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

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ABSTRACT: Climate and viticulture are indisputably linked and thus knowledge of the predominant weather and climate conditions of a given area is essential for optimum variety selection, viable production and overall wine quality. In this study, an assessment 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 average temperature, growing degree-days, Huglin index, biologically effective degree-days, dryness index and cool night index) at 23 weather stations proximal to the key mainland, coastal and island viticultural areas of Greece was performed. 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 derived from the regional climate model RegCM4 suggested significant shifts towards warmer and drier conditions across all locations in the future. These conditions are very likely to advance phenology and harvest beyond what is considered suitable and will likely have detrimental impacts on wine quality. 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. Overall, the changes projected for the future climate will challenge the Greek wine industry to increase its adaptive capacity through better understanding of temperature thresholds for the varieties grown and the adoption of new cultivation techniques and strategies.

KEY WORDS climate change; viticulture; regional climate model; RegCM4; Greece

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1. Introduction

Viticultural production is climate-dependent, requiring specific climatic conditions (thermal and hydrological) during the annual cycle in order to viably grow and yield a quality harvest (Jones *et al.*, 2005). While winegrape varieties have heat accumulation needs to drive growth, extremes beyond what is considered optimum are very likely to result in advanced vine developmental stages including an early onset of the ripeness stage and harvest (Duchêne and Schneider, 2005). 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). Despite grapevine's resilience to drought, severe dryness, especially during the early stages of its annual growth cycle, can cause adverse effects on growth and productivity (Cifre *et al.*, 2005).

Several effects of changing climate on grapevine phenology have already been reported (e.g. Webb *et al.*, 2011). Koufos *et al.* (2014) showed significant advancement in harvest dates of several grape varieties in Greece, ranging from 8 to 18 days over the last 20–40 years. The earlier occurrence was significantly associated with increasing temperatures during the growing season. Similar regional results were also reported in Bordeaux in France (Jones and Davis, 2000), Veneto in Italy (Tomasi *et al.*, 2011), Franconia in Germany (Bock *et al.*, 2011) and Australia (Petrie and Sadras, 2008). Increasingly warmer conditions in the future could lead to an overall displacement of traditional varieties further to the north, east (in the Northern Hemisphere), towards the coast and up in elevation with the likely result of a redistribution of cultivated areas (Moriondo *et al.*, 2013).

In light of the strong relationship between climate and grape cultivation, several bioclimatic indices have been developed and widely used for viticultural zoning (see Section 2.1). While these indices have been historically used at individual locations over short time periods (i.e. weather stations) their temporal and spatial evolution with the use of high resolution datasets derived from regional climate models is providing more spatially explicit assessments (Fraga *et al.*, 2015; Eccel *et al.*, 2016; Moral *et al.*, 2016).

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The cultural and economic importance of viticulture in Greece is highlighted by its cultivation over the majority of the country, covering an area of approximately 110 000 ha with over 200 indigenous varieties (Lacombe *et al.*, 2011; OIV 2016) as well as international ones. 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). 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 other hand, precipitation records showed significant trends to drier conditions, mostly in winter (Mavromatis and Stathis, 2011). However, there is a lack of studies investigating countrywide climate relationships with grapevine phenology, productivity and wine quality (Koufos *et al.*, 2014). This 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. Zanis *et al.*, 2015) show that future climatic changes in the Mediterranean basin could be significant, the aim of this study is threefold: (1) to create a comprehensive daily climatic database from several sources in order to investigate historical trends of the most important climatic elements and viticultural bioclimatic indices in Greece, (2) to categorize Greek 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.

2. Material and methods

Daily observations of maximum (TX) and minimum (TN) air temperature (°C) and precipitation (PR) (mm), from 23 weather stations were obtained from the Hellenic National Meteorological Service (HNMS). Each station was selected due to its proximity to a principal winegrape area in Greece (<30 km away, on average) covering a wide range of *'terroirs'* considering elevation, geology and legislation on varieties and cultivation methods (Figure 1 and Table S1). 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 (1981–2010, 19 locations) and four other stations in important wine producing areas with 19–25 year records. 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 was followed (see Section 1.1 in Appendix S1, Supporting Information).

2.1. Climatic and bioclimatic indices

The data quality control and homogeneity tests using the RClimDex software (Zhang and Yang, 2004) are presented in Section 1.2 in Appendix S1. This software utilizes daily precipitation and temperature for the estimation of 27 core climatic indices. Twelve temperature- and eight precipitation-based indices were selected and calculated for the purposes of this study. The winegrape area categorization was achieved through six bioclimatic indices commonly used in viticulture studies (Jones *et al.*, 2010) (Table S2 in Appendix S1):

