International Journal of *Geo-Information*

MDPI

Article

Challenges to Viticulture in Montenegro under Climate Change

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Abstract: The Montenegrin climate is characterised as very heterogeneous due to its complex topography. The viticultural heritage, dating back to before the Roman empire, is settled in a Mediterranean climate region, located south of the capital Podgorica, where climate conditions favour red wine production. However, an overall increase in warmer and drier periods affects traditional viticulture. The present study aims to discuss climate change impacts on Montenegrin viticulture. Bioclimatic indices, ensembled from five climate models, were analysed for both historical (1981–2010) and future (2041–2070) periods upon three socio-economic pathways: SSP1-2.6, SSP3-7.0 and SSP5-8.5. CHELSA (≈1 km) was the selected dataset for this analysis. Obtained results for all scenarios have shown the suppression of baseline conditions for viticulture. The average summer temperature might reach around 29.5 °C, and the growing season average temperature could become higher than 23.5 °C, advancing phenological events. The Winkler index is estimated to range from 2900 °C up to 3100 °C, which is too hot for viticulture. Montenegrin viticulture requires the application of adaptation measures focused on reducing temperature-increase impacts. The implementation of adaptation measures shall start in the coming years, to assure the lasting productivity and sustainability of viticulture.

Keywords: grapevine; winegrowing; bioclimatic indices; Shared Socioeconomic Pathways; projections; climate impacts; adaptation; Montenegrin viticulture; Western Balkans; CHELSA

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Citation: Fernandes, A.; Kovač, N.; Fraga, H.; Fonseca, A.; Šućur Radonjić, S.; Simeunović, M.; Ratković, K.; Menz, C.; Costafreda-Aumedes, S.; Santos, J.A. Challenges to Viticulture in Montenegro under Climate Change. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 270. https://doi.org/10.3390/ijgi13080270

Academic Editors: Wolfgang Kainz, Cheng Li, Fei Zhang, Mou Leong Tan and Kwok Pan Chun

Received: 4 June 2024
Revised: 18 July 2024
Accepted: 25 July 2024
Published: 30 July 2024

1. Introduction

Climate change involves an alteration of the mean and the variability of a wide range of climatic variables, associated with shifts in the Earth's atmosphere and subsequent effects on the other Earth system components [1,2]. In 1896, Savante Arrhenius had already anticipated anthropogenic climate change [3] by quantifying the contribution of CO_2 to the greenhouse effect. The first major conference on this topic, human activity affecting the world's climate, was the World Climate Conference in February 1979 in Geneva [4]. Thereafter, climate change communication to the general public and awareness thereof have witnessed a steep rise [5,6]. According to IPCC [7], the global temperature has faced an abrupt increase since 1950, mostly from anthropogenic-induced changes in climate [8]. The most pronounced climate change effects are the rise in temperature, increased occurrence of extreme weather events, and sea level rise [9–12]. Impacts of climate change affect all social and economic sectors to a higher frequency, and intensity of floods [13], severe droughts, and heatwaves, among other extreme weather and climate events [11]. Multiple laws, programs, and objectives have been settled to guide society to offset this escalating trend, but it is uncertain which pathway society will follow [14,15], and so, the application of mitigation measures is intrinsically vulnerable to political change and socio-economic development [16,17]. Under this uncertainty, future climate projections shall be analysed through an overarching overview encompassing different anthropogenic forcing scenarios, based on the Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) [18,19]. Data from climate projections are essential inputs for simulation models to quantify future environmental and/or socio-economic consequences. For example, in the scope of agriculture, using future climate data as an input for crop models will enable the estimation of future crop responses [20].

Specifically, for viticulture, there are indeed multiple consequences of climate change, starting with phenology [21,22]. With increased temperatures, the natural dormancy of grapevines is disturbed [23], and phenological events are advanced [24]. As a result, grape berry composition and wine quality parameters change [25]. When climate conditions are not suitable, wine quality may become compromised [26]. With warm temperatures, the trend is to produce unbalanced wines; grape berries accumulate more sugar and, subsequently, higher wine alcohol content and fewer flavours [27,28]. In the worst case, climate change makes areas unsuitable for viticulture, as conditions become too warm and dry [29–31]. Relative to other world regions, the Mediterranean is highly vulnerable to climate change, as it is anticipated to experience a faster temperature increase, with longer warmer and drier periods [32], and a decline in precipitation [33]. Accordingly, the viticulture sector direly needs strategies to guarantee water availability, achieve a balanced phenology alignment, maximise the yield, and achieve the necessary berry composition properties for wine production [21,34,35]. The review from Naulleau et al. [36] revealed that canopy management is effective for adapting phenology in the short term. In the long term, relocation, plant material changes, and changes to vineyard design are strategies with proven results. The selection of plant material, irrigation, and soil management are the most crucial aspects to achieve sustainable yields [36]. In connection with viticulture, several studies have been conducted that provide a global analysis concerning large researched areas (such as continents). Other studies, such as Jones and Alves' [37], portray smaller regions, depicting more detailed information. Nonetheless, there is still a lack of climate change impact studies focusing on viticulture in specific parts of the world. This is the case for Montenegro, where viticulture plays a significant role in the country's economy [38].

