,b	1705	1857	1519
Athiri M,W,a	1722	1795	1611
Moschofilero ^{M,W,a}	1738	1876	1577

Plyto M,W,a	1745	1831	1597
Sangiovese [M,R,b]	1772	1900	1568
Vidiano [M,W,a]	1775	2016	1628
Assyrtiko [M,W,a]	1783	2076	1517
Syrah M,R,b	1801	2067	1586
Cabernet-Sauvignon L,R,b	1872	2001	1737
Kotsifali [L,R,a]	1881	2074	1716
Agiorgitiko [L,R,a]	1883	2019	1750
Limnio L,R,a	1895	2098	1753
Mandilari [L,R,a]	1915	2074	1819
Nebbiolo [L,R,b]	1919	2101	1590
Roditis [L,R,a]	1986	2157	1843
Daphni L,W,a	1999	2119	1822
Mavrodaphni [L,R,a]	2011	2178	1852
Xinomavro [L,R,a]	2069	2241	1907

Vintage to vintage variations in GDD to reach harvest average 96 units over all varieties and regions, ranging from a low of 53 units for Malagouzia to a high of 153 units for Assyrtiko.

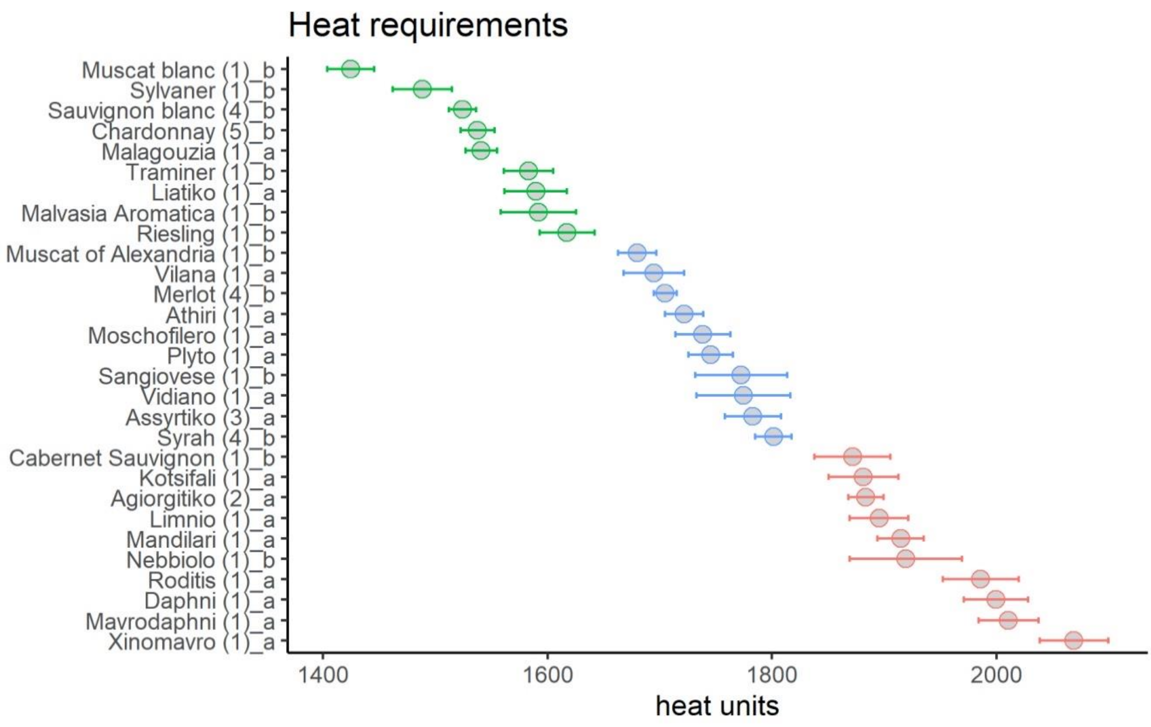

Figure 4.2. Heat requirements for the 29 winegrape varieties (16 indigenous and 13 international) cultivated in Greece. Heat units are estimated as mean growing degree-days (GDD) from April 1st to the harvest date. Y-axis shows the variety along with the number of vineyard sites used in each case (numbers in parenthesis). Letters a, b indicates indigenous and international winegrape varieties, respectively. X-axis shows the mean GDD units (see Materials and Methods). Horizontal bars represent the lowest and highest values in each case. Varieties are grouped according to the K-means cluster analysis [Cluster 1: early ripening varieties (green color), Cluster 2: mid-ripening varieties (blue color) and Cluster 3: late ripening varieties (red color)].

A Kmeans clustering analysis was performed on the GDD units required to reach maturity (harvest) for the 29 grapevine varieties. Figure 4.2 depicts three variety groups according to the GDD requirements to reach harvest. Cluster 1 consists of 9 winegrape varieties (2 indigenous and 7 international) with the lowest GDD units required for harvest (i.e., Muscat blanc, Sylvaner, Sauvignon blanc, Chardonnay, Malagouzia, Traminer, Liatiko, Malvasía Aromática and Riesling). These varieties are classified as early ripening varieties and ranged from 1425 (Muscat blanc) to 1617 (Riesling) GDD units. The second cluster groups 10 mid-season varieties (6 indigenous and 4 international) varying from 1680 (Muscat of Alexandria) to 1801 (Syrah) GDD units to achieve full maturity. Cluster 3 comprises 10 winegrape varieties (8 indigenous and 2 international). This cluster corresponds to late ripening varieties requiring from 1872 units for Cabernet Sauvignon to 2069 units for Xinomavro in order to achieve full maturity and are harvested in late September (on average). Comparing GDD units between the 3 clusters, cluster 3 exhibited a wider range of 197 GDD units, while cluster 2 and cluster 1 showed ranges of 121 and 192 GDD units, respectively.

4.4.3 Trends in grapevine parameters and relationships with climate

Overall, while the harvest in Greece was observed to average 4 September, it varied from 5 August (i.e., Muscat blanc in Samos) to 2 October (Moschofilero in Tripoli) (Table 4.3). Although the vineyards greatly varied in their latitude, elevation, and topography, the international varieties are skewed towards earlier ripening as compared to indigenous Greek varieties (Figure 4.3). The average harvest date for the international varieties is 30 August compared to 10 September for the Greek varieties (Figure 4.3).

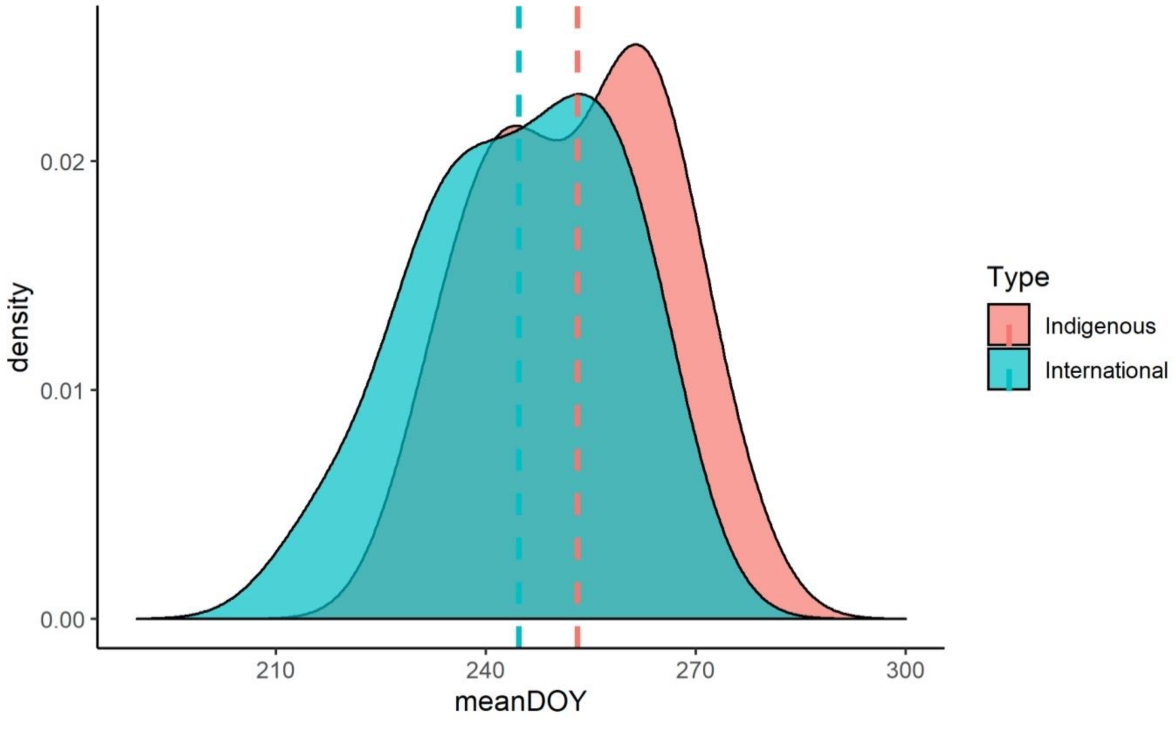

Figure 4.3. Variation in harvest dates across the 29 winegrape varieties examined (16 indigenous and 13 international) and currently cultivated in Greece. Expressed as DOY (day of year). Vertical dashed blue (red) lines indicate the mean harvest date for the international (indigenous) varieties.

The overall trend analysis revealed earlier harvest occurrence (negative trends) in 47 out of 49 cases with 18 statistically significant at p-value < 0.05 and 9 at p-value < 0.10 (Table 4.3). Two cases showed a slight delay in harvest timing, with only the variety Athiri on Rodos being statistically significant. The harvest dates for the early ripening varieties (16 cases) advanced, on average, by -0.88 days per year while harvest dates for the mid-season (19 cases) and late ripening (14 cases) varieties occurred earlier by -0.64 and -0.78 days per year, respectively (Table 4.3). Additionally, the harvest date evolutions of the international varieties (17 statistically significant cases) showed a stronger earlier occurrence (-1.17 days per year, on average) than the respective indigenous varieties (11 statistically significant cases, -0.72 days per year, on average). Averaged across all varieties and periods, harvest commenced significantly earlier by -0.76 days per year (Table 4.3).

Harvest date linear regression analysis revealed statistically significant negative relationships with TX during ripening in 44 out of 49 cases (Table 4.3). An additional 4 cases exhibited negative but non-significant relationships over time, while only one statistically significant case found delayed harvest under warmer ripening conditions (i.e., Athiri on Rodos). Averaged over all varieties and regions, harvest dates exhibited a five-day earlier occurrence per 1 °C (Table 4.3) and averaged 11 days earlier over the varying time periods of the data. White varieties showed slightly greater sensitivity to warmer conditions compared to red varieties (-5.21 vs. -4.78 days per 1 °C). By variety grouping, early varieties were most sensitive with nearly seven days per 1 °C while late varieties responded slightly more than mid ripening varieties (-4.67 vs. -3.81 days per 1 °C). In addition, international varieties responded more to warmer ripening periods (-5.53 days per 1 °C) compared to indigenous varieties (-4.38 days per 1 °C).

Over all varieties and regions with potential alcohol data, the trend average was 0.06 % per year with red and white varieties having same trends (0.06 % per year) and early and mid-maturing varieties exhibiting higher trends than later maturing varieties (Table 4.4). During the last couple of decades, potential alcohol at harvest has risen approximately 0.40 % over these varieties and locations. Potential alcohol levels exhibited significant positive relationships with TX during the ripening period in 14 out of 19 cases, while an additional five cases exhibited positive but non-significant associations with TXRP (Table 4.4). The average slope across all regions and varieties was 0.19 % per 1 °C warmer ripening periods, with little difference between white and red varieties, but with late-ripening varieties exhibiting a lower response than early- or mid-ripening varieties (Table 4.4). International varieties responded slightly higher than indigenous varieties with 0.24 % vs. 0.17 % per 1 °C warmer ripening periods.

Acid concentrations across all locations and varieties trended lower over the time periods with -0.04 g/L per year on average, with four cases statistically significant (Table 5). No differences in the trends were found for white vs. red varieties, however mid-maturing varieties exhibited a moderately higher trend (-0.05 g/L) than either early (-0.04 g/L) or late (-0.03 g/L) varieties. During the study period acid concentrations at harvest declined on average -0.46 g/L. Acid concentrations presented significant negative relationships with TXJuneJuly in 3 out of 9 cases with 6 more cases exhibiting negative but non-significant associations with maximum air temperatures during the summer (Table 4.5). The average slope between acid concentrations and TXJuneJuly was -0.15 g/L per 1 °C warmer mid-summer temperatures. Both white varieties and early varieties showed higher trends to lower acid concentrations compared to red or mid to late ripening varieties. However, there was no difference in acid concentrations between international and indigenous varieties.

Regarding maximum air temperature trends during the March-July (for the early ripening varieties) and RP (for the mid and late ripening varieties), the analysis revealed warmer conditions in 48 out of 49 cases with only one exception (Table 4.7). Of the statistically significant warming trends, positive ones were observed in 29 out of 48 cases. With regard to the average trends between the March-July and ripening period, the ripening period warming rate was +0.09 °C higher than the rate during the March-July period (0.16 vs. 0.07 °C, respectively, Table 4). It also important to note that during the period of records for these locations TN and average air temperature were also correlated with viticultural parameters but with lower magnitude.

Table 4.7. Air temperature details for the 29 Vitis vinifera winegrape varieties used in this thesis (16 indigenous and 13 international varieties) for the principal winegrape regions in Greece. Varieties and regions presented in the first two columns. Trend direction (- or +) and slope (b coefficient) for TXMarchJuly [for the early (E) ripening varieties] and TXRP [for mid (M) and late (L) ripening varieties] are given in column 3. The period of record for maximum air temperature is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties.