1. Growing season average temperature (GST) places winegrape areas into different climatic groups (Jones, 2006). This index also effectively relates mean growing season temperature with ripening potential of numerous varieties (Jones *et al.*, 2005).
2. Growing degree-days (GDD) classified into the Winkler Index (WI) (Winkler *et al.*, 1974). This index subtracts 10 °C (base temperature) from the daily mean temperature over the growing season (April–October for the Northern Hemisphere). GDD is very useful in predicting phenological stages, and when classed into Winkler Regions I–V, it gives an indication of the potential ripening of varieties and wine styles that can be produced (Anderson *et al.*, 2012).
3. Huglin Index (HI) is another formulation of GDD that gives more weight to maximum temperatures and uses a coefficient of a day length (k) [ranged from 1.005 (Si)–1.025 (Ka)]. HI is calculated for a 6-month period (April to September for the Northern Hemisphere) and is useful for characterizing areas according to their potential for viticulture (Huglin, 1978).
4. Biologically effective degree-days (BEDD) index (Gladstones, 1992) is similar to GDD but it is differentiated in three ways: (1) it reveals the concept of the effective daily heat summation introducing a specific upper threshold of 19 °C per day, (2) it uses a day length coefficient correction (K) similar to HI and (3) it employs daily adjustments according to the value of diurnal temperature range (Hall and Jones, 2010).
5. Dryness index (DI) classifies a given area according to its hydrologic conditions, introducing a water balance component (Riou *et al.*, 1994). It calculates, for a 6-month period (April–September for the Northern Hemisphere), the initial useful water reserve (200 mm), the precipitation (P), the potential transpiration (Tv) and the direct evaporation from the soil (Es). Tv and Es are then used to calculate the potential evapotranspiration (ETP) which in this study was calculated using the Thornthwaite method (Thornthwaite, 1948). The statistical package 'SPEI' was used to calculate the ETP (Beguería and Vicente-Serrano, 2013).
6. Cool night index (CI) relates daily temperature range with berry and wine quality attributes (e.g.

Figure 1. Map of Greece showing the locations of the weather stations used in this study. Bold letters indicate that the location has 30 years of climate records (1981–2010). Underlined bold letters indicate shorter period of records (see Table S1 in Appendix S1) while bold X's represents additional principal winegrape areas with no adequate climate data.

aroma) taking into account the nocturnal conditions of the ripening month (September in the Northern Hemisphere) (Tonietto and Carbonneau, 2004).

The temporal evolution of the bioclimatic and RClimDex indices was explored using ordinary least squares regression. 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. All statistical analyses and computations were carried out using the R statistical software (R Core Team, 2014).

2.2. Climate simulations and scenarios

General circulation models (GCMs) have been widely used to generate future projections in order to satisfy the growing interest for global climate change impacts. Regional climate models (RCMs) were developed in order 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). In this study, regional climate analysis was performed using daily simulations from the International Centre for Theoretical Physics Regional Climate Model v4.3 (RegCM). The RegCM enables a high horizontal resolution of $0.11° \times 0.11°$ (http://www.euro-cordex.net/). The representative concentration pathway 8.5 (RCP8.5) (the model simulations of RCP4.5 were not completed while this study was undertaken) was employed in order to assess the impacts of climate change for two different time windows [future projection 1 (FP1): 2021–2050 and future projection 2 (FP2): 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 (see Section 2.1 in Appendix S1). The results are presented in Figures 2–4. 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) 1981–2010. The respective mean monthly per cent changes were used in the case of the precipitation scenarios for the two future periods.

3. Results

3.1. Historical climate overview for the BP (averages and trends)

Mean TX during the growing season (GS; April–October) 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 1). 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. Diurnal temperature range (DTR: $\tau\chi - \tau\nu$) values were