Montenegro's climate is characterised by multiple studies [39–49]. Resorting to observed data, temperatures in Montenegro have increased in recent decades [40,49]. The country is also facing a decrease in precipitation during the summer, and an increase in the autumn, but overall, the total annual precipitation is slightly decreasing [39]. However, future projections of precipitation do not reveal significant changes until 2100 [42], while average annual temperatures will increase from 2 °C up to 5 °C [50,51]. Among the multiple consequences, it is estimated that there will be decreases in rainfed potato yields above 30% [52] and for olives there will be a decrease of approximately 15% [53]. In the scope of climate change impacts on viticulture, there are no studies for Montenegro, raising the necessity of exploring this. For this reason, the present study was accomplished to fulfil three main objectives: (1) to estimate future climate changes in Montenegro; (2) to assess potential impacts on local viticulture; and (3) to delineate adaptation strategies, to ensure the resilience of grape production in Montenegro.

2. Materials and Methods

2.1. Study Area

Montenegro is located in Southeastern Europe on the Balkan Peninsula (Figure 1a). According to CORINE Land Cover [54], the land comprises 79% forested areas, 16% agricultural areas, 3% wetlands and water bodies and 2% artificial surfaces (Figure 1b). Montenegro's landscape is characterised by its mountainous terrain (Figure 1c), over two-thirds of which features diverse macro relief units, such as mountain plains, valleys, basins, and mountains, leading to a rich variety of natural resorts [55]. This regional complex topography [56] results in the presence of multiple climate types, subtypes, and varieties across the country [43,45], from a Mediterranean climate on the coast [57] to alpine conditions in the inner mountains [58]. According to weather station data, the total annual precipitation ranges from 768 mm in the northern zone up to 4700 mm in the mountains [45,59]. Mean annual temperatures vary from 4 °C in the northern mountains to 17 °C near the Adriatic coast [45]. Montenegro's flora and fauna are remarkably diverse due to the complex interplay between topography, climate, geology, and soil complexity, making it a biodiversity hotspot [55,60].

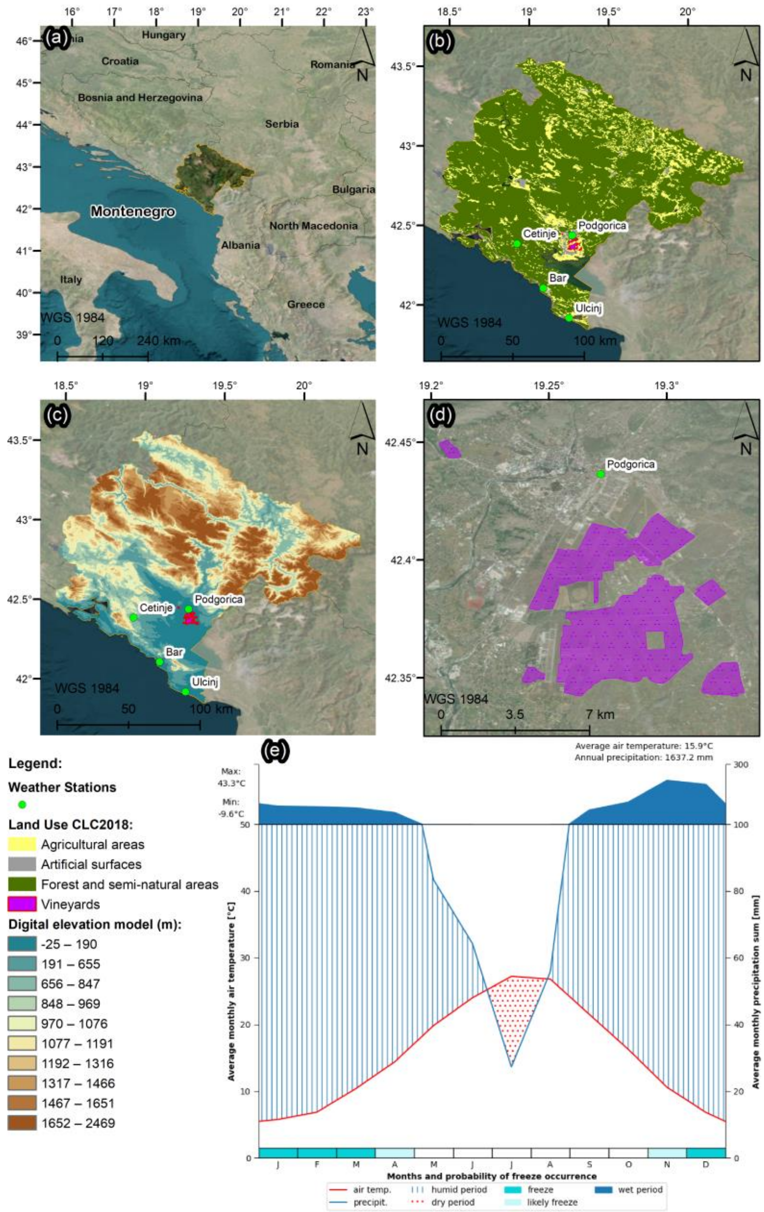

Figure 1. Representation of the Study Area. (**a**) is the location of Montenegro and contiguous countries. (**b**) is the location of Montenegro vineyards and other land uses, according to CLC 2018, and the location of weather stations. (**c**) portrays the elevation of Montenegro, in 10 quantiles. In (**d**), the vineyards of Montenegro near Podgorica's weather station are shown. In (**e**), an ombrothermic diagram of Podgorica weather station data (cf. legend for details) during the Historical period (1981–2010) is depicted.