Variety	**Region**	**TXMarchJuly and TXRP trends (°C)**	**Period of Record**
Muscat blanc [E,W,b]	Samos	***0.02***	1985-2017
Sylvaner [E,W,b]	Crete	***0.12***	2003-2013
Sauvignon blanc [E,W,b]	Drama	0.03	2004-2017
	Kavala	***0.06***	2001-2017
	Maronia	0.07	2005-2017
	Crete	***0.12***	2003-2013
Chardonnay [E,W,b]	Drama	0.03	2004-2017
	Kavala	**0.08**	2002-2017
	Tripoli	0.04	2001-2017
	Maronia	0.07	2005-2017
	Crete	***0.12***	2003-2013
Malagouzia [E,W,a]	Chalkidiki	0.07	2001-2017
Traminer [E,W,b]	Tripoli	0.04	2001-2017

Liatiko [E,R,a]	Crete	0.10	2003-2011
Malvasía Aromática [E,W,b]	Crete	*0.12*	2003-2013
Riesling [E,W,b]	Tripoli	0.04	2001-2017
Muscat of Alexandria [M,W,b]	Limnos	**0.11**	1974-2017
Vilana [M,W,a]	Crete	0.03	2003-2016
Merlot [M,R,b]	Drama	**0.14**	2004-2017
	Kavala	**0.12**	2001-2017
	Naousa	**0.09**	1991-2017
	Maronia	0.08	2005-2017
Athiri [M,W,a]	Rodos	**0.06**	1990-2017
Moschofilero [M,W,a]	Tripoli	*0.19*	2001-2017
Plyto [M,W,a]	Crete	-0.01	2006-2016
Sangiovese [M,R,b]	Drama	**0.27**	2004-2017
Vidiano [M,W,a]	Crete	0.06	2008-2016
Assyrtiko [M,W,a]	Santorini	**0.09**	1993-2017
	Drama	*0.19*	2004-2017
	Kavala	**0.30**	2002-2017
	Chalkidiki	0.09	2001-2017
Syrah [M,R,b]	Kavala	**0.28**	2002-2017
	Naousa	**0.11**	1991-2017
	Nemea	**0.21**	2004-2017

	Crete	0.03	2003-2013
Cabernet Sauvignon [L,R,b]	Drama	**0.26**	2004-2017
	Kavala	**0.30**	2002-2017
Kotsifali [L,R,a]	Crete	0.01	2003-2013
Agiorgitiko [L,R,a]	Drama	**0.41**	2005-2016
	Kavala	**0.29**	2002-2017
	Nemea	**0.26**	2004-2017
Limnio [L,R,a]	Maronia	0.12	2005-2017
Mandilari [L,R,a]	Crete	0.08	2003-2016
Nebbiolo [L,R,b]	Drama	**0.42**	2004-2017
Roditis [L,R,a]	Nemea	**0.19**	1998-2016
	Aigialia	0.15	2005-2017
Daphni [L,W,a]	Crete	0.10	2006-2015
Mavrodaphni [L,R,a]	Pyrgos	**0.14**	1989-2017
Xinomavro [L,R,a]	Naousa	**0.07**	1980-2017

Figure 4.4 shows the response of harvest date of each variety as a function of the average harvest date shift (Z-Score), with all varieties considered. Harvest dates for the mid-season and late ripening varieties (7 out of 10 cases for each) generally responded at a slower rate (positive index) to changes in temperature compared to early varieties (with the exception of Traminer, Riesling and Malagouzia). In addition, the majority of the varieties in the winegrape region of Crete (10 out of 12 cases) (both indigenous and international) showed the strongest responses to temperature (negative index).

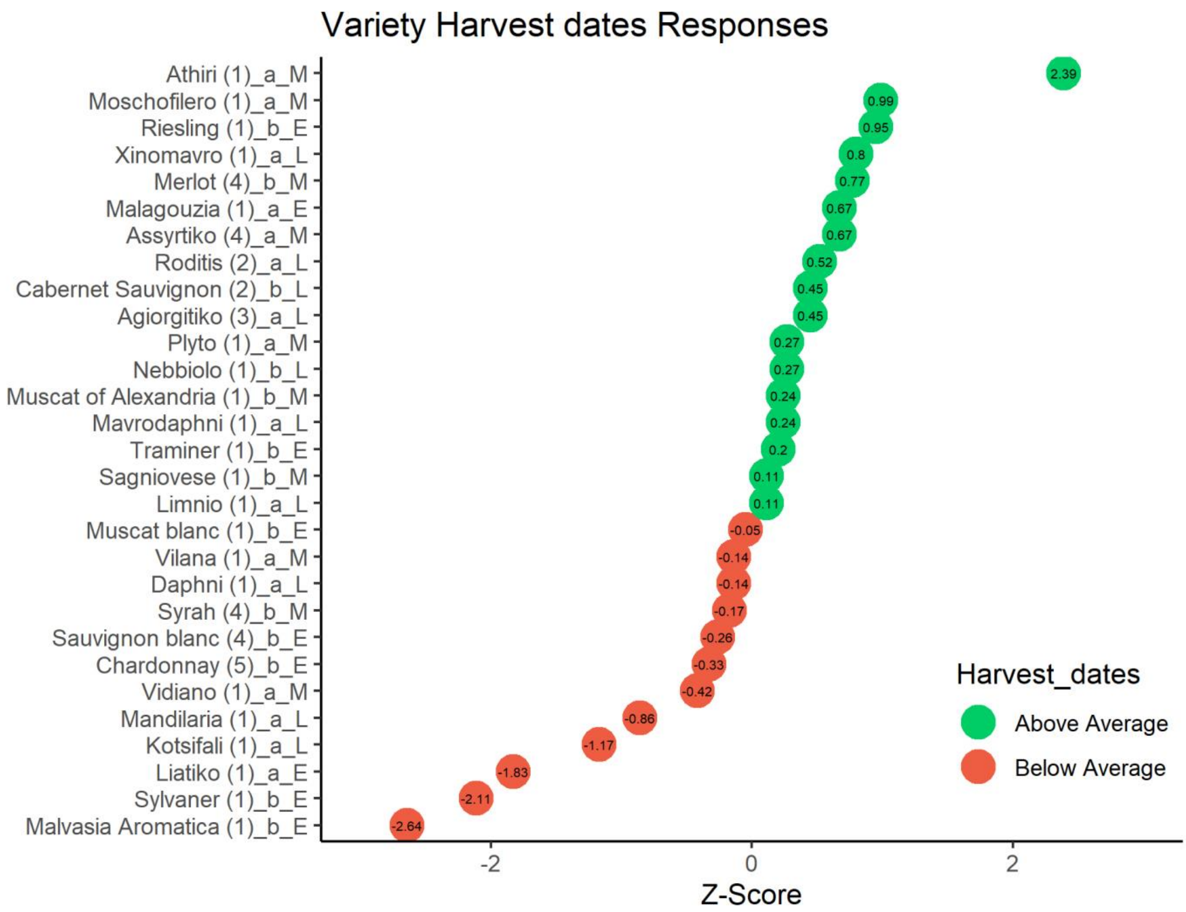

Figure 4.4. Harvest date responses for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece. Y-axis shows the variety along with the number of vineyard sites used in each case (numbers in parenthesis). Letters a, b indicates indigenous and international winegrape varieties, while E, M and L represent early, mid-season and late ripening varieties, respectively. X-axis shows the Z-Score (see Materials and Methods). The varieties with Z-Score above (below) zero are marked green (red) respectively.

4.4.4 Future climate change impacts on harvest dates

In order to project future harvest responses, the GDD heat units were calculated for a set of 29 (16 indigenous and 13 international) winegrape varieties for an ensemble future climate with two emission pathways (i.e., RCP4.5 and RCP8.5), derived from 10 regional climate models. The results are presented in Figure 4.5 and Figure 4.6. For the FP1 period (i.e., 2041-2065) and under the lower emission pathway (i.e., RCP4.5), the harvest dates of the late ripening varieties, which currently occur in mid-September, are projected to occur approximately 20 days earlier compared to the CP, while under FP2 the harvest is further advanced by 6 days. The higher emission pathway (i.e., RCP8.5) led to even more noticeable shifts. Overall, harvest for the late ripening varieties is projected to become earlier by over a month (i.e., almost 40 days) by the end of the century (FP2). The indigenous varieties of Mavrodaphni, Agiorgitiko, Roditis, Xinomavro and Limnio, exhibited the lower responses (19 and 35 days earlier on average, according to RCP4.5 and RCP8.5, respectively, Figures 4.5 and 4.6) while three varieties from Crete (i.e., Mandilaria, Kotsifali and Daphni) along with the international varieties of Cabernet Sauvignon and Nebbiolo showed the more pronounced shifts. The mid-season varieties (10 cases), harvested today in early-September, are projected to significantly advance by 17 days, on average, over the FP1 and under the RCP4.5 pathway. In the FP2, the harvest is projected to occur 22 days earlier. According to RCP8.5, two mid-season varieties (i.e., Moschofilero and Sangiovese) are projected to be over 40 days earlier during FP2. Finally, the harvest dates of the early ripening varieties (9 cases), which are currently occurring in the late August (on average), is projected to occur approximately two weeks earlier in FP1 and under the RCP4.5 pathway. The results were more pronounced when the analysis was based on the higher emission pathway and FP2 (34 days earlier) placing harvest in mid to late July.

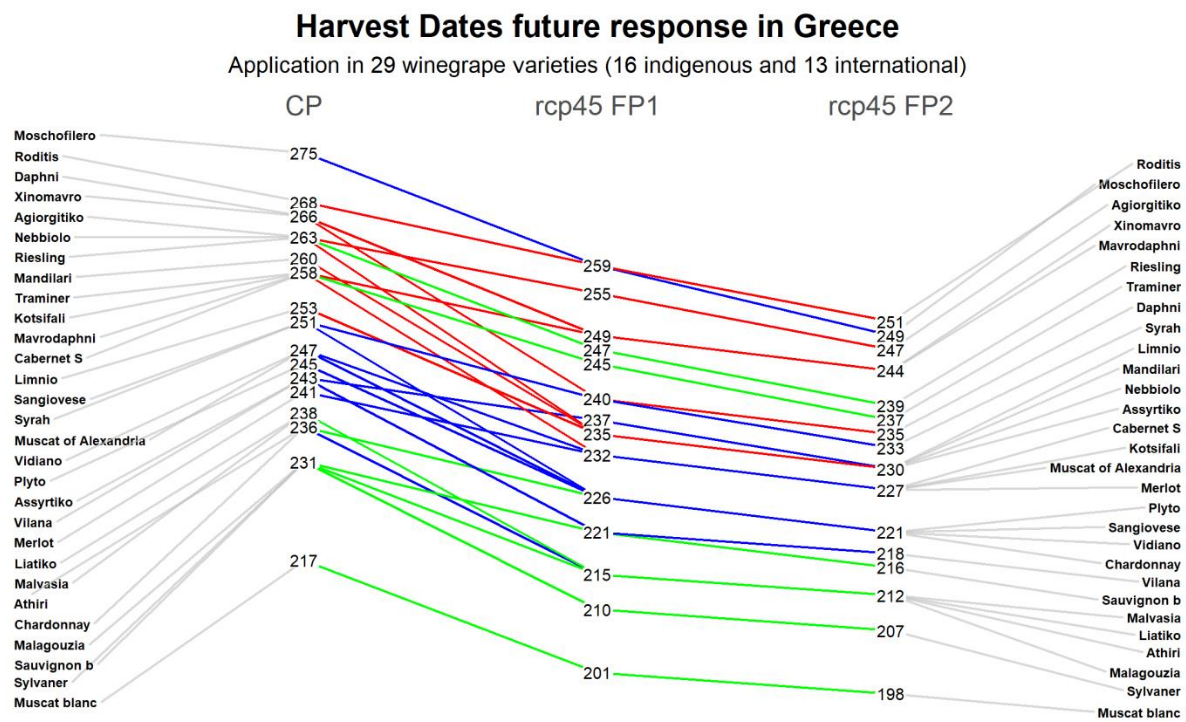

Figure 4.5. Current and projected harvest dates for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece. The left vertical axis (*i.e.*, Y-axis) shows the current time of maturity (CP) of the selected varieties while the right vertical axis shows the future projection of the date of maturity. The horizontal axis (*i.e.*, X-axis) shows the mean DOY evolution in days according to the RCP4.5 emission pathway and time windows (FP1: 2041-2065) used in this thesis. Early, mid-season and late ripening varieties are presented with green, blue, and red lines, respectively. Numbers represents the time of maturity according to Julian date [(mean DOY) *e.g.*, 275: 02 October, etc.)] (created using the R package CGPfunctions, Chuck Powell, 2019).

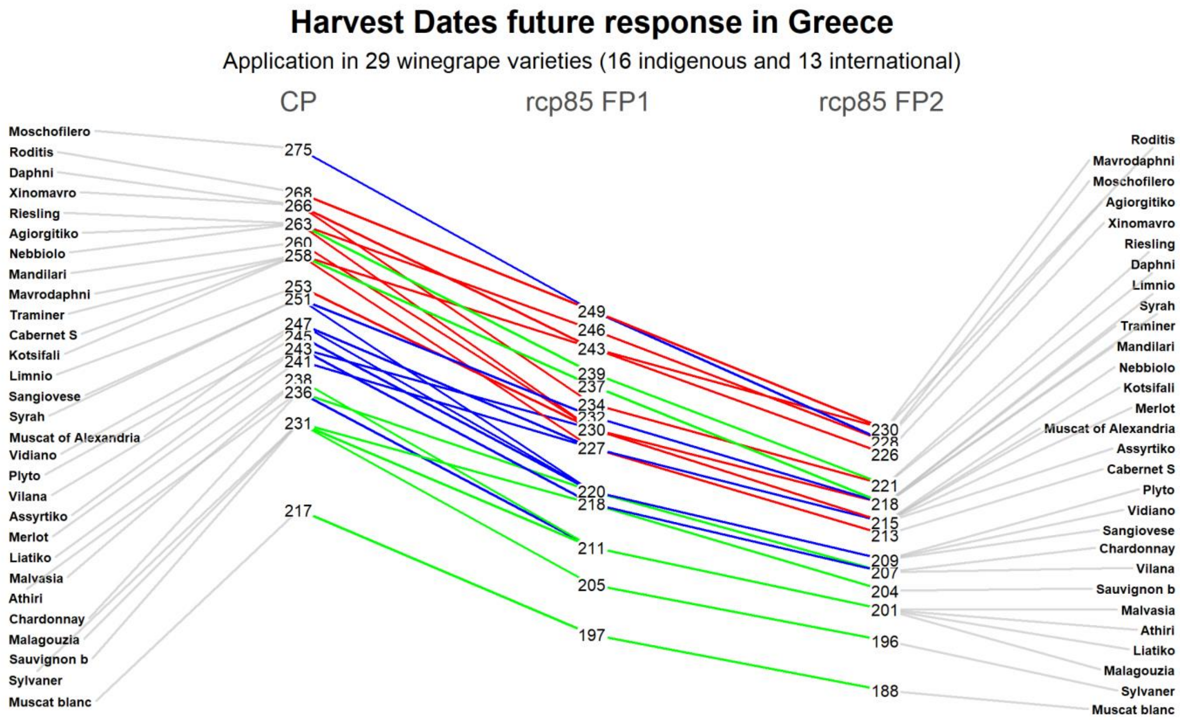

Figure 4.6. Current and projected harvest dates for the 29 winegrape varieties studied (16 indigenous and 13 international) in Greece. The left vertical axis (i.e., Y-axis) shows the current time of maturity (CP) of the selected varieties while the right vertical axis shows the future projection of the date of maturity. The horizontal axis (i.e., X-axis) shows the mean DOY evolution in days according to the RCP8.5 emission pathway and time windows (FP1: 2071-2095) used in this thesis. Early, mid-season and late ripening varieties are presented with green, blue, and red lines, respectively. Numbers represents the time of maturity according to Julian date [(mean DOY) e.g., 275: 02 October, etc)] (created using the R package CGPfunctions, Chuck Powell, 2019).