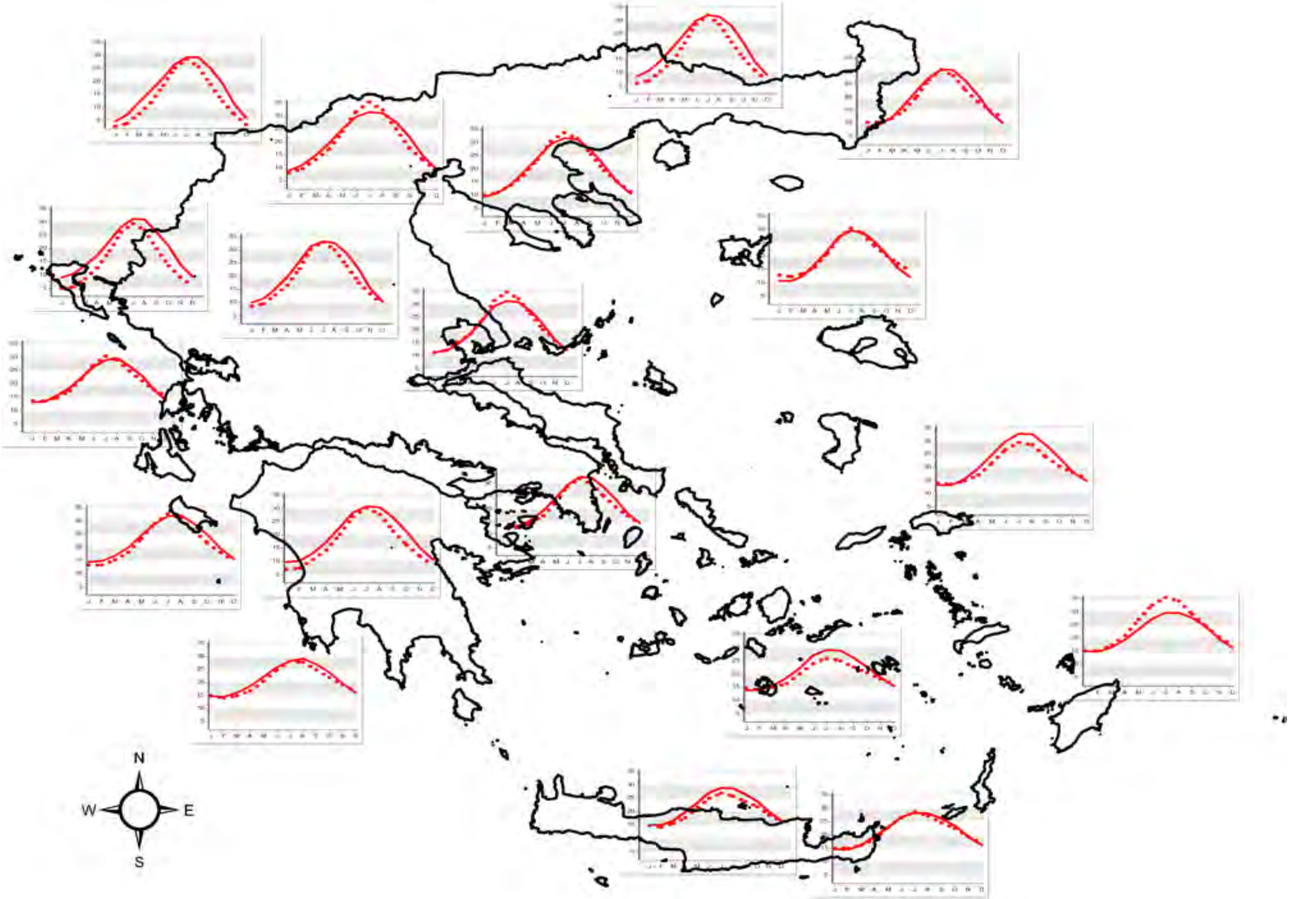

Figure 2. Comparison of mean monthly maximum air temperature (TX, °C) between observational data (solid lines) and the derived from the regional climate model (dashed lines) RegCM4 during 1980–2004. The vertical axes represent mean monthly maximum air temperature (TX), ranged from 2 to 36 °C, while the horizontal axes show the months starting from January. [Colour figure can be viewed at wileyonlinelibrary.com].

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 PR 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).

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 2). GST values ranged from a 17.3 (Ioannina) to 22.3 °C (Paros and Athens). With regard 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). Eighteen locations were characterized as 'Warm temperate' and 'Warm', according to HI, four as 'Very warm' and only Methoni as 'Temperate'. With regard to 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 regard to DI, 21 locations were classified as 'Moderate dry' while only Florina and Ioannina were considered as 'Sub-humid'.

The direction and magnitude of trends in each temperature-related indicator along with the statistical significance are also shown in Table 1. 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 regard 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 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