The viticulture sector in Montenegro is particularly relevant due to the quality of grapes and wine, with lower-elevation wines being distinctive for their superior quality [61]. Montenegro is located within the global vine belt at a similar latitude to famous wine regions like Tuscany and Umbria in Italy and La Rioja in Spain [62]. Considering this geographical position and the influence of the Mediterranean climate (Figure 1e), the long tradition of grape growing and winemaking legacy dates back to the pre-roman period [63]. Viticulture has a rich heritage in grapevine growing and winemaking, contributing to its economic success [64]. Montenegro is among the top 50 wine-producing countries; however, exportation has been decreasing in the last decade from USD 17M down to USD 15M in 2023 [65], with an average production of 38 thousand tons per year [66]. Still, viticulture practice is increasing in Montenegro, with currently more than 500 grape producers [67] across the four defined viticulture regions [68]. The biggest one is the Montenegrin basin of Lake Skadar, followed by the Montenegrin coast, the Montenegrin north, and the smaller viticulture region of Nudo. In terms of soil types, the basin of Lake Skadar contains mostly red clays, eutric cambisols, and alluvial soil; the coast also contains red clays and eutric cambisols, but also includes rankers [61,69,70]. The region of Nudo is dominated by rendzina, while, in the North Region, there are brown cambisols and also rendzina [69,70].

The core of viticulture, including the public and private sectors (with 97% of producers), is located between Podgorica and Lake Skadar, where ideal conditions for the growth and development of authentic grape varieties can be found. Plantaže, a state-owned company, owns around 2000 ha of vineyards (Figure 1d). The assortment of grape varieties is in line with warmer climatic conditions and the tradition of red wine production, considering the vineyard areas that are primarily based on black grape varieties. Still, other vineyards are also dedicated to white wine varieties, and the least acreage is allocated to table grape varieties intended for direct consumption [68]. The main part of the vineyard area is situated at elevations from 0 to 100 metres, and most of the registered vineyards are within this elevation range. Most vineyards are planted with Montenegrin autochthonous grape varieties, Vranac variety (over 97% of the vineyards), and a Kratošija variety (50.5% of the vineyards). Kratošija was the main grape variety in Montenegro until the onset of the phylloxera crisis caused the removal of many ageing vines, prompting their substitution with fresh planting material [71]. During this period, the replacement of withered Kratošija vines was done with grafted Vranac plants, so favoured by grape growers for their production of deeply dark red ruby wines [72]. Consequently, the cultivated area of Kratošija decreased, paving the way for Vranac to emerge as the prevailing and emblematic cultivar in Montenegro throughout the twentieth century [73]. Alongside these prominent varieties, lesser-known indigenous cultivars such as Žižak, Krstač, Čubrica, and Bioka can be identified in Montenegro, with unique simple sequence repeats [73–76].

In Montenegrin vineyards, agro-technical operations such as winter and green pruning, protection, cluster reduction and defoliation are applied. The space between rows varies from 0.6 to 1.2 m, with double and single Guyots and cordons being used. Montenegrin viticulture is moving towards the application of precision viticulture, with the installation of soil moisture and meteorological sensors, to support smart irrigation [77–79], and also the usage of digital pheromone traps. Towards the adaptation to climate change, rootstocks resistant to higher temperatures are being used and research is being performed to find autochthonous grape varieties which are resistant to climate change [80].

2.2. Datasets

Montenegro's future climate was analysed using the CHELSA dataset [81,82] of observations and climate model projections downscaled to a resolution of 30 arc-sec (approximately 1 km). The CHELSA dataset provides multiple sub-datasets, with different time steps, from daily to climate normal (30-year averages); also, the dataset is already bias-adjusted [83] using a trend-preserving bias correction [84]. Our analysis focuses on the historical period from 1981 to 2010 and the future period from 2041 to 2070. Future climate scenarios are derived from the Coupled Model Intercomparison Project Phase 6 scenarios

(CMIP6) [85], more specifically the Shared Socio-Economic Pathways [86]: SSP1-2.6; SSP3-7.0 and SSP5-8.5. For each pathway, simulations of 5 global climatic models (GCMs) were available [87], as presented in Table 1. For each future projection, data from the 5 GCMs were ensembled by median.

To further test the robustness of the CHELSA dataset, historical period data was compared with observation-based gridded climate data (with a spatial resolution of 0.1° latitude × longitude) from ERA5-Land [88] and E-OBS [89], version 27.0e. Additionally, the 3 datasets were compared with observed data from 4 weather stations (WSs), provided by the Institute of Hydrometeorology and Seismology [90]. These contain daily temperature and precipitation data in the cities of Podgorica, Bar, Cetinje, and the Ulcinj Municipality [90], Figure 1.

Table 1. Used climate models.

Abbreviation	Model	Source
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory Earth System Model Version 4.1	Dunne et al. [91]
UKESM1-0-LL	UK Earth System Model 1.0 Low Resolution	Sellar et al. [92]
MPI-ESM1-2-HR	Max Planck Institute Earth System Model Version 1.2—High Resolution	Gutjahr et al. [93]
IPSL-CM6A-LR	Institut Pierre-Simon Laplace Earth System Model—Coupled Model version 6A—Low Resolution	Lurton et al. [94]
MRI-ESM2-0	Meteorological Research Institute Earth System Model Version 2.0	Yukimoto et al. [95]

2.3. Methods

2.3.1. Validation of CHELSA Dataset

The first step was to validate the CHELSA historical observation dataset, by comparing it with observation-based data from E-OBS and ERA5-Land. Here, we focused on climatological means of temperature and precipitation within the grapevine growing season, from 1 April to 31 October [21,96]. This comparison was performed to validate if the spatial pattern of precipitation and temperature would be similar between the 3 datasets.