4.5 Discussion

This chapter adds to the developing knowledge of the relationships between climate (historical and future) and regional wine production in Greece. Greece is a predominately warm to hot climate region for wine production, exhibiting a diversity of landscapes across islands, coastal zones, and mainland elevated areas providing suitable conditions for a wide range of varieties and wine styles (Anderson *et al.*, 2014). Koufos *et al.* (2014) and the results from Chapter 3 identified that significant trends in climate parameters and viticulture–climate relationships were more evident for island than mainland locations. Moreover, areas with late ripening varieties were less sensitive to changes in climate. The same literature sources also suggest significant climate shifts towards warmer and drier conditions across all regions in Greece in the future.

The results from this chapter found earlier harvests, increased potential alcohol levels and decreased acidity for both indigenous and international varieties cultivated in Greece. These changes were associated with changes in temperature across the regions studied. In a similar manner, Neethling *et al.* (2012) found significant increasing (decreasing) trends in sugar levels (acid concentrations) in six white and red winegrape varieties in the *vallée de la Loire* (France) that explained (nearly 70 %) by the variability in climatic conditions. Higher potential alcohol levels associated with lower titratable acidity, such as those observed in Greece and other regions around the world, could have detrimental impacts on the compositional ratio within the ripening fruit leading to unbalanced wines and lower quality (van Leeuwen *et al.*, 2004; van Leeuwen and Destrac Irvine, 2017).

The harvest dates of the early ripening varieties were associated more with the variations in maximum air temperatures during March to July, while mid and late ripening varieties appeared to correlate more by maximum air temperatures during the ripening period. In addition, the late ripening, mostly indigenous, varieties were less associated by temperature increases compared to international varieties. Furthermore, the correlation between harvest dates and air temperature (minimum, maximum and average) during different periods [(i.e., April – October, April – September, March – September for the mid and late ripening varieties) and (i.e., April – September, April – August, March – August for the early ripening varieties)] showed that TX during March – September (for the mid-season and late ripening varieties) and March – August (for the early ripening varieties) was significantly higher. It is also important to note that the correlation between air temperature (maximum, minimum and average) during April – October and March – September is also very strong (r > 0.97) enhancing the possibility that the growing season in Greece moved forward or compressed for almost a month during the last decades (Figure 4.7).

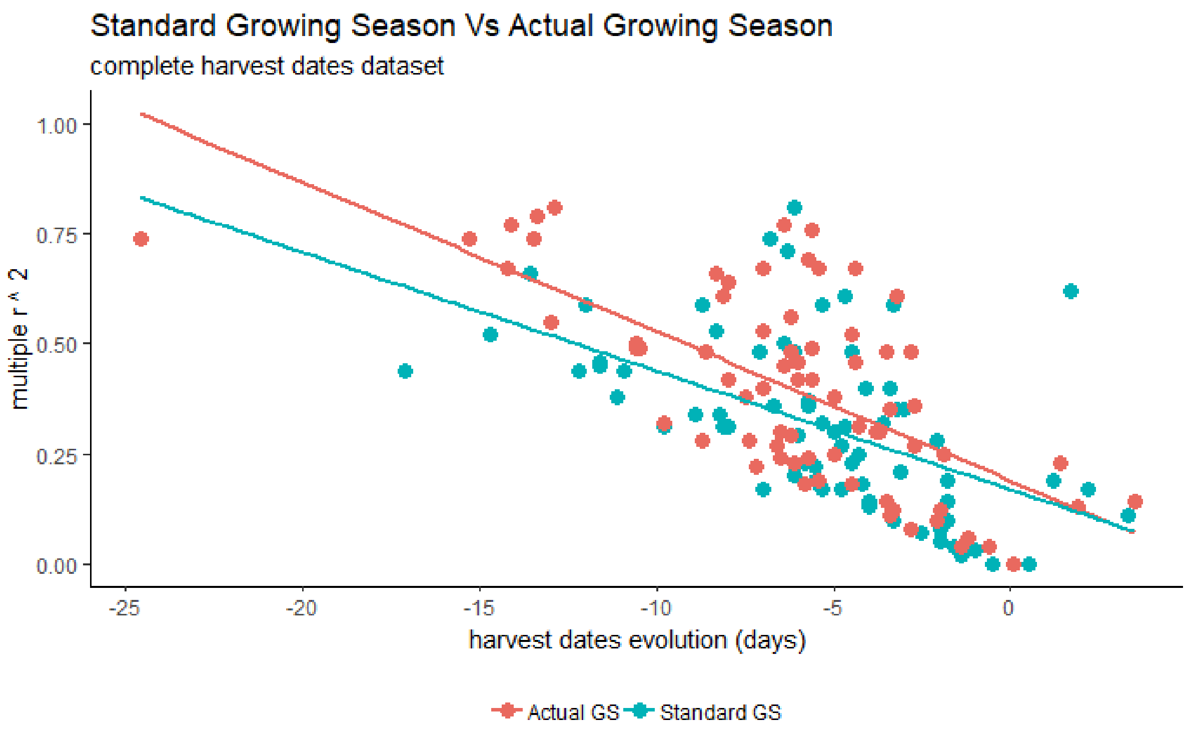

Figure 4.7. Comparison between the relative effect of different periods on harvest dates variation. The left vertical axis (i.e., Y-axis) shows the multiple r^2. The horizontal axis (i.e., X-axis) shows the mean harvest date (in days).

Similarly, in the Veneto region of Italy, Tomasi et al. (2011) observed that early ripening varieties appeared to associate more strongly than the respective mid-season and late ripening varieties to warmer conditions. In general, late ripening varieties often experience a maturation period that does not allow sugars to accumulate to maximum levels, thus warming would result in an improved sugar/acid ratio at harvest but without, or with a smaller shift in harvest timing. On the contrary, for early ripening varieties that consistently reach high sugar levels, warmer temperatures would necessarily lead to an earlier picking of grapes to avoid excessive potential alcohol levels in the wines. However, Ruml et al. (2016) reported for Serbia a significant advance in the beginning of harvest in all varieties, by 0.6 days per year on average due to higher average temperatures, showing moderate variability between varieties. Also, according to van Leeuwen and Darriet (2016) the reported harvest shifts related to increasing temperatures are the result of both the general temperature rise (warmer conditions during the whole vine growth cycle) and the resulting advancement of phenological stages, placing the ripening period during a hotter period of the year. This is mostly true for mid-season to late ripening varieties. For early ripening varieties, since maturation already takes place under warm to hot conditions (mid to late August), it is expected that harvest shifts to earlier dates would not significantly affect the thermal conditions of the final period of berry development. As such, changes in harvest dates are probably less related to an increment of the ripening speed but mostly to a general advancement of the whole cycle of grapevine phenology and likely very important during the véraison stage, marking the onset of berry ripening.

It is important to note that harvest needs to be considered carefully since it is not an actual phenological stage, but an event that is based on human judgement which may also depend on other factors such as wine style preference, flavor preference, seed ripening, available labor to harvest the fruit, room in the winery to accept the fruit, etc. (Mira de Orduña, 2010). However, long-term harvest dates have been used in several studies to reconstruct air temperature during the growing season in the past, providing additional insight to climate change impacts on viticulture (Chuine et al., 2004; Daux et al., 2012). Furthermore, designated maturity levels (i.e., harvest at a predetermined specific sugar [°Brix or total soluble solids] or potential alcohol levels) as opposed to the actual harvest date of many varieties also significantly progressed under warmer temperatures in Australia (Webb et al., 2011).

Climate modeling efforts have reported earlier future harvests in many winegrape regions around the world. Two relevant studies in Australia (i.e., Webb et al., 2007; Hall et al., 2016), using different approaches (a grapevine simulation model and a heat requirement method, respectively) and winegrape varieties (i.e., Chardonnay, Cabernet Sauvignon, and Shiraz) found noticeable shifts in harvest and growing cycle length based on a higher emission pathway. Similar results were identified for the widely cultivated variety Pinot noir in Europe (35 principal winegrape regions) (Fraga et al., 2016). Leolini et al. (2019) examining future climate change impacts on Sangiovese in Italy, found similar trends to increasing sugar content and declining acid concentrations, but also stressed the importance of examining increasing seasonality of temperatures on top of average temperature changes in climate change studies. From these and other studies it is likely that continued warming will lead to even earlier harvests, shifting the important processes of sugar accumulation and acid degradation further toward the hottest part of the season (i.e., summer months) likely resulting in unbalanced and altered wine flavors and styles. The latter is evident mostly for the early ripening varieties for which measures will be needed to delay the maturation process in the vineyard [e.g., mid-canopy late leaf removal or shoot trimming to reduce leaf area/fruit weight ratio (Poni et al., 2013; Palliotti et al., 2013; Parker et al., 2014)], or to delay the onset of the growing season [e.g., late winter pruning or pruning after budbreak (Friend and Trought, 2007; Petrie et al., 2017; Gatti et al., 2018)].

However, warmer conditions during the vintage and especially during ripening do not necessarily always mean earlier harvests. Using controlled temperature regimes, Greer and Weedon (2014) found that (a) higher temperatures late in the growing season can limit or even stop sugar accumulation and ultimately delay ripening; (b)the ripening process of grapevine cultivars was temperature-dependent, with the optimum temperature for ripening varying widely from 25 to 40 °C for Chardonnay, Semillon, and Merlot (low to high, respectively); and (c)excessively high temperatures are detrimental to grape development by inhibiting berry growth, delaying sugar accumulation, impeding fruit coloration, causing fruit to shrivel, and may cause abnormal pigmentation of white fruit. Similarly, Ramos and Martínez de Toda (2020) identified in Rioja (Spain) that grape composition was impacted by higher temperatures with a decoupling between phenolic maturity, anthocyanins, and sugar development along with lower acidity. In the irrigated areas the problem can be reduced with higher irrigation rates, but in rainfed areas there is no ability to use irrigation as a management strategy. In addition, an early study in South Australia by Sadras and Moran (2012), using different temperature regimes, reported that higher temperatures decouples anthocyanins and sugar in Shiraz and Cabernet franc varieties with no effect on the beginning of harvest. Research in Italy by Gaiotti et al. (2018) also suggested that the capacity for anthocyanin biosynthesis is enhanced by cool nights during véraison and that heat stress during ripening resulted in color loss, slowing of sugar accumulation, and potential later harvests with decoupled ripening profiles.

From this research, harvest dates, as determined by no further sugar increase after a number of consecutive measurements, exhibited earlier occurrences over numerous varieties and regions in Greece. Establishing heat accumulation requirements provides insights into how these varieties might respond with future warming. However, it is important to note that the GDD approach has some limitations. The accuracy of the GDD index in describing thermal requirements of a given variety is higher when the variety studied systematically reaches complete ripeness in a given area. Among the varieties of cluster 2, heat requirements for Moschofilero are possibly underestimated because in the Mantinia PDO area, one of the coolest in Greece (Koufos et al., 2017), it is commonly harvested at suboptimal sugar levels. In such cases, data for budbreak, flowering and véraison stages could be used or the approach proposed by Parker et al. (2020) targeting for specific sugar content. However, such observations are rarely recorded on a regular basis by Greek producers and if so, they are limited to only few varieties and years. To overcome this problem and to achieve a consistent approach for both current and future responses, 1st of April was selected as a starting point, despite the fact that it does not correspond to a phenological stage, and may be out of synchrony with development in future climate conditions.

The standard GDD formula used in this thesis also has limitations. For one, there is evidence that the base temperature threshold for accumulation is likely cultivar specific and is possibly as low as 5 °C (García de Cortázar-Atauri et al., 2009). Second, it considers that all temperatures above 10 °C have a similar positive and additive effect on grapevine development (it is well known that temperatures > 35 °C, often occurring in Greece, have mostly a negative impact [Greer and Weedon, 2014]). However, both the upper and lower thresholds have not been fully assessed for Greek varieties and therefore new thresholds may be defined in the future. Finally, the GDD formula does not account other climatic factors such as rainfall and sunshine hours. For example, the indigenous variety Xinomavro, cultivated in the areas of Amyndeon (near the city of Florina) and Naoussa with different average growing season temperatures (17.6 °C in Amyndeon vs. 19.4 °C in Naoussa), presented harvest date ranging from mid-September (Naoussa) to early October (Amyndeon). As a result, estimated GDD to reach harvest ranges from 1700 in Amyndeon vs. 2069 in Naoussa, for the production of red dry wines of similar style. A possible explanation would be that the Amyndeon region has more sunshine hours which are highly efficient physiologically, whereas Naoussa is characterized by higher precipitation, especially in September (Koufos et al. 2017).

Further warming, especially in maximum temperature extremes, could show an opposite response than what has been observed for some varieties in Greece. For example, two indigenous varieties, the mid-ripening white variety Athiri and the late ripening red variety Kotsifali showed a slight delay in harvest in this research, one being statistically significant (Athiri). More research needs to be done, both in controlled and open field experiments, to examine how this variety and others might behave in terms of harvest timing and fruit composition in the face of a changing climate in Greece.

Chapter 5: Greek wine quality assessment and relationships with climate: trends, future projections and uncertainties.

5.1 Introduction

It is widely admitted that the combination of abiotic factors (climatic and edaphic), vine and human intervention (a notion internationally known as "*terroir*" by the French), is considered essential to produce a desired wine style that reflects its distinctive characteristics according to origin (van Leeuwen and Seguin, 2006). It is also known that world's best winegrape regions are currently located in relatively narrow geographic boundaries (between the 35th and the 50th parallels in the Northern Hemisphere and 30th and 45th parallels in the Southern Hemisphere), where "*terroir*" components perfectly interact to produce exceptional wines, preserving their unique reputation (van Leeuwen and Darriet, 2016). Within these limits, climate (mainly air temperature) is without any doubt the most critical environmental factor largely controlling vegetative cycle, berry biochemistry, and wine quality (Jones and Davis 2000).

More specifically, few days with mean air temperature above 10°C combined with absence of spring frost events, can trigger budburst; after that, the accumulated heat, determines the onset of flowering, véraison and harvest (Mullins et al. 1992). Accordingly, phenology of many wine grape varieties within renowned wine producing regions showed a significant advancement, over the last several decades, due to higher temperatures (Jones et al. 2005a). The relationship between air temperature and phenology is so strong that flowering and véraison dates can be modelled with great accuracy, providing valuable tools to vine growers to adjust their viticultural techniques to changing climate (Parker et al. 2011, Parker et al. 2013). Moreover, air temperature affects berry chemical composition related to wine organoleptic properties (Coombe et al. 1987). Increasing temperatures can accelerate sugar accumulation and acid degradation in the must (Bock et al. 2013, Neethling et al. 2012), while too much warmth during night may impair the synthesis of secondary metabolites like anthocyanins and volatile compounds, leading in wines lacking aromatic expression and color (Jackson and Lombard 1993).