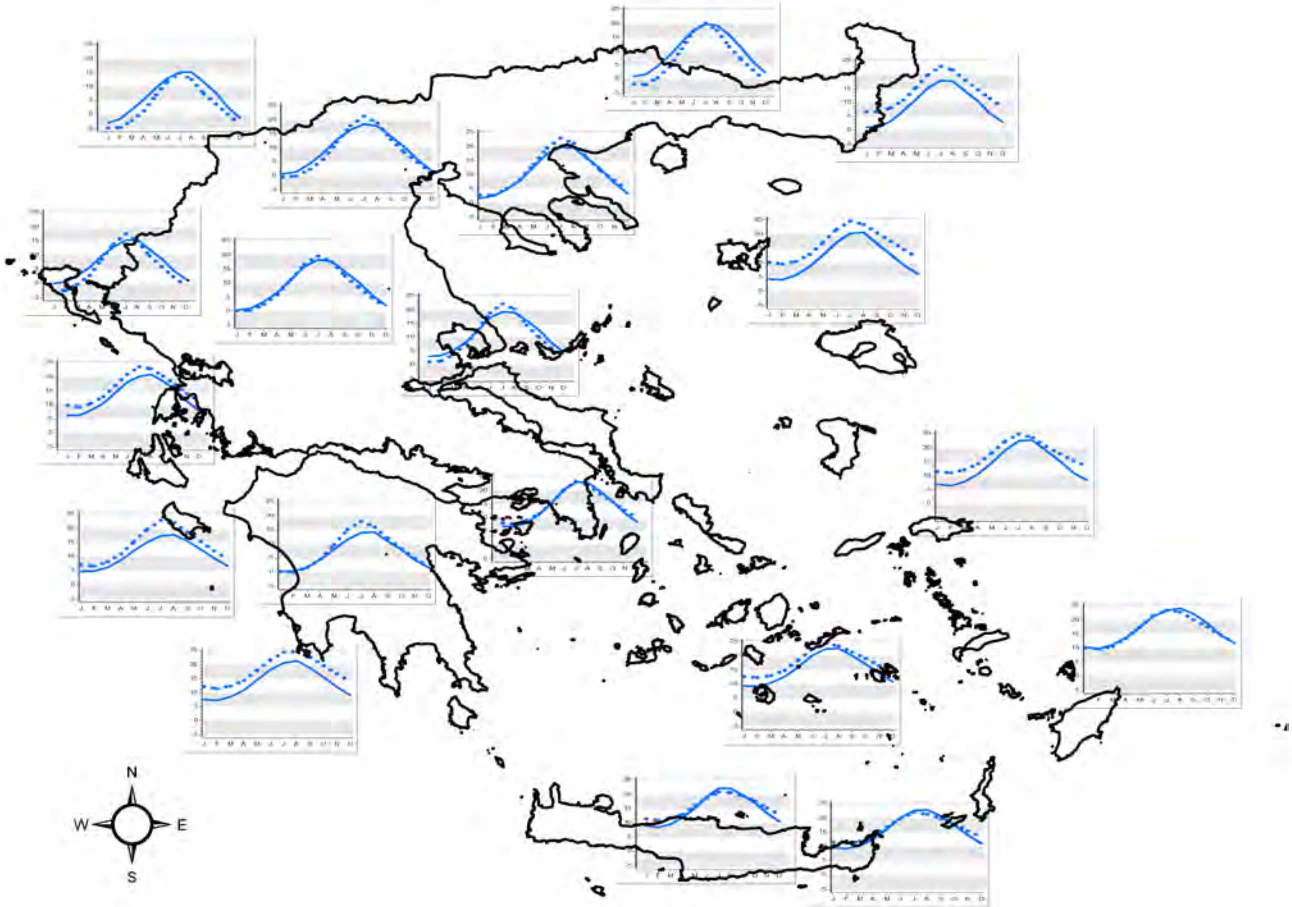

Figure 3. Comparison of mean monthly minimum air temperature (TN, °C) between observational data (solid lines) and the derived from the regional climate model (dashed lines) RegCM4 during 1980–2004. The vertical axes represent mean monthly minimum air temperature (TN), ranged from −5 to 25 °C, while the horizontal axes show the months starting from January. [Colour figure can be viewed at wileyonlinelibrary.com].

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 S1 and S2 in Appendix S1). However, Limnos and Drama were the only locations with consistent and significantly increasing trends on annual PR indices (not shown).

Regarding the trends in the bioclimatic indices (Table 2), 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 (not shown). 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, not shown). 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 2).

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

The regional classification according to bioclimatic indices for the BP and the FP1 and FP2 periods is presented in Figures 6–8 and Table 3. The wine producing areas classification for future climates and the climate overview is summarized in Section 2.2 and Tables S3 and S4 in Appendix S1. 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 6). For the FP1 period, the number of ‘Very hot’ locations markedly increased (from 3 to 14) (Figure 7), while under further warming (FP2 period) only six locations still remain within the range of being climatically suitable for viticulture (Figure 8).

The estimated GDD for the FP1 time period also led to noticeable shifts. The relatively cooler classes (i.e. ‘Regions III and IV’) were reduced (Figure 7) with respect to the BP (Figure 6), while the warmest class ‘Region V’ became more common. In FP2, the locations with suitable

Figure 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. [Colour figure can be viewed at wileyonlinelibrary.com].

thermal conditions for quality viticulture were limited to the higher elevation areas only (Florina and Ioannina) (Figure 8). Regarding the HI, eight locations were characterized as 'Temperate' and 'Warm temperate' over the BP (Figure 6). 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' (Figure 7). All locations, except for Methoni, are projected to be unsuitable for viticulture according to HI in the FP2 period (Figure 8). 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). 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 time period, four locations were characterized as insufficient ('Very dry') of meeting the hydrologic requirements for viticulture (Table 3). Under FP2, 13 more locations are projected to show unfavourable water availability conditions for viticulture.

The results from the analysis of the threshold indices are presented in Figures S1 and S2 in Appendix S1. 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.

4. Discussion and conclusion

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 PR) 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

Table 1. 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.