Furthermore, the three observational datasets were compared with the observed data from the 4 WSs, to confirm the feasibility of CHELSA. Temperature and precipitation climatologies of each dataset (CHELSA, E-OBS, ERA5-Land) were compared for the historical period using 6 performance metrics: Mean Absolute Error (MAE); Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Percent Bias (PBIAS), Nash–Sutcliffe Efficiency (NSE), and Pearson Correlation.

2.3.2. Evaluation of Future Climate Changes

The next step was to estimate the climate for Montenegro's Viticulture, calculating bioclimatic indices for the historical and future periods, using the 5 GCMs for future SSP scenarios. Projections for each scenario were ensembled from the GCMs, to capture the range of uncertainty in regional climate projections [97], providing better results than individual models [98]. Between the ensemble, through average or median, median was selected to minimize the effect of outliers on the reported projections for Montenegro [99].

Six bioclimatic indices were selected: mean temperature from April to October; mean temperature of the warmest quarter; temperature seasonality; growing degree days heat sum above 10 °C (GDD10); Winkler index (WI); and growing degree days (NGD10) with average temperature above 10 °C. The average temperature from April to October is particularly important since it marks the beginning of flowering until leaf fall. The mean temperature of the warmest quarter is relevant, not only for its influence on grape growth and development but also because high temperatures during the warmest quarter might lead to heat stress, and in consequence, impact the grape development and subsequently the wine quality. Temperature seasonality, the standard deviation of monthly average temperature, is a relevant indicator since it assesses seasonal temperature transitions.

Growing degree days (GDD10) and Winkler index were selected for this study since both are characteristic bioclimatic indices in the scope of viticulture. Both are the sum of temperature degrees above the growth threshold (10 °C, for grapevines), with the difference that GDD10 is calculated for the full year, while WI is specific for the growing season. The growing degree days with an average temperature above 10 °C (NGD10) is a similar parameter, representing the number of days with suitable growing conditions. Furthermore, we also considered three additional bioclimatic indices for this study, but these are only reported in the Supplementary Material: mean annual temperature; precipitation amount from April to October, and annual precipitation amount.

The vineyards of Montenegro (henceforth MVAs—Montenegro Vineyard Areas) were identified in CORINE Land Cover 2018 (Figure 1b–d). For the MVAs, data was analysed for the historical and future periods, but the values of all models for each SSP scenario were analysed without ensembling, to understand the differences among GCMs, while for the whole country, projections were ensembled by the median.

The characterisation of the climate in the MVAs was performed using the data from Podgorica's WS, which is located in the vicinity of the vineyards (Figure 1d). To compare the temporal trend of the bioclimatic indexes in vineyards during the historical period, the annual average of each of the selected indices was calculated, and then Sen's slope was calculated with a statistical significance of 5% using the Scipy Python library.

3. Results and Discussion

3.1. Validation of CHELSA Dataset

Climate change in Montenegro and MVAs was assessed through the CHELSA dataset. To understand if CHELSA is a viable dataset, the CHELSA observations (for the historical period) were compared with the data from E-OBS and ERA5-Land (Figures 2 and 3).

A clear difference in resolution among datasets is visible, and in terms of temperature range, the dataset differences are not perceptible (Figure 2). Precipitation (Figure 3) patterns and values are highly different between the three datasets, with CHELSA showing a much more heterogeneous distribution and values up to 1700 mm during the growing season. E-OBS and ERA5-Land show a considerably lower peak precipitation with 600 mm and 1200 mm, respectively. In the Supplementary Material a scatterplot of the grid boxes of each dataset is provided, converted into the grid distribution and grid size of E-OBS, Figure S1.

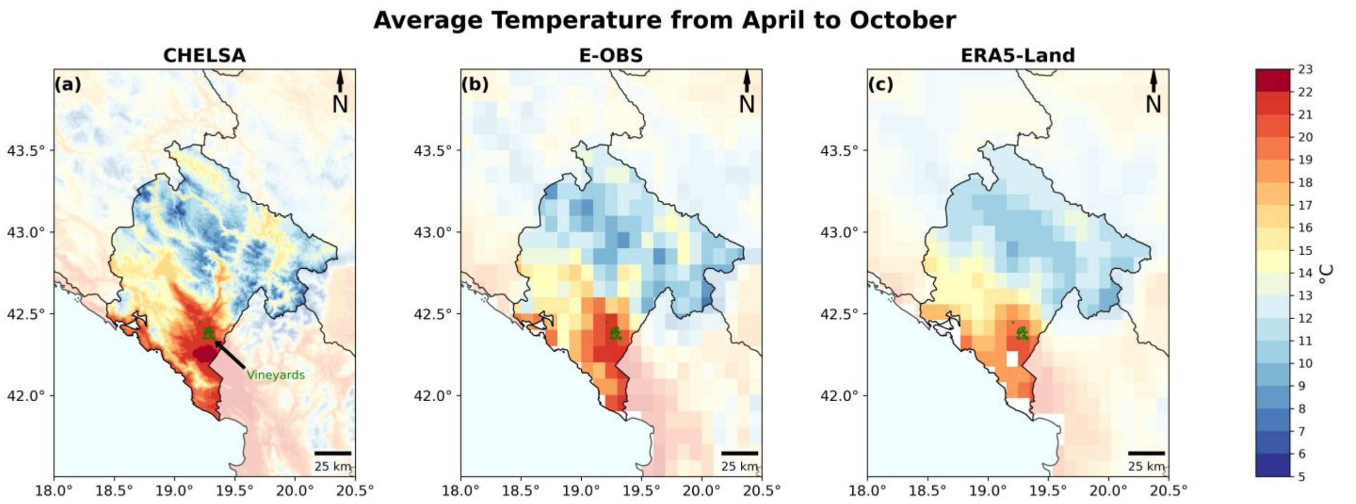

Figure 2. Representation of the climate average of daily average temperature during the growing season (from April to October), for the Historical period (1981–2010), for CHELSA (**a**) with a resolution of 0.008°, E-OBS (**b**) with a resolution of 0.1°, and ERA5-Land (**c**) with a resolution of 0.1°.