Regarding future conditions, it is very likely that climate change will expand the current limits of viable viticulture and add pressure to the traditional European areas located in the southern end (Moriondo et al. 2013; Fraga et al. 2016). This is the reason why, the suitability of a region to produce high quality wines can only be evaluated within the framework of wine-climate relationships. However, understanding how well weather conditions explain wine quality variation from year to year (i.e., vintage effect) is a challenging task (Jones et al. 2005b). On one hand, contribution of other factors such as management, innovation techniques, tradition and consumers' preferences are not easily quantified. On the other hand, large datasets with vintage ratings around the world showed that better vintages were characterized by very few weather extremes (e.g., spring frost, heat waves etc.), warmer flowering and véraison phases and ripening period with mild water deficit and limited temperature variability between day and night (Nemani et al. 2001; White et al. 2006; Webb et al. 2008; Baciocco et al. 2014; Davis et al. 2019). However, an upper growing season temperature threshold was identified for some varieties within specific regions, beyond which the general rule of thumb "the warmer the better" is being questioned (Jones et al. 2005b).

Wine making is an important sector in many economies around the world. Greece as part of the traditional "Old World" winegrape regions, produces wine for centuries and ranked as the 9th highest wine producing country within Europe (OIV, 2019). The cultural and economic importance of viticultural sector in Greece is mainly highlighted by: (i) the total wine production that reached 2 200 000 hL in 2018 (OIV, 2019), (ii) the wide range of indigenous varieties (>300), currently cultivated across the Greek territory, representing approximately 100 000 ha of areas under protected designation of origin and (iii) wine exports that reached 274 000 hL in 2016 (OIV, 2016) (see Chapter 2 for more details). Findings from chapters 3 and 4 categorised the Greek winegrape areas using bioclimatic indices and investigated the relationships between harvest dates and berry composition (potential alcohol and acid levels) with climate during critical periods of the vegetative cycle. The results showed that: (i) most of the areas were characterised as hot and very hot, (ii) harvest dates shifted significantly earlier in most of the varieties studied and most importantly (iii) the indigenous varieties appeared better adapted to recent and future warmer conditions by responding less compared to the international ones. The last finding adds knowledge by providing information about the response of native varieties which might be heat tolerant enough to become a key adaptation measure to climate change to preserve the production of high-quality wines (Schultz and Jones 2010). Despite the importance of viticultural sector to Greek economy, the relationship between wine quality and climate are still unexplored.

5.2 Aims of the chapter

On this context, the objectives of this chapter were: (i) to update the climate databases created in previous chapters (by adding the most recent period of records of 2011-2019) and estimate air temperature and precipitation trends, (ii) assess wine quality evolution of both indigenous and international varieties growing in viticultural areas throughout the Greek territory, (iii) identify the most efficient weather variables and climatic indices that correlate with wines produced from the indigenous varieties, and (iv) predict overall Greek wine quality under different representative concentration pathways (i.e., RCP4.5 and RCP8.5) in two future periods (i.e, 2041-2065 and 2071-2095), using an ensemble dataset.

5.3 Materials and methods

5.3.1 Vintage indicators (wine quality ratings and wine quality prices)

Wine prices is one of the most common metrics used in order to explain the variation of wine quality between vintages (Ashenfelter et al. 1995). The ideal growing season conditions, produces wines that are rated higher and hence, obtain higher prices on the respective market (Jones and Goodrich 2008). For example, Ashenfelter (2010) used auction wine prices (from 1952 to 1980 vintages) for mature Bordeaux wines and showed that four parameters (i.e., wine age, average temperature during the growing season, total precipitation in August and total precipitation in the months prior to vintage), explain more than 80% of the variation on wine prices. As a result, high rated wines, produced under warmer summer conditions and lower precipitation during harvest, received higher prices. The econometric model used in the above-mentioned study, can predict in great accuracy the wine price at maturation for the Bordeaux wines. Additionally, Ramirez (2008) showed that the relationships between weather variables and wine prices appeared to be more robust compared to the relationships between weather and wine ratings in the Napa Valley region (USA). However, long-term sufficient wine price data for numerous regions and/or varieties are very seldom. In Greece specifically, such data are rarely recorded on a regular base and if so, the accessibility is extremely difficult.

On the other hand, wine quality ratings (or vintage charts) have been kept for numerous years, varieties and regions (Jones 2020). Practically, vintage ratings provide a wine score on a year basis for a given variety or an aggregate score for an entire region. A variety of ratings (i.e., wine quality scores) exist varying in scales, according to source (e.g., 1-5, 0-20 and more often 0-100) and/or categorical structure (e.g., "Superb", "Exceptional" etc.), but originated under the same objective of providing a wine classification (derived from a wine expert or a panel of experts), based on flavor, aroma (genuineness, persistence and intensity), clarity, sight, and total harmony evaluation (Jones 2020). Therefore, in order to meet the abovementioned aims, the compilation of long timeseries of vintage ratings, is the most common metric of wine quality, over numerous winegrape regions in Greece.
Data of wine quality ratings, for 12 white (W) and five red (R) wine grape varieties (*Vitis vinifera* L., cvs) grown in Greece (both indigenous and international), covering a period of approximately 14 years for the indigenous and 17 years for the international varieties, on average, were obtained from the database of Thessaloniki International Wine and Spirits Competition (TIWC). The wine quality dataset consisted of 10 indigenous (Assyrtiko, Agiorgitiko, Athiri, Debina, Malagouzia, Moschofilero,

Robola, Savatiano, Vilana and Xinomavro) (Table 5.1) and seven widely cultivated international varieties (Chardonnay, Cabernet Sauvignon, Merlot, Muscat of Alexandria, Sauvignon blanc, Syrah and Viognier) (Table 5.2), each of them cultivated in a wide range of regions in Greece, except for the indigenous varieties that are cultivated in specific regions (in most cases), creating a total number of 17 wine quality timeseries. Most of the wine producing locations belong to areas of protected designation of origin (PDO) and are currently cultivated with indigenous varieties while the rest are simple geographical indications (GI, hereafter) covered by both indigenous and international cultivations. Although the variety Muscat of Alexandria is an international variety, it is widely cultivated on Limnos and the wines produced are labeled as PDO. This is the reason why it appears on both tables (Table 5.1 and Table 5.2). It is important to note that, the database was provided based upon anonymity and hence is not freely available. Details of wine quality time series along with the respective variety abbreviations and region's location are summarized in Tables 5.1, 5.2 and Figure 5.1. Wine quality score for each variety derived from a panel of wine experts whose selection was based on their ability to recognize specific characteristics of a given variety in the evaluated wines. Wine rating scores (ranging from 0 to 100) greater than 84 corresponded to a medal category (i.e., 84-86 Bronze, 87-89 Silver and >90 Gold medal). Lower scores (<70), although rarely appeared (in less than 1% of the cases) were excluded from the analysis. More than 4000 wine-labels were evaluated (both indigenous and international varieties).

Regarding the indigenous varieties, the timeseries of each region was constructed as follow:

a. All wines produced from the same winegrape region were grouped together providing an average region-wide wine score per year for the specific variety. Although Agiorgitiko variety is currently cultivated on different areas across Greece (see Chapter 4 for more details), only wines produced within Nemea region (PDO), the longest available timeseries, were considered. On the other hand, two representative areas for the indigenous varieties Assyrtiko (i.e., Drama and Santorini), Malagouzia

(Athens and Chalkidiki) and Xinomavro (Amyndeon and Naoussa) were selected, due to their importance.

b. Wines that age in oak barrel from 12 to 24 months (matured process) were grouped together and characterised as "aged wines". This label was adopted only for the late red varieties of Agiorgitiko and Xinomavro (3 cases in total).
c. Wines that appeared in the competition for evaluation one year after their production were grouped together and characterised as "young wines".

On the contrary, each of the international varieties, even produced from different regions across Greece were grouped together in order to create the longest available timeseries.

Table 5.1. Details for the 11 principal winegrape varieties (10 indigenous and 1 international) cultivated in 13 principal winegrape areas in Greece. Varieties and regions are presented in the first two columns. The predominant type of wine produced per region, the period of records and the respective total number of wines used per variety, are given in the last two columns. Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties (see Chapter 4 for more details); and red (R), white (W) varieties. **correspond to two missing wine quality scores on each case.

Variety/Abbreviation	**Region**	**Type of wines produced**	**Period of records (total number of wines used)**
Agiorgitiko[L,R,a]	Nemea – PDO	Red dry	2009-2018 (583)
Assyrtiko[M,W,a]	Santorini – PDO	White dry	2003-2018 (248)
	Drama – GI	White dry	2009-2018 (44)
Athiri[M,W,a]	Rodos – PDO	White dry and sparkling	2003-2019** (89)
Debina[L,W,a]	Ioannina – PDO	White dry and sparkling	2006-2019 (55)
Malagouzia[E,W,a]	Chalkidiki – GI	White dry	2005-2019 (31)
	Athens – GI	White dry	2006-2019 (45)
Moschofilero[M,W,a]	Tripoli – PDO	White dry	2003-2019 (207)
Muscat of Alexandria[M,W,b]	Limnos – PDO	White dry	2003-2019 (100)
Robola[E,W,a]	Kephalonia – PDO	White dry	2004-2019** (42)
Savvatiano[L,W,a]	Athens – GI	White dry	2004-2019 (184)
Vilana[M,W,a]	Crete – PDO	White dry	2004-2018 (71)

Xinomavro[L,R,a]	Florina – PDO	Red dry	2003-2016 (77)
	Naoussa – PDO	Red dry	2008-2017 (152)

Table 5.2. Details for the seven international winegrape varieties (Muscat of Alexandria also included in Table 5.1) cultivated in the principal winegrape areas in Greece. Varieties and regions are presented in the first two columns. The predominant type of wine produced per region, the period of records and the respective total number of wines used per variety, are given in the last two columns. **correspond to two missing wine quality scores on each case.

Variety/Abbreviation	**Region**	**Type of wines produced**	**Period of records (total number of wines used)**
Chardonnay	All regions included	White-Rose dry and sparkling	2003-2019 (396)
Cabernet Sauvignon	All regions included	Red dry	2003-2019 (277)
Merlot	All regions included	Red dry	2003-2019 (256)
Muscat of Alexandria	All regions included	White dry and dessert wines	2003-2019 (100)
Sauvignon blanc	All regions included	White dry	2003-2019 (284)
Syrah	All regions included	Red-Rose dry	2003-2019 (377)
Viognier	All regions included	White dry	2003-2018** (36)

Figure 5.1. The map presented the main locations of the wine-producing areas in Greece.

5.3.2 Climate data collection and procedures

The temporal evolution of the commonly used climatic variables and indices, for the period 1981-2010 for the main wine producing areas of Greece was investigated in Chapter 3. The present chapter, extents the above-mentioned period up to 2019 for a sub-group of these areas (11 out of 23 locations) and divides it into two data periods (i.e., HP1: historical period 1980-1999 and HP2: historical period 2000-2019) to compare the results. The Hellenic National Meteorological Service (HNMS) provided daily observations of maximum (TX) and minimum (TN) air temperature (°C) as well as daily precipitation (PRCP, mm). Weather stations are close enough (<15 km, on average) to the principal viticultural areas providing a good reference of the air temperature and precipitation trends of the PDO and GI areas. Statistical and visual checks for errors have been already performed for the period 2011-2017 (see Chapter 4 for more details), while the additional data (i.e., 1980 and 2018-2019) were subjected to a similar quality control adopted in Chapters 3 and 4 using the RClimDex software (Zhang and Wang 2004). Averages of TX, TN and PRCP totals during calendar year, growing season and ripening period (that was assumed to be the 45 days, on average, before harvest) (CY, GS and RP, respectively, hereafter) were then calculated for the HP1 and HP2.

Consequently, TX, TN and PRCP were used to calculate: (i) the diurnal temperature range index (DTR, Gladstones 1992), (ii) the extreme heat index which is the total number of days with TX above 30°C on a given period (Jones and Davis 2000) and DI using the following formula (Tonietto and Carbonneau 2004):

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

This index estimates the water soil reserve (W) of a given period by calculating precipitation (P), potential transpiration (Tv) and direct evaporation (Es) from the soil by assuming an initial useful water reserve (Wo = 200mm). Tv and Es were then used to calculate potential evapotranspiration (ETP) which in this thesis was estimated during the period April to September using the Hargreaves formula (Hargreaves and Samani, 1982). Then DI = W at the final month. The statistical R package "SPEI" was used to calculate the ETP (Beguería and Vicente-Serrano, 2013).

To calculate future conditions the DEAR-Clima database was used (http://meteo3.geo.auth.gr:3838/). This is a user friendly online platform providing climate data (on daily, monthly and yearly basis) from high resolution (0.11° X 0.11°) regional climate models simulation runs from the Coordinated Regional Downscaling Experiment (CORDEX) programme. In this chapter (as in Chapter 4 as well), future wine projection was performed using daily simulations of TX, TN and PRCP from 10 regional climate models (Table 5.3). The representative concentration pathways (RCP4.5 and RCP8.5) were employed to project future Greek wine quality in near future and far future periods [future period 1 (FP1): 2041-2065 and future period 2 (FP2): 2071-2095]. The TX and TN scenarios for FP1 and FP2 were then constructed by adjusting the historical timeseries of the models with the mean monthly changes estimated between the baseline period (BP: real observations during 1981-2005) and FP1, FP2 (see Chapter 3 and 4 for more details). The respective mean monthly percent (%) changes were used in the case of precipitation.

Table 5.3. Summary of Global Climate/Regional Climate Model chains (GCM / RCM) used in this thesis over the 2041 – 2065 (FP1) and 2071 – 2095 (FP2) future periods.

Global Climate Model (GCM, Driver)	**Regional Climate Model (RCM)**	**Scenario**
CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	historical rcp45 rcp85
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN53	historical rcp45 rcp85
CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	historical rcp45 rcp85
ICHEC-EC-EARTH	KNMI-RACMO22E	historical rcp45 rcp85
IPSL-IPSL-CM5A-MR	IPSL-INERIS-WRF331F	historical rcp45 rcp85
IPSL-IPSL-CM5A-MR	SMHI-RCA4	historical rcp45 rcp85
MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	historical

		rcp45 rcp85
MOHC-HadGEM2-ES	SMHI-RCA4	historical rcp45 rcp85
MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	historical rcp45 rcp85
MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	historical rcp45 rcp85

GCM: Global Climate Model, RCM: Regional Climate Model, RCP: Representative Concentration Pathway

5.3.3 Statistical analysis

The temporal evolution of climate parameters (i.e., TX, TN and PRCP) and wine quality scores (i.e., WQ) were explored using the basic linear regression equation ($Y = a + bX$). Statistical significance was evaluated at p-value <0.05 and <0.10. The relative contribution of climate variables on each grape variety and eventually wine quality was tested using a mixed effect modelling approach (Zuur et al. 2009). The mixed effect model was performed by using the *lme4* R package. Initially, the linear mixed effect model was set according to the following equation:

$$WQ = TX + TN + PRCP + Extreme\ Heat + DTR + \ DI + (1|variety)$$

where WQ: wine quality, TX: maximum air temperature, TN: minimum air temperature, PRCP: total precipitation amount, Extreme Heat: total number of days with TX ≥ 30°C, DTR and DI. WQ was considered as the response variable while the set of climate variables (i.e., TX, TN, PRCP, Extreme Heat, DTR and DI) and (1 | variety) as fixed and random effect, respectively (Zuur et al. 2009).