Locations (winegrape areas)	TX mean (°C)	TN mean (°C)	DTR (°C)	SU30 (days)	TR20 (days)	PR (mm)
Aktio (Lefkada)	23.5 (0.6)	15.3 (0.7)	8.2 (0.5)	15 (7)	23 (16)	265 (97)
	(+0.6)	**(+1.8)**	**(−1.2)**	**(+9.0)**	**(+33.0)**	(+87.0)
Alexandroupoli (Maronia)	24.9 (0.7)	13.4 (0.9)	11.5 (0.6)	47 (13)	16 (11)	198 (76)
	(+1.5)	**(+1.8)**	(−0.6)	**(+27.0)**	**(+27.0)**	(+135.0)
Anchialos	26.3 (0.6)	15.2 (0.6)	11.2 (0.4)	66 (13)	32 (15)	208 (89)
	(+1.2)	**(+1.2)**		**(+24.0)**	**(+27.0)**	(+60.0)
Argostoli[a] (Kephalonia)	23.5 (0.7)	15.0 (0.6)	8.5 (0.9)	18 (9)	22 (10)	229 (103)
Athens (Spata)	26.7 (0.8)	17.8 (0.7)	8.9 (0.4)	69 (17)	80 (15)	108 (46)
	(+1.5)	**(+1.2)**	(+0.3)	**(+39.0)**	**(+30.0)**	(−60.0)
Drama	26.2 (0.8)	14.9 (1.4)	11.3 (1.4)	66 (15)	35 (22)	265 (98)
	(+0.9)	**(+3.9)**	**(−3.3)**	(+9.0)	**(+57.0)**	**(+243.0)**
Florina (Amyndeo)	24.0 (0.9)	11.3 (0.7)	12.7 (0.9)	42 (15)	3 (3)	302 (131)
	(+0.3)	**(+1.8)**	**(−1.5)**	(+12.0)	**(+3.0)**	(−48.0)
Heraklio (Peza)	23.9 (0.6)	16.5 (0.5)	7.3 (0.2)	12 (5)	50 (10)	98 (60)
	(+1.5)	**(+0.9)**	**(+0.6)**	(+6.0)	**(+21.0)**	(+3.0)
Ioannina (Zitsa)	24.2 (0.8)	10.4 (0.6)	13.8 (1.0)	41 (13)	2 (3)	391 (141)
		(+1.2)	**(−1.2)**	(+3.0)		**(+255.0)**
Kavala[b] (Podochori)	23.7 (0.6)	13.8 (0.8)	9.9 (0.6)	22 (10)	13 (10)	165 (114)
Larisa (Tyrnavos)	27.3 (0.8)	13.1 (0.8)	14.1 (0.8)	84 (14)	12 (8)	210 (78)
	(+1.2)	**(+1.8)**	(−0.9)	**(+15.0)**	**(+18.0)**	
Limnos	24.5 (0.6)	15.9 (0.7)	8.7 (0.5)	33 (13)	54 (14)	156 (87)
	(+1.2)	**(+1.5)**	**(−0.6)**	**(+30.0)**	**(+27.0)**	**(+213.0)**
Methoni (Triffilia)	22.7 (0.5)	14.9 (0.5)	7.8 (0.2)	4 (3)	21 (9)	168 (73)
	(+0.9)	**(+0.9)**			**(+15.0)**	(+105.0)
Paros[a]	26.0 (0.7)	18.6 (0.6)	7.4 (0.7)	45 (12)	98 (13)	77 (54)
Pyrgos	27.4 (0.7)	14.5 (1.0)	12.9 (0.8)	74 (13)	17 (16)	219 (72)
	(+1.2)	**(+2.7)**	**(−1.5)**	**(+21.0)**	**(+36.0)**	(−108.0)
Rodos (Ebonas)	23.4 (0.5)	17.6 (0.6)	5.8 (0.4)	7 (4)	72 (17)	105 (86)
	(+0.9)	**(+1.5)**	**(−0.6)**	**(+3.0)**	**(+42.0)**	(−108.0)
Samos	24.9 (0.6)	15.4 (1.0)	9.5 (0.7)	42 (14)	43 (15)	112 (57)
	(+1.2)	**(+2.7)**	**(−1.5)**	**(+30.0)**	**(+39.0)**	(−90.0)
Santorini	25.2 (0.5)	19.0 (0.9)	6.2 (0.7)	29 (11)	101 (18)	56 (45)
	(+0.6)	**(+2.1)**	**(−1.5)**	**(+15.0)**	**(+54.0)**	(+33.0)
Sitia (Zakros)	25.1 (0.5)	19.1 (0.9)	5.9 (1.0)	19 (6)	107 (20)	98 (78)
		(+2.1)	**(−2.1)**	(+3.0)	**(+42.0)**	**(−135.0)**
Thessaloniki (N. Messimvria)	26.4 (0.7)	15.5 (0.8)	10.9 (0.7)	69 (14)	44 (20)	208 (65)
	(+0.9)	**(+2.1)**	**(−1.2)**	**(+18.0)**	**(+57.0)**	(+60.0)
Trikala_Imathias (Naoussa)	25.6 (0.7)	13.1 (0.7)	12.6 (0.7)	52 (15)	8 (9)	247 (89)
	(+1.5)	**(+1.5)**		**(+30.0)**	**(+18.0)**	(+96.0)
Tripoli (Mantinia)	25.7 (0.9)	10.5 (1.2)	15.1 (1.0)	60 (15)	4 (3)	239 (83)
	(+0.6)	(+0.6)		(+15.0)	(+3.0)	(−42.0)
Velo[c] (Nemea)	26.0 (0.7)	13.9 (0.9)	12.1 (0.8)	60 (14)	15 (15)	137 (50)

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. Bold letters indicate statistical significant trends at the 5% level, while underlined bold letters indicate lower statistical significance (10%). 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.

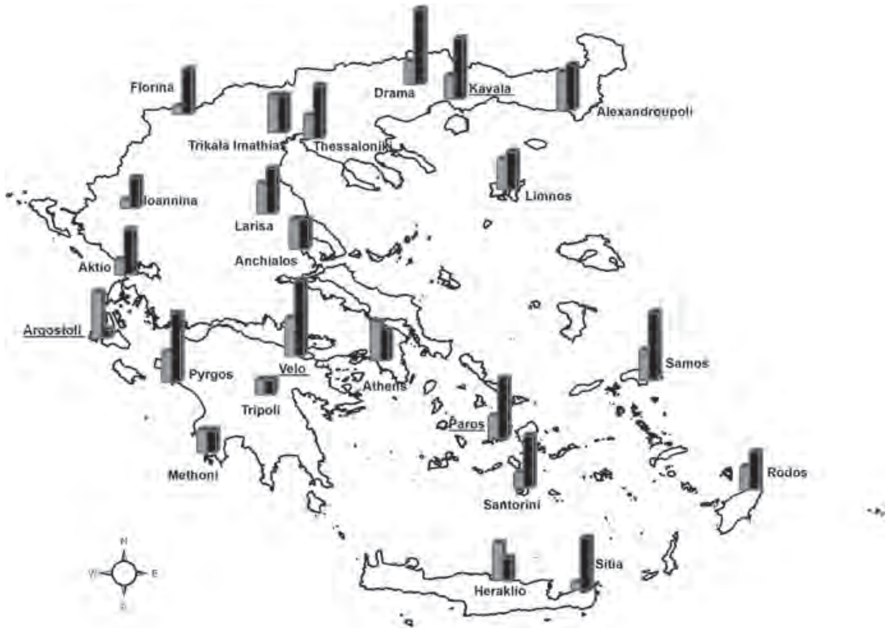

Figure 5. Magnitude of trends of mean maximum (TX, grey bars) and minimum air temperature (TN, black bars) during the baseline period (1981–2010). Underlined bold letters indicate shorter period of records (see Table S1 in Appendix S1).

CI and TR20) with more humid conditions (higher DI and PR) 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 PR, 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).