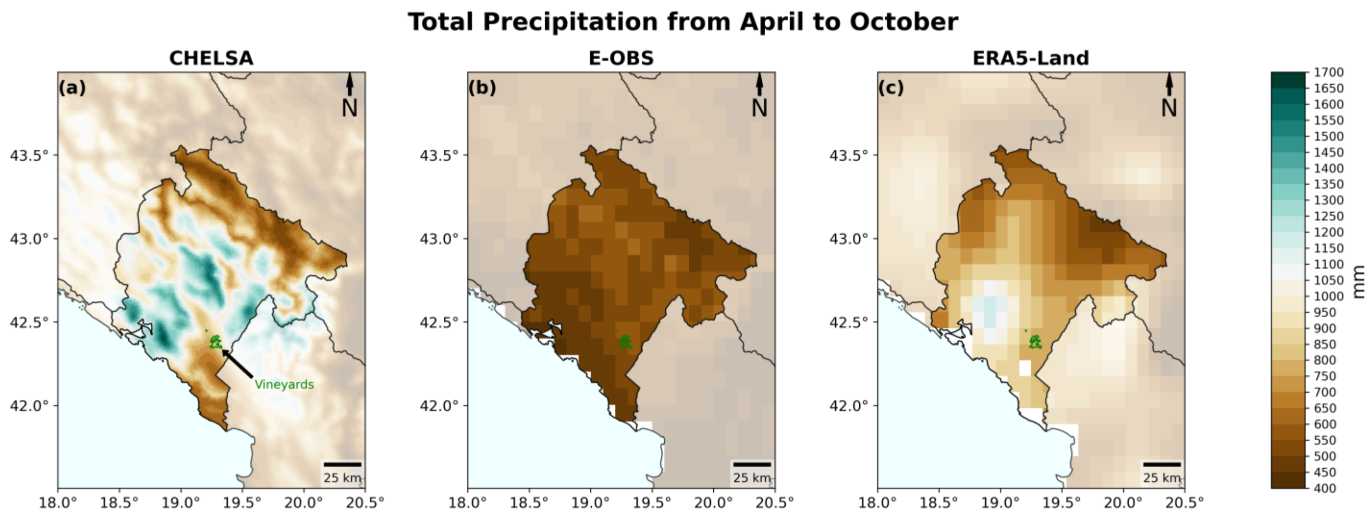

Figure 3. Representation of the climate annual precipitation during the growing season (from April to October), for the Historical period (1981–2010), for CHELSA (**a**) with a resolution of 0.008°, E-OBS (**b**) with a resolution of 0.1°, and ERA5-Land (**c**) with a resolution of 0.1°.

Temperature distribution from CHELSA is closer to E-OBS, while ERA5-Land features a more scattered pattern (Figure S1a–c). Precipitation reveals apparent differences among all datasets (Figure S1a–c). E-OBS precipitation is far more homogeneous and lower compared to the other two datasets, with values ranging between 400 to 600 mm in all of Montenegro. CHELSA and ERA5-Land are more similar in terms of precipitation intensities but also differ considerably in patterns. In general, CHELSA temperatures and precipitation resemble the orographic features of Montenegro. The dataset differences, especially for precipitation, raise the question of if CHELSA is a reliable dataset, portraying a realistic climate of Montenegro. Therefore, various statistics for temperature and precipitation (Table 2) were calculated for each dataset to compare them with the data from four weather stations in lowland Montenegro. The ERA5-Land grid contains data for Ulcinj weather station. CHELSA and E-OBS show a higher agreement across the temperature statistics with the WSs, except for the Cetinje station. E-OBS is most accurate for Podgorica's WS, which is the closest WS to the MVAs, with an MAE and RMSE of 0.3 °C. However, CHELSA MAE and RMSE are only slightly higher (0.5 °C). Despite ERA5-Land showing a more homogeneous MAPE among the weather stations (13.3% to 23.7%), the error is higher. In summary, CHELSA is considered the most suitable database to portray Montenegro's temperature, since it reaches the best scores across all statistics for most WSs.

When it comes to precipitation, all datasets have a lower accuracy when compared to temperature. The CHELSA dataset overestimates precipitation for 3 weather stations, ERA5-Land overestimates two stations, and EOBS underestimates all WSs. E-OBS seems to be an accurate database (MAPE ranging from 12.9% to 18%); however, for the Cetinje weather station, the MAPE is a much higher 62.4%. ERA5-Land is not as accurate as E-OBS, as MAPE values are 14.5%, 25.2%, and 49.1%. For CHELSA, the error is more homogeneous among weather stations. However, for CHELSA, the monthly precipitation in Podgorica is overestimated by 49 mm, while in E-OBS, it is overestimated by 19 mm, and in ERA5-Land, it is overestimated by 20 mm. In this sense, the precipitation data raises questions, possibly due to the complex topography, so precipitation data is hard to validate. Therefore, for precipitation, CHELSA seems to be the best dataset for Montenegro, but with the disadvantage of having a higher error for Podgorica WS, and overestimating values comparatively relative to the other databases.