In addition, we suppose that climate variables may differ between areas where each of the studied varieties are cultivated and for this reason, an interaction term between each one the selected climate variables and variety was introduced to the initial model as follow:

$$WQ = TX + TN + PRCP + Extreme\ Heat + DTR + \ DI + (ClimVar|variety)$$

Where the *ClimVar | variety* component specifies the interaction between each climate variable and variety.

If one of the selected variables have a p-value greater than > 0.01 it was removed from the analysis and the procedure repeated with the remaining variables until all variables showed a high level of statistical significance (i.e., p-value < 0.01); then the optimal model was reached. In this thesis the final model used for further analysis was:

$$WQ = TX + TN + PRCP + DI + \ (1|variety)$$

The above-mentioned equations were calculated on CY, GS (April-October) and ripening period (RP). Overall, 15 different mixed effect models were constructed and tested for their accuracy to explain Greek wine quality. Akaike's Information Criterion (AIC) was undertaken to test the goodness of the models, and the model with lower AIC was the based on GS:

$$WQ = TX\_GS + TN\_GS + PRCP\_GS + DI + \ (1|variety)$$

This was used to project Greek wine quality for the two future periods (i.e., 2041-2065 and 2071-2095) using the ensemble dataset derived from 10 regional climate model. All statistical analyses were performed using the R statistical software and the respective packages (R Core Team, 2014) while figures were created using the ArcGIS software.

5.4 Results

5.4.1 Historical climate overview for HP1 and HP2 (averages and trends)

An overview of the climatic conditions during CY, GS, and RP and winegrape regions' classification in Greece has already been conducted in the previous chapters (i.e., Chapter 3 and chapter 4). Only the results of TX, TN and PRCP over the two historical time windows (i.e., HP1 and HP2) during CY, GS and RP are presented in this chapter. The direction and magnitude of trends on each climate variable (i.e., TX, TN and PRCP) along with the statistical significance are shown in tables 5.4-5.6 and figure 5.2.

Overall, the analysis of the CY on both periods showed positive trends for TX and TN in almost every case except for TN on Tripoli during HP1. Island locations experienced, on average, (considering both periods), warmer (21.5℃ versus 20.7℃) and relatively drier conditions (548mm versus 588mm) than mainland locations (Tables 5.4-5.6). During HP1, the total number of statistically significant cases for TN was higher than the respective number for TX (7 versus 4 out of 11 cases, respectively). The statistically significant cases of TX noticeably increased during the HP2 (10 versus 4 cases). Regarding the average magnitude of trends, across all locations, the TN warming rate was slightly higher on HP1 (0.04℃/yr^{-1} versus 0.03℃/yr^{-1}) but equal to TX (0.05℃/yr^{-1}) during HP2 (Table 5.4). While precipitation exhibited great regional variability only in one case its trend was significant (Table 5.4). Specifically, 5 negative (1 statistically significant case) and 6 positive trends were identified during the HP1 while the number of negative trends markedly decreased during the HP2 (1 negative trend) leading to slightly greater PRCP totals, considering all regions.

Table 5.4. Annual descriptive statistics for climate variables for two historical time windows (first row of each weather station corresponds to mean values and standard deviation (in parenthesis) while trends yr^{-1} for each variable are presented in the second row respectively) for the 11 principal winegrape areas in Greece. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10).

Weather stations (winegrape areas)	**TX mean (°C)**		**TN mean (°C)**		**Prcp (mm)**	
	1980-1999	2000-2019	1980-1999	2000-2019	1980-1999	2000-2019
Alexandroupoli (Maronia)[Cs]	19.1 (0.6) 0.03	20.3 (0.6) **0.06**	9.0 (0.5) ***0.03***	10.4 (0.7) **0.08**	488 (115) 2.99	554 (167) 8.36
Athens (Markopoulo)[Cs]	22.0 (0.6) **0.06**	22.9 (0.5) **0.04**	14.1 (0.6) **0.07**	14.7 (0.6) **0.05**	368 (94) 0.20	386 (104) 5.00
Crete (Peza)	21.8 (0.5) **0.05**	22.5 (0.5) 0.02	14.9 (0.4) 0.02	15.6 (0.5) **0.06**	456 (103) -5.02	476 (104) -5.05
Ioannina (Ioannina)	19.6 (0.6) 0.00	20.1 (0.6) **0.07**	7.4 (0.4) **0.05**	8.0 (0.5) 0.02	981 (157) 0.36	1079 (249) 9.21
Kephalonia (Valsamata)	21.3 (0.4) 0.01	22.3 (0.4) **0.05**	14.2 (0.4) 0.00	14.3 (0.4) **0.07**	805 (171) 0.18	841 (194) 12.13
Limnos (Limnos)	19.3 (0.5) 0.01	20.3 (0.6) **0.07**	11.5 (0.5) 0.02	12.6 (0.7) **0.08**	454 (125) ***8.25***	562 (162) 2.05
Larisa (Rapsani)	21.3 (0.7) ***0.05***	22.2 (0.6) ***0.04***	8.8 (0.6) **0.07**	9.8 (0.5) **0.04**	429 (82) -1.68	426 (97) 2.97

Rodos (Ebonas)	22.0 (0.4) 0.01	22.7 (0.5) **0.05**	16.5 (0.5) **0.05**	17.3 (0.4) **0.04**	666 (187) 3.33	602 (163) 1.30
Santorini (Santorini)	21.0 (0.5) 0.02	21.8 (0.6) **0.07**	15.3 (0.6) **0.09**	16.3 (0.5) 0.04	301 (155) -6.92	320 (101) 0.23
Thessaloniki (Epanomi)	20.3 (0.6) ***0.04***	21.0 (0.6) ***0.04***	10.3 (0.6) **0.07**	11.5 (0.4) 0.03	423 (89) -2.17	431 (111) 5.39
Tripoli (Tripoli)	19.9 (0.7) 0.03	20.2 (0.7) **0.07**	6.9 (0.5) -0.02	7.1 (1.2) **0.09**	752 (152) -8.09	743 (223) 12.74
Overall:	*20.7 (0.6)* *0.03*	*21.5 (0.6)* *0.05*	*11.7 (0.5)* *0.04*	*12.5 (0.6)* *0.05*	*557 (130)* *-0.8*	*584 (152)* *4.9*
Island locations	*21.1 (0.5)* *0.02*	*21.9 (0.5)* *0.05*	*14.5 (0.5)* *0.04*	*15.2 (0.5)* *0.06*	*536 (148)* *0.0*	*560 (145)* *2.1*
Mainland locations	*20.4 (0.6)* *0.04*	*21.1 (0.6)* *0.05*	*9.4 (0.5)* *0.05*	*10.3 (0.7)* *0.05*	*574 (115)* *-1.4*	*603 (159)* *7.3*

Table 5.5. Descriptive statistics for climate variables for two historical time windows during the growing season (April-October) [first row of each weather station corresponds to mean values and standard deviation (in parenthesis) while trends yr^{-1} for each variable are presented in the second row respectively] for the 11 principal winegrape areas in Greece. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10).

Weather stations (winegrape areas)	**TX mean (°C)**		**TN mean (°C)**		**Prcp (mm)**	
	1980-1999	2000-2019	1980-1999	2000-2019	1980-1999	2000-2019
Alexandroupoli (Maronia)	25.0 (0.6) 0.03	26.2 (0.7) **0.06**	13.3 (0.7) **0.06**	14.9 (0.7) **0.06**	183 (55) 2.57	234 (91) 3.54
Athens (Markopoulo)	27.0 (0.8) **0.08**	28.0 (0.7) 0.03	18.2 (0.7) **0.08**	18.9 (0.6) 0.04	105 (43) -2.19	118 (50) 2.19
Crete (Peza)	25.5 (0.5) **0.06**	26.1 (0.4) 0.02	18.1 (0.5) **0.04**	18.9 (0.5) **0.05**	95 (49) -2.63	100 (65) -1.12
Ioannina (Ioannina)	25.4 (0.8) -0.02	25.9 (1.0) **0.09**	11.4 (0.6) **0.06**	12.1 (0.5) 0.02	378 (100) 1.75	437 (183) 0.22
Kephalonia (Valsamata)	25.3 (0.6) 0.01	26.5 (0.6) **0.05**	17.4 (0.6) 0.02	17.6 (0.7) **0.07**	227 (73) -1.44	260 (107) 5.12
Limnos (Limnos)	24.3 (0.6) 0.02	25.2 (0.7) **0.06**	15.5 (0.6) ***0.04***	16.7 (0.6) **0.07**	132 (70) 3.54	192 (86) -2.49
Larisa (Rapsani)	27.7 (0.8) 0.04	28.3 (0.7) 0.04	13.3 (0.7) **0.08**	14.5 (0.4) 0.02	201 (75) -2.36	225 (75) 0.50

Rodos (Ebonas)	25.9 (0.4) -0.01	26.6 (0.5) **0.05**	20.0 (0.5) **0.05**	20.9 (0.4) **0.04**	116 (98) 4.59	98 (42) 2.36
Santorini (Santorini)	25.0 (0.6) 0.02	25.8 (0.7) **0.08**	18.6 (0.8) **0.11**	19.7 (0.5) 0.03	47 (37) -0.51	61 (47) -2.03
Thessaloniki (Epanomi)	26.3 (0.6) ***0.04***	26.9 (0.7) 0.04	14.9 (0.7) **0.09**	16.3 (0.3) 0.00	204 (73) -1.30	235 (68) 2.14
Tripoli (Tripoli)	25.6 (0.9) 0.06	25.8 (0.9) 0.06	10.4 (0.5) 0.00	10.7 (1.3) ***0.09***	247 (84) -2.85	268 (105) **8.75**
Overall:	*25.7 (0.7)* *0.03*	*26.5 (0.7)* *0.05*	*15.6 (0.6)* *0.06*	*16.5 (0.6)* *0.04*	*176 (69)* *-0.1*	*203 (84)* *1.7*
Island	*25.2 (0.5)* *0.02*	*26.0 (0.6)* *0.05*	*17.9 (0.6)* *0.05*	*18.8 (0.5)* *0.05*	*123 (65)* *0.7*	*142 (69)* *0.4*
Mainland	*26.2 (0.8)* *0.04*	*26.9 (0.8)* *0.05*	*13.6 (0.7)* *0.06*	*14.6 (0.6)* *0.04*	*220 (72)* *-0.7*	*253 (95)* *2.9*

Table 5.6. Descriptive statistics for climate variables for two historical time windows during the ripening period (45 days before harvest) [first row of each weather station corresponds to mean values and standard deviation (in parenthesis) while trends yr^{-1} for each variable are presented in the second row respectively] for the 11 principal winegrape areas in Greece. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10).

Weather stations (winegrape areas)	**TX mean (°C)**		**TN mean (°C)**		**Prcp (mm)**	
	1980-1999	2000-2019	1980-1999	2000-2019	1980-1999	2000-2019
Alexandroupoli (Maronia)	29.4 (1.1) 0.03	31.2 (1.2) **0.14**	16.6 (1.2) 0.06	18.9 (1.0) **0.11**	16 (13) **1.03**	28 (36) -1.38
Athens (Markopoulo)	31.1 (1.1) **0.11**	32.4 (1.0) 0.03	21.9 (0.9) **0.11**	23.0 (0.8) ***0.06***	5 (8) -0.07	11 (20) -0.24
Crete (Peza)	28.0 (0.8) **0.09**	29.2 (0.8) 0.03	21.4 (0.6) **0.07**	22.3 (0.6) **0.05**	3 (8) -0.11	8 (17) -0.55
Ioannina (Ioannina)	29.9 (1.4) -0.03	30.5 (1.7) **0.16**	14.5 (1.1) ***0.08***	15.2 (0.9) 0.04	56 (35) -0.81	71 (72) -1.52
Kephalonia (Valsamata)	29.2 (1.0) 0.02	30.4 (0.9) **0.10**	20.8 (1.0) ***0.08***	21.2 (0.8) **0.08**	16 (21) 0.87	41 (48) -1.44
Limnos (Limnos)	27.9 (0.8) 0.05	29.5 (0.8) **0.09**	19.4 (0.8) ***0.06***	21.0 (1.0) **0.11**	11 (14) 0.50	22 (27) -0.41
Larisa (Rapsani)	31.5 (1.1) 0.04	32.5 (1.0) **0.08**	16.6 (0.8) **0.09**	18.1 (0.8) **0.06**	26 (23) 0.17	37 (28) 1.62

Rodos (Ebonas)	29.2 (0.6) 0.01	30.1 (0.8) **0.06**	23.6 (0.6) **0.06**	24.5 (0.4) **0.04**	1 (2) **0.13**	3 (7) 0.31
Santorini (Santorini)	28.1 (0.8) 0.04	29.3 (0.8) **0.08**	21.7 (1.1) **0.15**	23.1 (0.6) 0.03	1 (1) 0.03	3 (9) 0.29
Thessaloniki (Epanomi)	30.2 (1.0) 0.06	31.2 (0.9) **0.07**	18.4 (1.0) **0.12**	20.2 (0.7) 0.02	28 (16) 0.71	34 (33) 1.47
Tripoli (Tripoli)	29.8 (1.4) 0.05	30.2 (1.5) **0.13**	13.7 (0.9) 0.01	14.1 (1.6) **0.15**	38 (36) 2.14	44 (40) 0.35
Overall:	*29.5 (1.0)* *0.04*	*30.6 (1.0)* *0.09*	*19.0 (0.9)* *0.08*	*20.1 (0.8)* *0.07*	*18 (16)* *0.4*	*27 (31)* *-0.1*
Island	*28.5 (0.8)* *0.04*	*29.7 (0.8)* *0.07*	*21.4 (0.8)* *0.08*	*22.4 (0.7)* *0.06*	*6 (9)* *0.3*	*15 (22)* *-0.4*
Mainland	*30.3 (1.2)* *0.04*	*31.3 (1.2)* *0.10*	*17.0 (1.0)* *0.08*	*18.3 (1.0)* *0.07*	*28 (22)* *0.5*	*38 (38)* *0.1*