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). 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

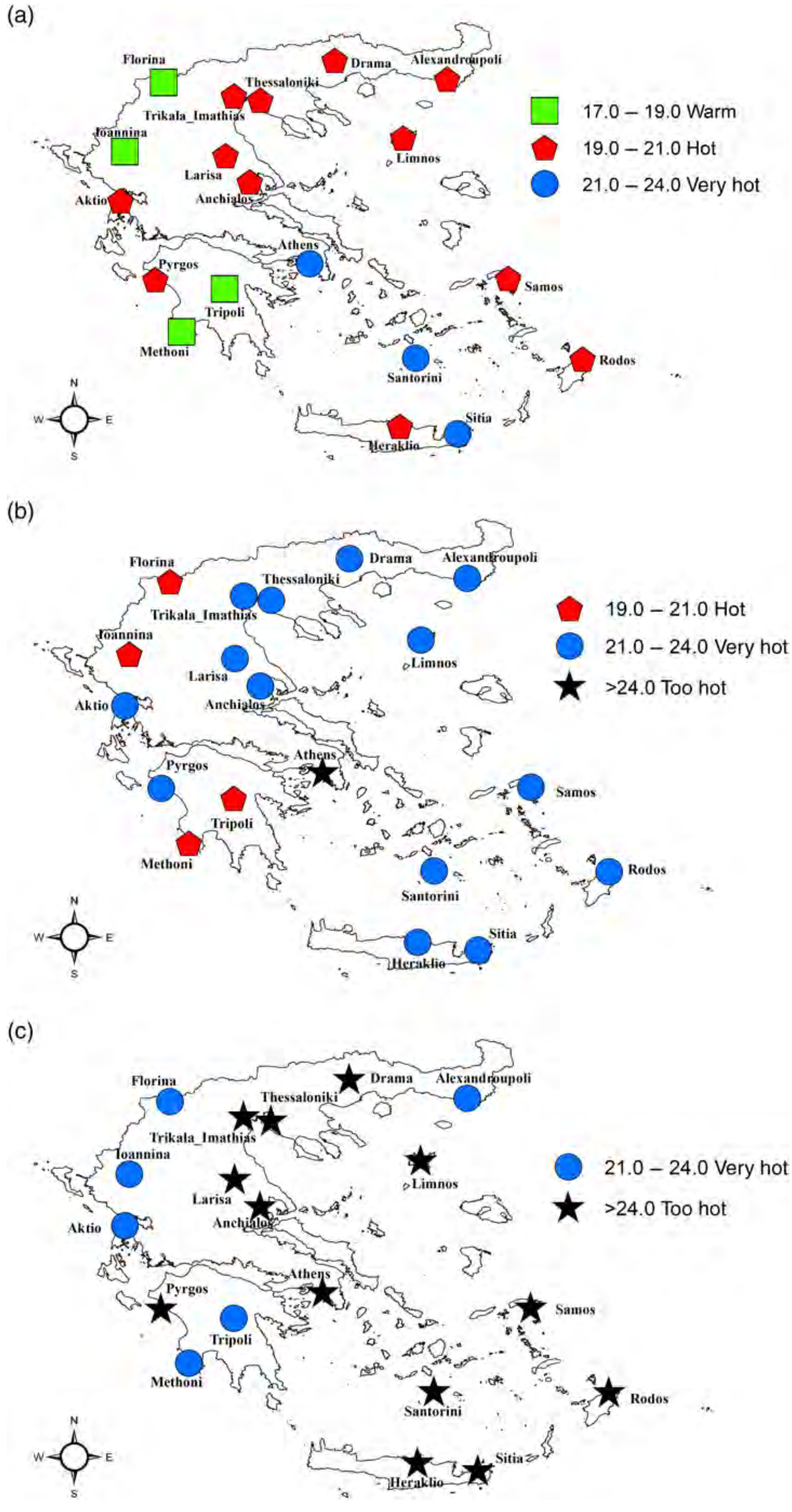

Figure 6. Direct impacts of climate trends on GST classification for (a) BP, (b) FP1 and (c) FP2 period. [Colour figure can be viewed at wileyonlinelibrary.com].