Table 2. Comparison of monthly average of daily temperature and monthly precipitation among stations and datasets. The comparison is made between the observed data (4 weather stations) and data from different databases for the period 1981 to 2010.

Average Temperature							
Station	Dataset	MAE (°C)	RMSE (°C)	MAPE (%)	PBIAS (%)	NSE	Pearson Correlation
Bar_(B)	CHELSA	0.8	0.9	4.6	−5.0	0.97	1.00
Cetinje_(C)		2.3	2.4	66.7	−22.6	0.88	1.00
Podgorica_(P)		0.5	0.5	3.4	−0.6	0.99	1.00
Ulcinj_(U)		0.7	0.8	6.4	−4.3	0.98	1.00
Bar_(B)	E-OBS	2.9	3.0	22.8	17.7	0.72	1.00
Cetinje_(C)		2.0	2.1	57.6	−19.6	0.91	1.00
Podgorica_(P)		0.3	0.3	2.3	2.0	1.00	1.00
Ulcinj_(U)		0.6	0.7	5.0	1.5	0.99	1.00
Bar_(B)	ERA5-Land	2.2	2.2	16.8	13.4	0.85	1.00
Cetinje_(C)		0.8	0.9	23.7	−5.3	0.98	0.99
Podgorica_(P)		1.6	1.7	13.3	10.2	0.95	1.00
Ulcinj_(U)		-	-	-	-	-	-
Precipitation							
Station	Dataset	MAE (mm)	RMSE (mm)	MAPE (%)	PBIAS (%)	NSE	Pearson Correlation
Bar_(B)	CHELSA	11	14	8.9	−10.2	0.90	1.00
Cetinje_(C)		44	53	18.5	5.5	0.88	0.97
Podgorica_(P)		43	49	30.4	−31.4	0.42	1.00
Ulcinj_(U)		12	14	12.4	−12.1	0.88	0.99
Bar_(B)	E-OBS	19	21	18.0	16.9	0.77	0.97
Cetinje_(C)		184	219	62.4	67.3	−1.04	0.95
Podgorica_(P)		18	19	13.0	12.9	0.91	1.00
Ulcinj_(U)		9	10	12.9	6.7	0.94	0.99
Bar_(B)	ERA5-Land	59	69	49.1	−53.3	−1.36	0.98
Cetinje_(C)		85	116	25.2	28.9	0.43	0.92
Podgorica_(P)		18	20	14.5	−12.3	0.90	0.99
Ulcinj_(U)		-	-	-	-	-	-

3.2. *Montenegro Climate Change*

To assess the impact of climate change on viticulture, we evaluated various bioclimatic indices from CHELSA climate simulations (Figures 4–9 and S2–S4). These figures contain the data for the historical period (Figures 4a–9a), and the results for the future climate (2041–2070) for different SSP scenarios in (Figures 4b–d–9b–d). The Kernel density estimations (KDEs) are also displayed (Figures 4e–9e).

The spatial pattern of average growing season temperature (Figure 4) is similar among the historical period and future projections, as well as for the warmest quarter (Figure 5) and annual mean temperature (Figure S2). When looking at the KDEs (Figures 4e, 5e and S2e) a clear bimodal distribution is visible, resulting from the complex reliefs of Montenegro. The first peak corresponds to the "cold" temperatures of the mountain regions. Warmer regions are found in the valleys between the northeast mountains, and also on the coast, corresponding to the second peak of the KDEs. The second peak also renders the temperatures in the MVAs, which represent the valleys near Podgorica and Bjelopavlici Valley located in the south of Podgorica city, the warmest zones of Montenegro. Additionally, the terrain in this area is predominantly flat (Figure 1c), favouring agricultural practices. In terms of SSP scenarios, the results reveal that the SSP3-7.0 and SSP5-8.5 temperature increases are similar, while the SSP1-2.6 temperature is closer to that of the historical period (Figures 4e, 5e and S2).