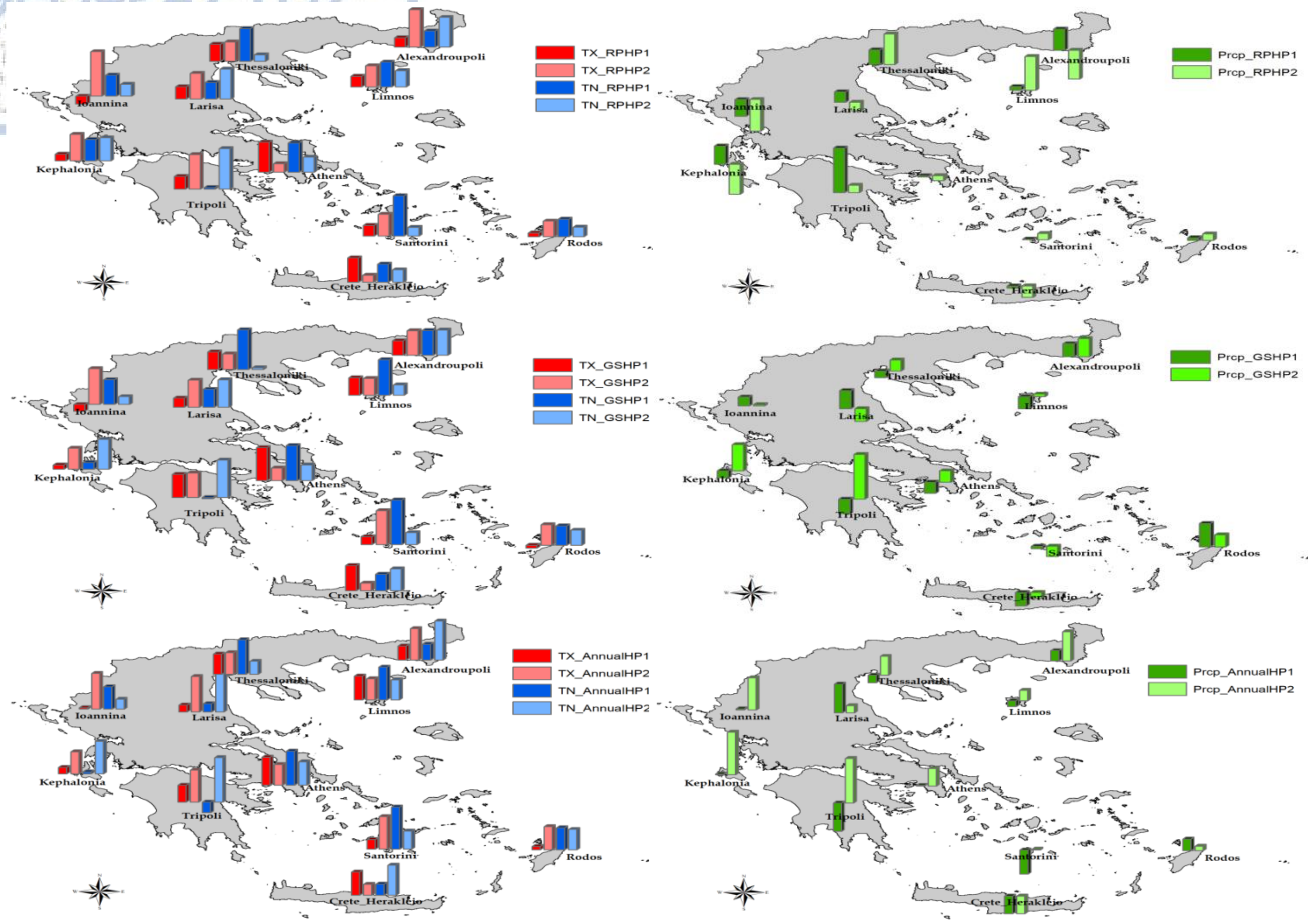

Figure 5.2. Magnitudes of trends of mean maximum (TX, red bars) and minimum (TN, blue bars) air temperature (°C) and precipitation (PRCP, mm, green bars) during the HP1 (1980-1999) and HP2 (2000-2019) periods. Top, middle and bottom graphs refer to ripening period (RP), growing season (GS) and annual base, respectively.

Upward trends for TX and TN across all locations, were also identified (42 out 44 cases) during the GS considering HP1 and HP2 (Table 5.5). Mainland locations generally exhibited warmer daily (higher TX values) and relatively wetter conditions while highest TN means were more pronounced at island locations presenting a general coherence (18.3°C versus 14.1°C, on average, considering both HP1 and HP2). The total number of statistically significant cases for TN were greater than the respective number of TX (9 versus 3 cases) during HP1. Moreover, the magnitude of TN trends was greater than TX (0.06°C/yr^{-1} versus 0.03°C/yr^{-1}) during the same period. However, opposite results regarding the total number of significant cases (6 statistically significant cases for each variable) and magnitude of trends (0.04°C/yr^{-1} for TN versus 0.05°C/yr^{-1} for TX) were identified when the analysis was performed on

HP2 (Table 5.5). The estimated negative trends of PRCP were greater than the respective positive ones (7 out of 11 cases) during the HP1. Considering all locations and periods, the total number of negative trends was reduced during the HP2, although no statistically significant cases was identified (Table 5.5).

Finally, the analysis during RP considering both periods, revealed positive trends for TX and TN nearly on every location (except for TX at Ioannina during HP1) with the total number of statistically significant cases for TX and TN being 11 out of 22 cases. The latter number markedly increased when the analysis was focused on HP2 (17 cases). In addition, the magnitude of TX trends during HP2 noticeably increased compared to the respective rate during HP1 (0.09°C/yr^{-1} versus 0.04°C/yr^{-1}). Moreover, most locations exhibited higher PRCP and TX than TN (Table 5.6) during HP2. On the contrary, the negative trends of PRCP during the RP were more pronounced during the HP2 (6 versus 3 cases).

5.4.2 Greek wine quality evolution

5.4.2.1 Trends on Greek wines produced from indigenous varieties

Wine quality rating statistics and trends for the one international and 10 indigenous varieties are presented in Table 5.7. Overall, the analysis showed an average Greek wine quality score of 82.7 on a 100-scaling rate and a standard deviation of 2.9. White dry wines are rated slightly lower than country average (i.e., 82.4 points) while red dry wines achieved slightly higher score on average (+1.0). The variety with the lowest ranking is the international variety Muscat of Alexandria (i.e., 81.2 points) and with the highest the indigenous white variety Assyrtiko cultivated in Drama region (i.e., 85.3 points). Early maturing varieties achieved slightly lower average score than mid and late ripening varieties (82.3 vs. 82.6 and 83.0 points, respectively). Finally, the wines produced on mainland locations appeared to be rated slightly higher than the respective produced in islands (83.0 versus 82.2 points/yr^{-1}, respectively).

The overall trend analysis revealed positive trends in all cases (14 cases) with 2 statistically significant at p-value <0.10 and 9 at <0.05 while 3 cases presented insignificant positive trends (Table 5.7). Overall quality ratings for wines from red varieties increased at a higher rate than the respective wines from white varieties (0.51 points/yr^{-1} versus 0.39 points/yr^{-1}). Wine quality for the early maturing varieties increased by 0.46 points/yr^{-1} while wines from mid and late ripening varieties increased by 0.38 and 0.43 points/yr^{-1}, respectively. Finally, quality of wines produced on mainland locations increased by +0.19 points/yr^{-1} higher than the respective wines produced on island locations (Table 5.7). Greek wine quality overall increased by 0.41 points/yr^{-1}.

Table 5.7. Wine quality rating statistics and trends for the 11 principal winegrape varieties (10 indigenous and 1 international) cultivated in 13 principal winegrape areas in Greece. Varieties and regions are presented in the first two columns. Averages and standard deviation (in parenthesis) for wine quality are given in column 3. Wine quality direction, slope and r^2 given in column 4. The period of records for each variety is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05), while italicized blue bold letters indicate lower statistical significance (p-value < 0.10). Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties. **correspond to two missing wine quality scores on each case.

Variety	Winegrape area	Average (Standard deviation)	Trend yr^{-1}	Period of records
Malagouzia^{E,W,a}	Chalkidiki	81.9 (4.0)	**0.62 (0.48)**	2005-2019
	Athens	82.3 (2.2)	**0.37 (0.50)**	2006-2019
Robola^{E,W,a}	Kephalonia	82.8 (3.0)	**0.38 (0.39)**	2004-2019**
Muscat of Alexandria^{M,W,b}	Limnos	81.2 (3.2)	0.21 (0.11)	2003-2019
Moschofilero^{M,W,a}	Tripoli	81.9 (3.1)	**0.52 (0.74)**	2003-2019
Vilana^{M,W,a}	Crete	82.1 (2.2)	**0.35 (0.48)**	2004-2018
Athiri^{M,W,a}	Rodos	82.5 (2.2)	0.09 (0.05)	2003-2019**
Assyrtiko^{M,W,a}	Santorini	82.6 (3.7)	**0.44 (0.32)**	2003-2018
	Drama	85.3 (2.9)	**0.66 (0.49)**	2009-2018
Debina^{L,W,a}	Ioannina	81.3 (3.3)	***0.40 (0.26)***	2006-2019
Agiorgitiko^{L,R,a}	Nemea	82.5 (4.8)	0.71 (0.20)	2009-2018
Savvatiano^{L,W,a}	Athens	82.7 (1.5)	**0.21 (0.44)**	2004-2019

Xinomavro[L,R,a]	Florina	84.2 (1.6)	**0.31 (0.63)**	2003-2016
	Naousa	84.6 (2.8)	***0.51 (0.31)***	2008-2017
Summary	*Overall*	*82.7 (2.9)*	*0.41*	
	Early	*82.3 (3.0)*	*0.46*	
	Mid	*82.6 (2.9)*	*0.38*	
	Late	*83.0 (2.8)*	*0.43*	
	Red	*83.7 (3.1)*	*0.51*	
	White	*82.4 (2.8)*	*0.39*	
	Mainland	*83.0 (2.9)*	*0.48*	
	Island	*82.2 (2.9)*	*0.29*	

5.4.3.2 Trends of Greek wines produced from international varieties

Wine quality rating statistics and trends per studied international variety are presented in Table 5.8. Overall, the analysis showed an average wine quality score of 83.1 on a 100-scaling rate and a standard deviation of 2.2. White dry wines are rated slightly lower than country average (i.e., 82.9 points) while red dry wines achieved similar score on average. The variety with the lowest ranking is the variety Muscat of Alexandria (i.e., 81.5 points) and with the highest the white variety Viognier (which also exhibited the highest standard deviation) cultivated mainly in Northern Greece (i.e., 84.9 points).

The trend analysis revealed positive trends in all cases (7 cases) with 5 statistically significant at p-value <0.05 while 2 cases presented insignificant positive trends (Table 5.8). Overall, quality ratings for white wines increased at a higher rate than the red wines (0.24 points/yr^{-1} versus 0.15 points/yr^{-1}). Greek wine quality overall increased by 0.20 points/yr^{-1}.

Table 5.8. Wine quality rating statistics and trends for the 11 principal winegrape varieties (10 indigenous and 1 international) cultivated in 13 principal winegrape areas in Greece. Varieties and regions are presented in the first two columns. Averages and standard deviation (in parenthesis) for wine quality are given in column 3. Wine quality direction, slope and r^2 given in column 4. The period of records for each variety is given in the last column. Red bold letters indicate statistically significant trends (p-value < 0.05). **correspond to two missing wine quality scores on each case.

Variety	**Region**	**Average (standard deviation)**	**Trend y-1 (r^2)**	**Period of records**
Chardonnay	All regions included	82.5 (2.0)	**0.32 (0.82)**	2003-2019 (396)
Cabernet Sauvignon	All regions included	83.3 (2.7)	0.09 (0.17)	2003-2019 (277)
Merlot	All regions included	82.9 (1.8)	**0.20 (0.56)**	2003-2019 (256)
Muscat of Alexandria	All regions included	81.5 (2.5)	**0.24 (0.48)**	2003-2019 (100)
Sauvignon blanc	All regions included	83.0 (1.7)	**0.19 (0.58)**	2003-2019 (284)
Syrah	All regions included	83.4 (1.2)	**0.17 (0.68)**	2003-2019 (377)
Viognier	All regions included	84.9 (3.3)	0.21 (0.30)	2003-2018** (36)
Summary	Overall Red White	83.1 (2.2) 83.2 (1.9) 82.9 (2.4)	0.20 0.15 0.24	

5.5 Relationships between climate and wine quality

The mixed effect model analysis of the response variable (i.e., WQ) during GS with a set of climate variables gave a highly significant effect (Table 5.9). The positive contribution of TX was the most important predictor of Greek wine quality ratings followed by a negative, but to a lesser degree, effect of TN. Regarding DI and total precipitation amounts, the analysis revealed a significant positive (negative) impact of DI (PRCP_GS). Three out of four climate variables appeared to be statistically significant at p-value <0.001 while PRCP_GS at p-value = 0.01 (Table 5.9).

Table 5.9. Results of mixed effect model analysis of Greek wine quality with climate.

Model	**Fixed components**	**Estimate**	**p-value**
WQ=TX_GS+TN_GS+DI+PRCP_GS	Intercept	46.41	***
	TX_GS	1.99	***
	TN_GS	-0.77	***
	DI	0.03	***
	Prcp_GS	-0.01	**
Model summary	*Number of varieties: 14* *Number of observations: 197* *Marginal R^2 / Conditional R^2: 0.22/0.39*		

Significant codes: *** <0.001, **<0.01

The projections of Greek wine quality response, based on the selected mixed effect model to an ensemble future climate with two representative concentration pathways (i.e., RCP4.5 and RCP8.5), derived from 10 regional climate models (Table 5.2) are presented in Table 5.10. For the FP1 period (i.e., 2041-2065) and under the lower representative concentration pathway (i.e., RCP4.5), the overall Greek wine quality remained stable at 82.7 points while during FP2 (i.e., 2071-2095) Greek wines ratings slightly increased (by +0.7 points) compared to the reference period. The higher representative concentration pathway (i.e., RCP8.5) led to more noticeable increases in Greek wine quality, especially during FP2 (Table 5.10). Overall, Greek wine quality is projected by +0.8 points higher than the baseline period (83.5 versus 82.7 points, on average, respectively) over FP1 and by further +1.8 points by the end of the century (85.3 versus 82.7 points, on average, respectively).

Table 5.10. Future wine quality rating statistics and trends for the 11 principal winegrape varieties (10 indigenous and 1 international) cultivated in 13 principal winegrape regions in Greece. Varieties and regions are presented in the first two columns. Average wine quality rating scores for FP1 and FP2 under rcp4.5 and rcp8.5 are given in columns 3-6. Each variety has superscript letters indicating indigenous (a) and international varieties (b); early (E), mid (M) and late (L) season varieties; and red (R), white (W) varieties (see Chapter 4).