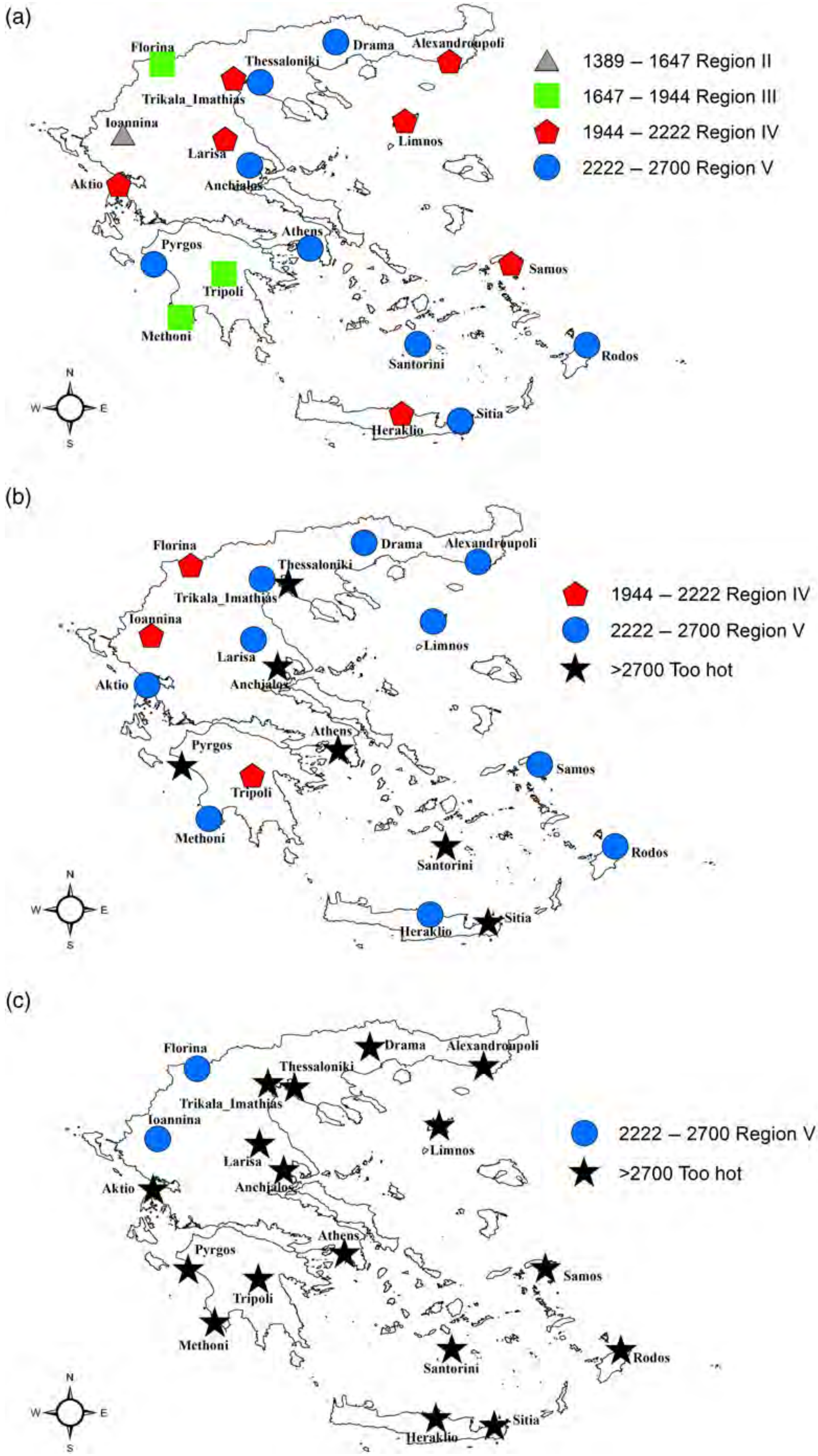

Figure 7. Direct impacts of climate trends on GDD classification for (a) BP, (b) FP1 and (c) FP2 period. [Colour figure can be viewed at wileyonlinelibrary.com].