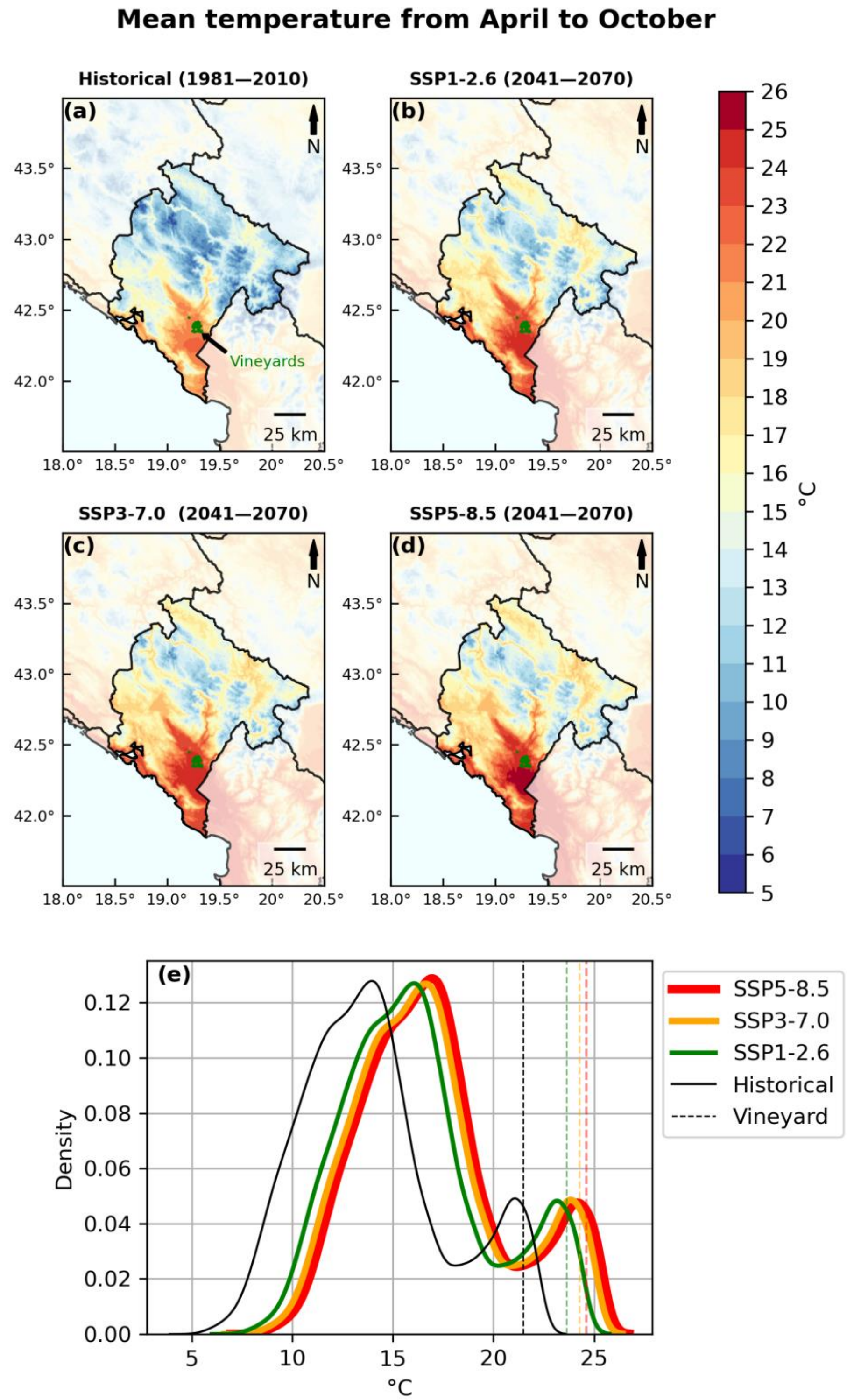

Figure 4. Climate mean daily average temperature during the vineyard growing season from April to October, for Montenegro, according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070) under (**b**) SSP1-2.6, (**c**) SSP3-7.0, and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were ensembled from 5 climate models through the median.