Variety	**Winegrape area**	**WQ FP1 rcp4.5**	**WQ FP1 rcp8.5**	**WQ FP2 rcp4.5**	**WQ FP2 rcp8.5**
Malagouzia^{E,W,a}	Chalkidiki	81.3	82.1	81.9	83.9
	Athens	81.6	82.4	82.3	84.2
Robola^{E,W,a}	Kephalonia	82.9	83.8	83.6	85.5
Muscat of Alexandria^{M,W,b}	Limnos	82.5	83.3	83.2	85.1
Moschofilero^{M,W,a}	Tripoli	82.3	83.2	83.0	84.9
Vilana^{M,W,a}	Crete	83.0	83.8	83.7	85.6
Athiri^{M,W,a}	Rodos	82.9	83.7	83.6	85.5
Assyrtiko^{M,W,a}	Santorini	83.7	84.6	84.4	86.3
	Drama	83.5	84.3	84.1	86.0
Debina^{L,W,a}	Ioannina	81.4	82.3	82.1	84.0
Agiorgitiko^{L,R,a}	Nemea	81.4	82.2	82.0	83.9
Savvatiano^{L,W,a}	Athens	82.0	82.8	82.7	84.6
Xinomavro^{L,R,a}	Florina	85.2	86.1	85.9	87.8
	Naousa	83.8	84.6	84.4	86.3

Summary	Overall	82.7	83.5	83.3	85.3
	Early	81.9	82.8	82.6	84.5
	Mid	83.0	83.8	83.7	85.6
	Late	82.8	84.3	83.4	85.3
	Red	83.5	84.3	84.1	86.0
	White	82.5	83.3	83.1	85.1
	Mainland	82.5	83.3	83.2	85.1
	Island	83.0	83.8	83.7	85.6

Finally, wines produced from white and early maturing indigenous varieties responded less than these derived from indigenous mid and late ripening red varieties (Table 5.10). WQ of wines produced from the early maturing varieties increased at a lower rate than these from mid and late ripening varieties. The early indigenous variety Malagouzia showed the lowest increase in wine quality rating while late maturing variety Xinomavro presented the highest increase (Table 5.10).

5.6 Discussion

These results provide additional knowledge to the domestic and international growing interest regarding the evolution and the relationships between Greek wine quality and climate. The analyses were carried out over key mainland and island locations during the historical and future expected climate.

The majority of winegrape areas in Greece are recently categorized as warm to hot while regional climate simulations suggest even warmer and drier conditions in the future (see Chapter 3). The statistically significant increasing GS trends of TN identified during 1981-2010 were higher than these of TX in most of the cases (see Chapter 3). These results are in line with previous research in the majority of the European winegrape regions (Jones et al. 2005a). However, two relevant studies conducted in 3 principal wingegrape areas in Spain (Ramos et al. 2008) and the Veneto in Italy (Tomasi et al. 2011) showed that TX increased at a higher rate comparing to the TN. An early study conducted in central California showed that regardless the season, surface minimum temperatures warmed at a higher rate than the respective maximum. One possible explanation might be the introduction of irrigated cultivations and higher ambient moisture conditions (Christy et al. 2006). Furthermore, Duchêne and Schneider (2005) reported that trends of TN in Alsace were significantly higher than TX only in Autumn. These results, indicate that changes in air temperature does not affect every region in the same way. For example, Jones et al. (2005b) showed that winegrape regions located in the Northern hemisphere (which is more covered by land) faced proportionally warmer conditions compared to the areas located in the Southern hemisphere. In this chapter, mainland areas experienced higher mean TX while TN were more pronounced on island locations. In addition, the total number of statistically significant cases and magnitude of trends of TN were significantly higher during the first period (i.e., HP1: 1980-1999). On the contrary, mean TX increasing trend was slightly higher than the respective TN (0.05°C/yr^{-1} versus 0.04°C/yr^{-1}) leading to a remarkable increase in the total number of statistically significant cases over the second period (i.e., HP2: 2000-2019). These results were not particularly sensitive to period selection (i.e., CY, GS, and RP). The higher TX trends over the last decade (i.e., 2011-2019) compared with these of TN imply a turning point at which TX increases at a higher rate than the respective TN. However, additional spatially distributed temperature records are required to confirm this result. PRCP showed the least significant changes over the studied periods. In particular, the total amount of rainfall during GS were significantly reduced when the analysis was based on the HP2 compared to HP1, indicating relative wetter conditions.

Air temperature is highly correlated with vine phenology, development and wine quality around the globe. Most grapevine varieties are currently grown in regions with favorable climatic-edaphic conditions which are considered essential, over several decades, for producing balanced wines. Nevertheless, as temperature increases, grape maturity is very likely to take place during summer months where, in general, warmer, and drier conditions prevail (see Chapter 4) and consequently, wine balance may be negatively affected (van Leeuwen et al. 2008). Although, increasing temperatures might lead to changes in phenological timing, vineyard management practices, water-nutrient stress and/or pest disease control (van Leeuwen and Darriet, 2016), it may be either beneficial or detrimental depending on the specific variety and wine style. In fact, a sufficient number of studies reported that climate variation is very likely to be highly regional and variety-specific (e.g., Jones et al. 2005). For example, the results from the previous chapter found that even though air temperature significantly increased across the Greek territory resulting in earlier harvest occurrence, a wide range of indigenous varieties responded less compared to international ones, on average. Moreover, mid, and late ripening indigenous varieties were found to be more resilient to further warming than the respective early ones.

Warmer growing season resulting in earlier harvest dates, do not necessarily lead to lower wine quality. Jones et al. (2005) using large datasets with vintage ratings and climate over a numerous of winegrape regions around the world found that better vintages were frequently associated with earlier harvest dates and higher growing season temperatures. Davis et al. (2019) also reported that top ranked vintages in Burgundy region are highly linked with warmer growing season temperatures and drier conditions. Lebon et al. (2003) reported similar results in Saint Emillion (France) where better vintages were identified under higher water deficit and warmer conditions. The results from this chapter confirm that wine quality ratings improved with the increased water deficit because of the warmer [the magnitude of the positive coefficient of TX_GS was larger than the respective negative of TN_GS in the mixed effect model analysis (see Table 5.9)] and drier conditions. This is not an expected finding given the fact that flavor compounds of grapes and wines was negatively affected by increased temperatures (Tarara et al. 2008, Torres et al. 2020). Even though there are recent reports that Greek indigenous varieties may be more resilient to thermal stress (Alatzas et al. 2021), the positive relation of Greek wines produced from late ripening indigenous varieties with temperature is mostly the result of a shift in harvest time towards earlier dates placing the late stages of ripening under more consistently favorable weather conditions. In addition, WQ of wines produced from the early maturing varieties and on island locations appeared to increase at a lower rate compared to mid, late ripening varieties and mainland locations. Similarly, wines produced from the international varieties in Greece also showed a positive trend (Table 5.8). The trends between the indigenous and international varieties differed.

This chapter does not account for the upper temperature limits regarding variety resistance as well as their adaptive capacity. For example, the red indigenous variety of Xinomavro is currently cultivated in the north winegrape regions of Amyndeon (near Florina) and Naoussa. These regions, having different edaphic conditions, presented different growing season averages (17.6°C in Florina versus 19.4°C in Naoussa) which in turn placed them in different classes according to growing season temperature index (warm versus hot, see Chapter 3). As a result, total heat requirements to reach harvest significantly differ between regions (i.e., 1700 in Florina versus 2069 in Naoussa, on average). However, the wine quality analysis revealed similar positive trends for the produced wines. Even though, further warming seems to be beneficial (positively associated) for maintaining high quality wines in both regions, wine quality in Florina increases at a higher rate than in Naoussa (Table 5.7). One explanation might be that temperature-based indices placing Florina at lower classes with milder temperatures (lower frequency of temperature extremes) and thereby a better target sugar/acid ratio achieved more frequently over the years as result of global warming (see Chapter 3). On the other hand, Naoussa temperature conditions seem to reach the varietal upper temperature limit beyond of which maintaining the production of high-quality wines might be a challenging task.

In addition, vintage quality ratings might not be the appropriate indicator for assessing wine quality. A recent study from Gambetta and Kurtural (2021) that investigated the relationships between warming and fruit ripening, including wine quality, in the Napa Valley (USA) and Bordeaux (France), reported that warmer conditions resulted in higher wine quality. They also suggested that measurement of specific secondary metabolites might be a better wine quality indicator. On the contrary, Jones et al. (2005b) predicted an optimum growing season temperature threshold of 17.3°C for the Bordeaux region above which wine quality tended to decline, a limit that is already surpassed over the last decades (Gambetta and Kurtural 2021).

Moreover, as the previous chapters, this chapter did take into consideration possible adaptations of grape growers to climate change (i.e., resistant rootstocks, delayed pruning, modifications of canopy management etc.) as well as advancements in winemaking equipment and biotechnology which could have a significant contribution to the rise of wine quality in Greece over the study period. For example, ripeness can be delayed in most cases by the implementation of viticultural practices such as (i) late leaf removal and reduced leaf area/fruit weight ratio (Poni et al. 2013; Pallioti et al. 2013), (ii) late winter pruning or pruning after budburst (Gatti et al. 2018; Petrie et al. 2017), (iii) mechanical trimming (Parket et al. 2016) and the use of late-ripening varieties among the traditional varieties in some wine-growing regions. For example, Poni et al. (2013) and Pallioti et al. (2013) investigated the effects of pre- and post-veraison defoliation on berry ripeness in the Sagniovese variety. They both reported that technological ripeness (i.e. berry sugar/acid levels) noticeably reduced (1 to 2 weeks) without significant changes in both color and phenolic compounds in the wine produced. In addition, late pruning treatment on the winegrape varieties of Pinot noir, Cabernet Sauvignon and Shiraz were found to be very effective compared to winter pruning in delaying fruit ripening from 2 to 3 weeks depending on the variety (Gatti et al. 2017; Petrie et al. 2017). However, in both cases a reduction in total yield was also reported. These results provided the viti-vini cultural sector with valuable information in order to plan future strategies to mitigate climate change effects on the phenology, grape composition and eventually wine quality attributes. Nevertheless, the impacts of the treatments differ depending on the viticultural technique, winegrape region and variety. For this reason, it is very important to explore the response of native varieties to such applications by gathering data to use in future climate studies. However, since this was also true for the international varieties that did not show the same magnitude of trends in WQ. Therefore, the overall positive response of Greek indigenous varieties to warming conditions probably indicates a higher resilience to current and future climate conditions.

Chapter 6: General conclusions

In Greece, there is a lack of studies investigating the impacts of climate change on viticulture. We believe that this thesis will contribute to fill that gap and be a part of the basic knowledge that the scientific community providing to the wine producers in order to mitigate the impacts of climate change. Each research chapter within this thesis attempted to provide valuable information regarding the following vital for the wine industry in Greece issues:

6.1 To what extent the winegrape regions in Greece will be at risk in the future according to the principal viticultural indices?

Chapter's 3 main objective was to explore the response of the main winegrape regions and consequently the suitability for viticulture in Greece, in the expected future warming conditions. This is a key issue since, climate and viticulture are highly connected and thus knowledge of the predominant weather and climate conditions of a given area is critical for optimum variety selection, viable production and overall wine quality in the future. To address this, a comprehensive daily climate database of the current (1981–2010) and future conditions (2021–2050 and 2061–2090) through principal climatic elements and six bioclimatic indices [i.e. growing season temperature (GST), growing degree days (GDD), huglin index (HI), biologically effective degree days (BEDD), dryness index (DI) and cool night index (CI)] at 23 weather stations proximal to the key mainland, coastal and island viticultural areas of Greece was created (database 1). The data consisted of daily observations of air temperature (maximum and minimum) and precipitation, all obtained from the archive of the HNMS. Secondary variables and indices, commonly used in winegrape region categorization based on their ability to ripen quality fruits to produce premium wines (Jones et al. 2010), were computed from the above-mentioned database. The temporal evolution of air temperature and precipitation within the same regions was also investigated. Afterwards, the winegrape regions were classified through the calculated indices from the previous step. Finally, an assessment of future climate conditions and possible shifts in classification and anticipation of future risks for viticulture suitability in Greece was performed.

Most of the studied areas in Greece are currently placed in warm and very warm classes with moderate dry conditions. Mainland locations were generally colder due to their wider variety of terroir aspects and elevation, while coastal locations and islands faced proportionally more extreme temperatures and drier conditions. Trend analysis revealed that minimum temperatures increased at higher rates than the respective maximum temperatures at most locations. Climate change scenarios suggested significant shifts towards warmer and drier conditions, resulting in a substantial change in winegrape region classification. As such, Greek viticulture will likely face climate change impacts in the future that could challenge the future of the industry. Considering the earlier occurrence of vine phenological stages according to future climate modelling, differences in impacts will likely be seen between wine areas currently cultivated with early ripening (reducing variety suitability) versus those with later-ripening (increasing consistency in ripening) varieties. Future studies could consider an adjustment to the period used for calculation of the bioclimatic indices (i.e., March–September for the Northern Hemisphere for GDD or August for CI) instead of the period used in bibliography (i.e., April–October for the Northern Hemisphere for GDD or September for CI). This adjustment would greatly depend upon the heat requirements of specific varieties.

It is therefore of outmost importance for the future of the Greek wine industry to (i) continue to investigate the heat tolerance of cultivated indigenous varieties (perhaps by establishing specific limits for temperature extremes), (ii) increase its adaptive capacity through better understanding of temperature thresholds for the varieties grown and (iii) adopt new cultivation techniques and strategies for producing high quality wines outside the current temperature ranges.

6.2 How does recent and future warming influences harvest of greek indigenous varieties vs. to international ones? Does the varietal time of maturity (early, mid-season and late ripening varieties) play a significant role in varieties' resistance in climate change?

The aims of chapter 4 were to: (1) investigate the relationships between harvest dates and berry composition with air temperature during important periods during the growing season (i.e., GS), across a range of indigenous and international winegrape varieties grown in wine regions over the majority of Greece; (2) calculate growing degree days (i.e., GDD) from 1st of April until the harvest date of each variety and group the winegrape varieties according to their heat requirements; and (3) predict future harvest dates based upon heat requirements under different representative emission pathways (i.e., RCP4.5 and RCP8.5) and future time periods (2041-2065 and 2071-2095), using an ensemble projection dataset. To address this, a phenological and maturity database, that includes dates of the main phenological events and sugar-acid concentration levels, was created (database 2). In Greece specifically, from the four main developmental stages of grapevines, only harvest date is regularly recorded by grape growers. The rest of the stages are recorded only recently.