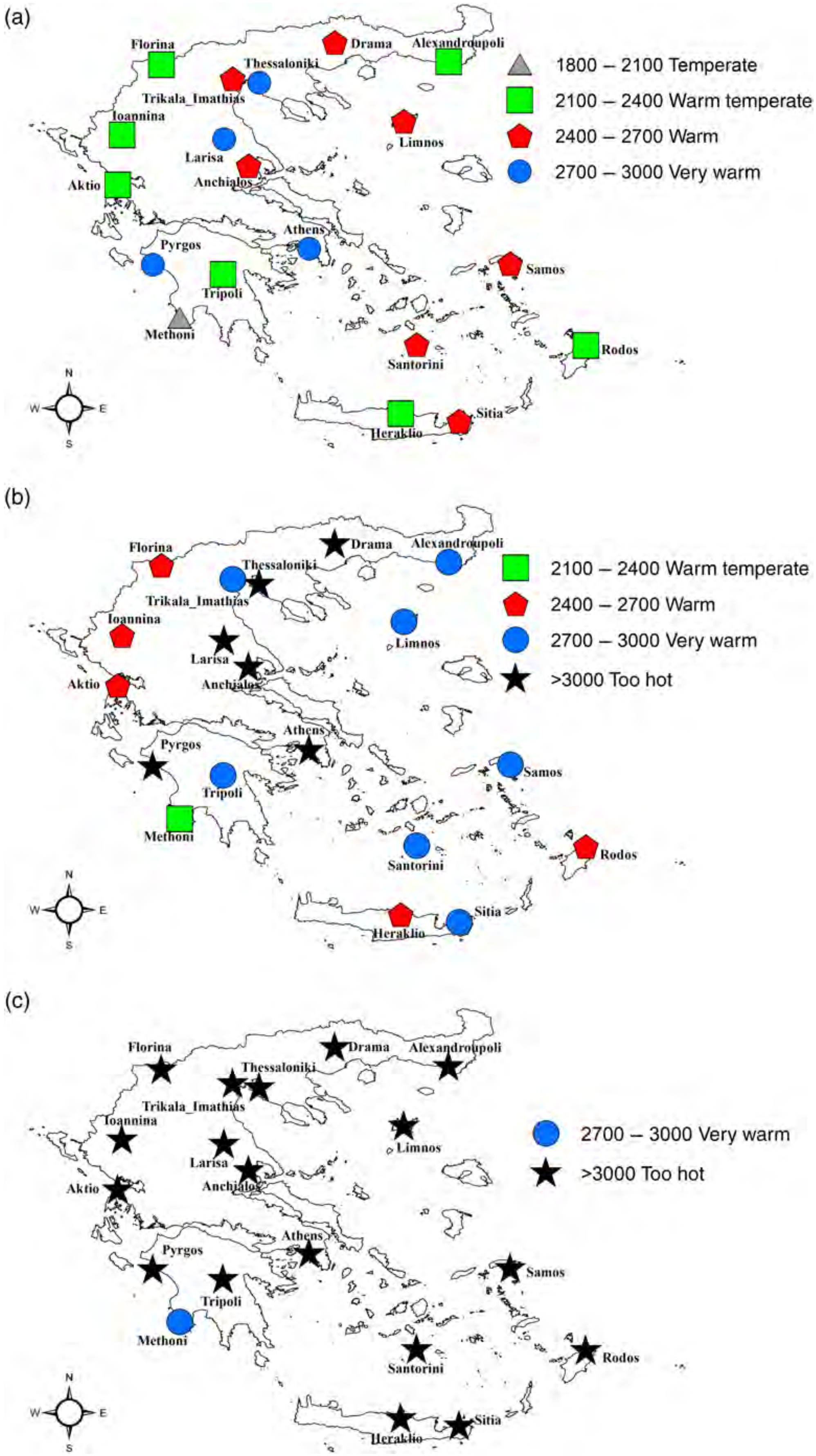

Figure 8. Direct impacts of climate trends on HI classification for (a) BP, (b) FP1 and (c) FP2 period. [Colour figure can be viewed at wileyonlinelibrary.com].

Table 2. 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.

Locations (winegrape areas)	GST (°C)	GDD (°C units)	HI (°C units)	BEDD (°C units)	DI (mm)	CI (°C)
Aktio (Lefkada)	**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)	**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	**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)	19.2 (Hot)	1981 (Region IV)	2173 (Warm Temperate)	1528 (4)	14.0 (Moderate dry)	16.6 (Temperate nights)
Athens (Spata)	**22.3 (0.06) (Very Hot)**	**2624 (12.0) (Region V)**	**2795 (12.3) (Very Warm)**	**1713 (2.5) (5)**	**−96.0 (−1.3) (Moderate dry)**	19.0 (0.01) (Warm nights)
Drama	**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)	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)	**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)	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)	18.7 (Warm)	1882 (Region III)	2234 (Warm Temperate)	1456 (4)	−8.0 (Moderate dry)	14.1 (Temperate nights)
Larisa (Tyrnavos)	**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	**20.2 (0.05) (Hot)**	**2184 (9.4) (Region IV)**	**2423 (7.9) (Warm)**	1562 (1.9) (4)	−35.0 (0.4) (Moderate dry)	16.9 (0.03) (Temperate nights)
Methoni (Triffilia)	**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[a]	22.3 (Very Hot)	2640 (Region V)	2699 (Warm)	1746 (5)	−94.0 (Moderate dry)	20.1 (Warm nights)
Pyrgos	**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)	**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	**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	**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)	**22.1 (0.04) (Very Hot)**	**2588 (7.6) (Region V)**	2553 (2.6) (Warm)	1741 (0.6) (5)	−71.0 (−1.3) (Moderate dry)	**20.8 (0.07) (Warm nights)**
Thessaloniki (N. Messimvria)	**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)	**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)	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)	19.9 (Hot)	2133 (Region IV)	2521 (Warm)	1592 (4)	−31.0 (Moderate dry)	15.2 (Temperate nights)

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. Full description of the classes and the period of calculations are described in Table S2. Bold letters indicate statistical significant trends at the 5% level. Superscript letters [a](1992–2010), [b](1986–2010) and [c](1988–2010) indicate shorter period of records and therefore, trends were not calculated.

Table 3. 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.

Index	Classes	1981–2010		2021–2050		2061–2090	
		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

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 favourable period (between 10 September and 10 October for optimal varietal expression) for the Northern Hemisphere (Van Leeuwen and Seguin, 2006). More 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 the months of 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 S5 in Appendix S1, future budburst dates were estimated using a simple model adopted by Jones and Davis, 2000) which would likely result in unbalanced wines through higher sugar and lower acid concentration in the grape must. Moreover, higher nocturnal temperatures during July and 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.

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 time period) (Table S5 in Appendix S1). However, further warming will likely result in a significantly earlier harvest (about a month earlier than today under FP2 time period) and actions should be taken to preserve the variety's flavour uniqueness. 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 this relationship have been suggested.

In conclusion, Greece has a long tradition of viticulture and wine production and has been doing so in one of the world's hottest grape growing territory. As such, Greek viticulture will likely face climate change impacts in the future that could challenge the future of the industry. Taking into account the earlier occurrence of vine phenological stages according to future climate modelling, an adjustment to the standard period of calculation of bioclimatic indices (i.e. April–October for the Northern Hemisphere for GDD or September for CI) could be considered in future climate studies. However, this adjustment would greatly depend upon the heat requirements of specific varieties. In this study, the standard period of calculation as used in previous studies (e.g. Hall and Jones 2010; Jones *et al.* 2010) was selected for computing bioclimatic indices, in order to keep a common approach with published literature. While this study examined the highest emission scenario (RCP8.5) for future climates, it is plausible that society could transition to a lower emission pathway (RCP4.5) which would likely lead to lower impacts on winegrape production. Regardless of the emission trajectory, the viability of the Greek viti-vinicultural sector will likely be challenged in the near future. It is therefore of outmost importance for the Greek wine industry to continue to investigate the heat tolerance of cultivated indigenous varieties in order to establish specific thresholds in temperature extremes and explore their suitability for producing high quality wines outside the current temperature ranges.

Supporting information

The following supporting information is available as part of the online article:

Appendix S1. Observational data preparation and model evaluation.

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