The analysis of heat requirements based on GDD during the GS identified consistent maturity groups of the indigenous varieties, enabling a first estimation of heat requirements for the indigenous varieties planted across the greek territory. Trend analysis using the basic linear regression model showed that during the last few decades both indigenous and international winegrape varieties have been harvested earlier with generally higher potential alcohol and lower acidity. These trends have been tied to warming conditions in many Greek wine regions during important growing periods during the vintage (see Chapter 3). Analysis of future projections using a global multi-climate model ensemble dataset (10 regional climate models) showed that harvest dates are projected to shift earlier for over a month (i.e., 40 days or more) in two future time periods (i.e., 2041-2065 and 2071-2095) depending on the variety and the emission pathway. The results also point out that mostly the indigenous varieties with late ripening were less affected by recent and projected temperature increases in Greece compared to international varieties. These findings come in agreement with recent studies (Wolkovich et al., 2018; Morales-Castilla et al., 2020) suggesting that increasing diversity of varieties planted and better clonal selection (Martinez-Zapater et al., 2010) are potential adaptive responses to a changing climate. To further address these needs, the International Organisation of Vine and Wine (i.e., OIV) is currently undertaking research that is looking at the selection and improvement of varieties for adaptation to climate change (Compés and Sotés, 2018).

This thesis indicates that in the future, the Greek wine sector is expected to face additional pressure as grape maturity is expected to shift toward warmer summer conditions (see Chapter 3), likely affecting negatively berry composition and final wine quality. Although the results of varietal clustering with the use of the GDD formula presented in this research are promising, especially regarding the number of indigenous varieties in the late ripening group, adaptation of viticulture to future conditions based on the thermal requirements of the grape varieties alone will probably not be sufficient. The development of a more complex indicator(s) than the traditionally used agro- or bio-climatic indices, capable of incorporating a variety's level of resilience to both heat and drought conditions, will better enable growers and researchers to efficiently select the best varieties and locations for their vineyards for the next generation of wine producers.

6.3 Will Greek wine quality benefits from future climatic conditions? Which climatic indices are best related to Greek wine quality variation?

The objectives of this chapter include (a) the temporal evolution of air temperature (TX and TN) and precipitation (PRCP) on two different periods using an extension of the existed climatic database and (b) explore, for the first time, the evolution of Greek wine quality (based on vintage ratings) and the relationships with climate parameters. To serve this purpose, wine quality ratings (database 3) for 12 white (W) and five red (R) wine grape varieties (Vitis vinifera L,) were obtained from the Thessaloniki International Wine and Spirits Competition (TIWC). The wine quality dataset consisted of 10 indigenous and 7 international variety which are all cultivated in the best-known winegrape regions in Greece.

Overall, TN increased at a faster rate than the respective TX during the historical period: 2000-2019 (i.e., HP2) while precipitation (i.e., PRCP) showed the least significant cases over the studied periods. These trends associated with warmer annual and growing season conditions in almost every winegrape areas throughout the Greek territory and resulted in earlier harvest dates in most of the studied varieties (both indigenous and international) (see Chapter 4). Greek wines exhibited a statistically significant upward trend over the recent past and are mainly related with higher TX and dryer conditions. This finding is in line with some previous works (e.g., Jones et al. 2005b and Davis et al. 2019) indicating that higher growing season temperatures and a mild water deficit resulting in better vintages. Future wine quality projections applied on the outcome of the mixed effect model, using two representative concentration pathways (i.e., RCP4.5 and RCP8.5) found increasing trends in wine quality under warmer conditions. This thesis, however, did not consider other climatic factors that interfere with wine quality and berry biochemical synthesis (e.g., solar radiation). In addition, husbandry practices, vineyard management, winemaking equipment and techniques that also contribute to better vintages as well as variety resilience to climate change were not also taken into account. Therefore, the results are considered as a first step towards the full spectrum of potential climate change impacts on Greek wines rather than a conclusion.

Moreover, a better understanding of how other non-climate related factors (e.g., canopy management, winemaking innovations) affect wine quality becomes increasingly important and thus further research must be undertaken.

Regardless of wine quality trends, it is of high importance for Greek wine industry to continue their research on the cultivation and vinification of the indigenous varieties that seemed to be better adapted and more heat tolerant to current and future warmer conditions than international (see Chapter 4).

Extended Abstract

Viticulture is a multifactorial science. Among these factors, climate (mainly air temperature) chiefly determines whether a given region can be considered suitable for producing wines of optimum quality. Greece is one of the traditional "Old World" winegrape regions and the home country for a significant number of indigenous varieties largely unexplored. The cultural importance and status of wine making in Greece is very important and hence wine sector attracts considerable attention due to its economic contribution in Greek domestic product.

The aims of this thesis were to 1) define the climate structure for each one of the principal winegrape areas in Greece; 2) classify the winegrape areas according to the main bioclimatic indices from the literature; 3) use this output to investigate potential future threats for viable viticulture in Greece; 4) investigate the temporal and spatial evolution of harvest dates and berry composition in Greece; 5) estimate heat demands of the currently cultivated winegrape varieties (both indigenous and international); 6) project future harvest dates of the studied varieties according to their heat requirements; 7) investigate wine quality trends; 8) explore the relative influence of climate-related varieties on wine quality and 9) project future wine quality in Greece.

The doctoral dissertation is divided in 6 chapters. Chapter 1 and 2 introduces the topics of interest through literature review. Chapter 3 used historical daily climatic temperature and precipitation to address the 1st, 2nd and 3rd aims of the thesis (i.e., 1st research question). For the 4th, 5th and 6th objectives (i.e., 2nd research question), chapter 4 used the climate dataset created in Chapter 3 to depict harvest dates and berry composition trends and to estimate the heat requirements of the studied varieties. Additionally, the output used to project future harvest dates in Greece. Chapter 5 used wine ratings from the Thessaloniki International Wine and Spirits Competition (TIWSC) and the climate dataset from Chapter 3 to investigate wine quality trends for the main indigenous varieties in Greece and determine if future climatic conditions would be beneficial to Greek wine quality in general. Finally,

Chapter 6 provides the conclusions of all chapters, tying together the findings of the thesis.

The results showed that mainland locations were generally colder while coastal and island are experiencing more extreme events and drier periods. Moreover, minimum temperatures significantly increased at a higher rate than the respective maximum in most of the cases. Climate change scenarios suggested significant shifts towards warmer and drier conditions according to the bioclimatic indices used putting additional pressure to the already hot regions in Greece. Furthermore, harvest dates are shifted significantly earlier, due to warmer conditions mainly during ripening period. In addition, trends in potential alcohol (acid) levels were found to be positively (negatively) correlated with maximum air temperatures in most cases. Future projection analysis showed that harvest dates are projected to shift earlier for over a month depending on the variety and the emission pathway. The indigenous Greek varieties (mainly the late ripening varieties) appear better adapted to the recent and projected future climate of the region, responding less to warming as compared to international varieties. Finally, wine quality trend analysis showed a statistically significant upward trend over the recent past in most of the varieties. Future wine quality predictions suggested wines of higher quality, especially during the later time period. These results reveal that Greek wine quality rating variations are mainly driven by higher maximum temperatures and drier conditions during the growing season of the grapevines.

This thesis presents a potential valuable tool for the producers to consult in order to manipulate phenological and region-specific climate changes under future conditions. However, there is a necessity for better understanding the upper thresholds of the traditional bioclimatic indices for each variety as well as the probability of underestimating the progress in wine making procedures and techniques and the implementation of the adaptive measures by the growers.

Ελληνική Περίληψη

Τα ζητήματα που πραγματεύεται η επιστήμη της αμπελουργίας είναι πολυπαραγοντικά. Η παράμετρος του κλίματος και ιδιαίτερα η θερμοκρασία του αέρα, καθορίζει σε μεγάλο βαθμό αν μια περιοχή μπορεί να θεωρηθεί κατάλληλη για την παραγωγή οίνων υψηλής ποιότητας, καλλιεργώντας συγκεκριμένες ποικιλίες. Η καλλιέργεια της αμπέλου στην Ελλάδα (όπου φιλοξενείται μεγάλος αριθμός γηγενών ποικιλιών) έχει μεγάλη παράδοση και ο κλάδος της οινοποιίας είναι ένας από τους σημαντικότερους τομείς της εγχώριας οικονομίας.

Σκοπός της παρούσας διατριβής είναι να: 1) καθορίσει τις κλιματικές συνθήκες που επικρατούν σε κάθε μια από τις «φημισμένες» αμπελουργικές περιοχές της χώρας, 2) κατηγοριοποιήσει τις περιοχές αυτές σύμφωνα με τους βιοκλιματικούς δείκτες της βιβλιογραφίας, 3) χρησιμοποιήσει τα παραπάνω αποτελέσματα για την διερεύνηση των κλιματικών συνθηκών των περιοχών σε μελλοντικές περιόδους, 4) διερευνήσει την διαχρονική εξέλιξη του σταδίου του τρύγου και των κύριων συστατικών της σταφυλής (ποσοστό αλκοόλης και επίπεδα οξύτητας) σε αρκετές από τις σημαντικότερες ποικιλίες και περιοχές αμπελοκαλλιέργειας της Ελλάδας, 5) υπολογίσει τις θερμικές ανάγκες των ποικιλιών (γηγενών και διεθνών ποικιλιών) που καλλιεργούνται στην χώρα, 6) εκτιμήσει μελλοντικά την πραγματοποίηση και εξέλιξη του σταδίου του τρύγου σύμφωνα με τις θερμικές απαιτήσεις κάθε ποικιλίας, 7) διερευνήσει την διαχρονική εξέλιξη της ποιότητας του παραγόμενου οίνου στην Ελλάδα, 8) διερευνήσει την επίδραση των κλιματικών παραμέτρων στην μεταβολή της ποιότητας του οίνου και 9) να προβάλλει την τάση του οίνου στο μέλλον υπό το πρίσμα της παγκόσμιας κλιματικής αλλαγής.

Η παρούσα διδακτορική διατριβή χωρίζεται σε 6 κεφάλαια. Τα 1ο και 2ο κεφάλαιο, αποτελούν μια εισαγωγή των ερευνητικών ερωτημάτων καθώς και μια βιβλιογραφική ανασκόπηση αυτών. Στο 3ο κεφάλαιο χρησιμοποιούνται ημερήσια κλιματικά δεδομένα για τις ανάγκες του 1ου ερευνητικού ερωτήματος (σκοπός 1, 2 και 3). Για τους σκοπούς 4, 5 και 6 (2ο ερευνητικό ερώτημα) χρησιμοποιήθηκαν τα αποτελέσματα του προηγούμενου κεφαλαίου για την αποτύπωση της τάσης του σταδίου του τρύγου, των συστατικών της σταφυλής και τον υπολογισμό των θερμικών απαιτήσεων των ποικιλιών. Τα αποτελέσματα αυτά χρησιμοποιήθηκαν στην συνέχεια για την προβολή του σταδίου του τρύγου στο μέλλον. Στο κεφάλαιο 5, χρησιμοποιούνται οινικές αξιολογήσεις από τον Διεθνή Διαγωνισμό Οίνου και Αποσταγμάτων Θεσσαλονίκης καθώς και τα κλιματικά δεδομένα του 3ου κεφαλαίου. Σκοπός είναι να αποτυπωθεί η πορεία της ποιότητας των παραγόμενων οίνων στην χώρα, να διερευνηθεί η σχέση μεταξύ ποιότητας οίνου και κλίματος και να προβληθεί η ποιότητα των ελληνικών οίνων σε δύο μελλοντικές περιόδους. Τέλος, το κεφάλαιο 6 αποτελεί μια ανακεφαλαίωση των ερευνητικών αποτελεσμάτων της διδακτορικής διατριβής.

Η ανάλυση των κλιματικών παραμέτρων έδειξε μια διαφοροποίηση του κλίματος κυρίως στις περιοχές της νησιωτικής Ελλάδας με θερμότερες και ξηρότερες συνθήκες κατά τον ετήσιο κύκλο της αμπέλου και κατά την περίοδο της ωρίμανσης της παραγωγής. Επιπλέον, η ελάχιστη θερμοκρασία αέρα αυξάνεται με γρηγορότερο ρυθμό και ένταση, από την αντίστοιχη μέγιστη στην πλειοψηφία των περιοχών μελέτης. Η ανάλυση του μελλοντικού κλίματος υπαγορεύει ακόμα θερμότερες και ξηρότερες συνθήκες , σύμφωνα με τους χρησιμοποιούμενους από την βιβλιογραφία δείκτες. Το στάδιο του τρύγου παρουσίασε στατιστικά σημαντική πρωίμιση στην πλειοψηφία των περιπτώσεων ενώ η περιεκτικότητα του γλεύκους σε αλκοόλ και οξέα, παρουσίασε αυξητική και πτωτική τάση, αντίστοιχα. Η ανάλυση της προβολής του σταδίου του τρύγου στο μέλλον έδειξε ότι αυτό θα μετακινηθεί έως και 40 ημέρες νωρίτερα, ανάλογα με την ποικιλία και το σενάριο μελέτης. Οι ελληνικές όψιμες ποικιλίες εμφανίζουν μεγαλύτερη ανθεκτικότητα σε σχέση με τις αντίστοιχες μέσης και πρώιμης ωρίμανσης και διεθνείς ποικιλίες. Τέλος, η ανάλυση της ποιότητας του οίνου στο πρόσφατο παρελθόν αλλά και στο μέλλον, παρουσιάζει σημαντική αυξητική τάση επηρεαζόμενη κυρίως από τις θερμότερες και ξηρότερες συνθήκες που επικρατούν κατά την βλαστική περίοδο ανάπτυξης του φυτού.

Η παρούσα διδακτορική διατριβή θα μπορούσε δυνητικά να αποτελέσει ένα σημαντικό συμβουλευτικό εργαλείο για την υποστήριξη των παραγωγών στα πλαίσια των φαινολογικών αποκρίσεων των ποικιλιών και των κλιματικών συνθηκών των περιοχών υπό το πρίσμα της κλιματικής αλλαγής. Ωστόσο, θα πρέπει να ληφθεί υπόψη ότι υπάρχει ανάγκη βελτίωσης ή/και αναθεώρησης των παραδοσιακών βιοκλιματικών δεικτών. Τα ανώτερα θερμοκρασιακά όρια μέσα στα οποία μια ποικιλία μπορεί να παράγει οίνους εξαιρετικής ποιότητας, πρέπει να οριοθετηθούν. Τέλος, σημαντικό ρόλο στην αυξητική πορεία της ποιότητας του ελληνικού οίνου πιθανότητα διαδραματίζει η βελτίωση των τεχνικών οινοποίησης αλλά και η αποτελεσματική εφαρμογή των μέτρων αντιμετώπισης που υιοθετούν οι παραγωγοί.

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