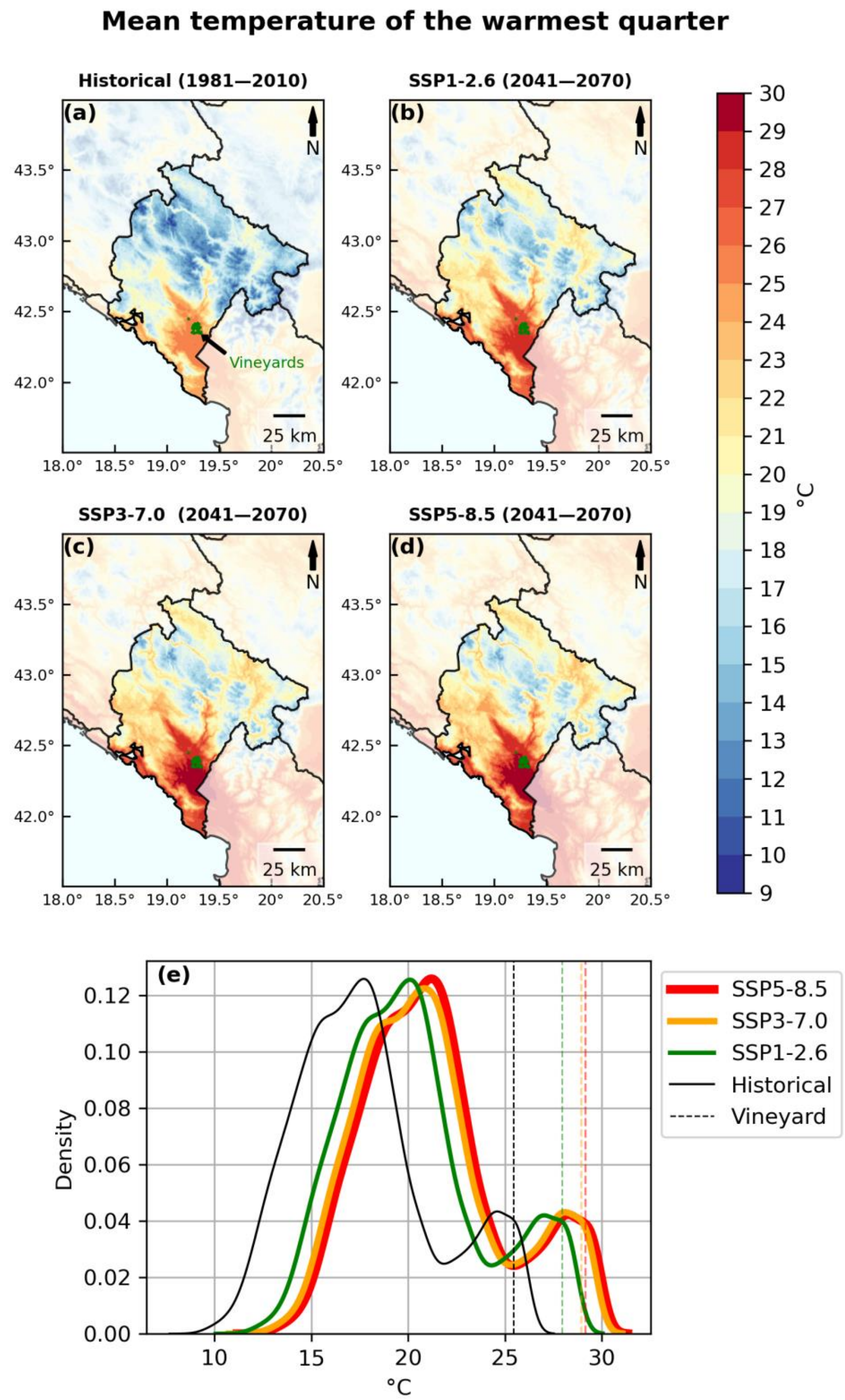

Figure 5. Climate mean daily average temperature during the warmest quarter for Montenegro according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070) under (**b**) SSP1-2.6, (**c**) SSP3-7.0, and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were estimated by the ensemble median from 5 climate models.

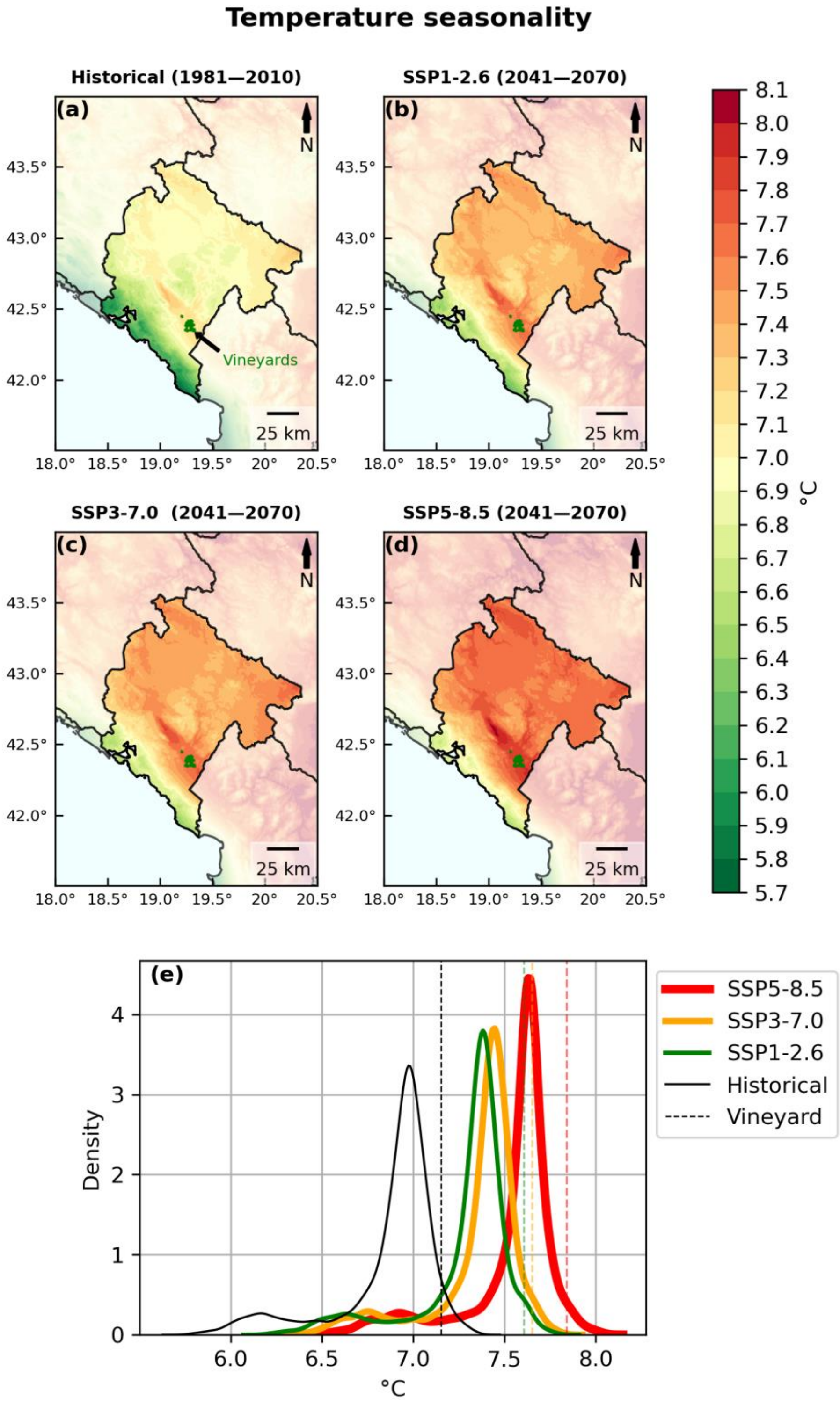

Figure 6. Climate mean of temperature seasonality; the standard deviation of the monthly means for Montenegro according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070) under (**b**) SSP1-2.6, (**c**) SSP3-7.0 and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were estimated by the ensemble median from 5 climate models.

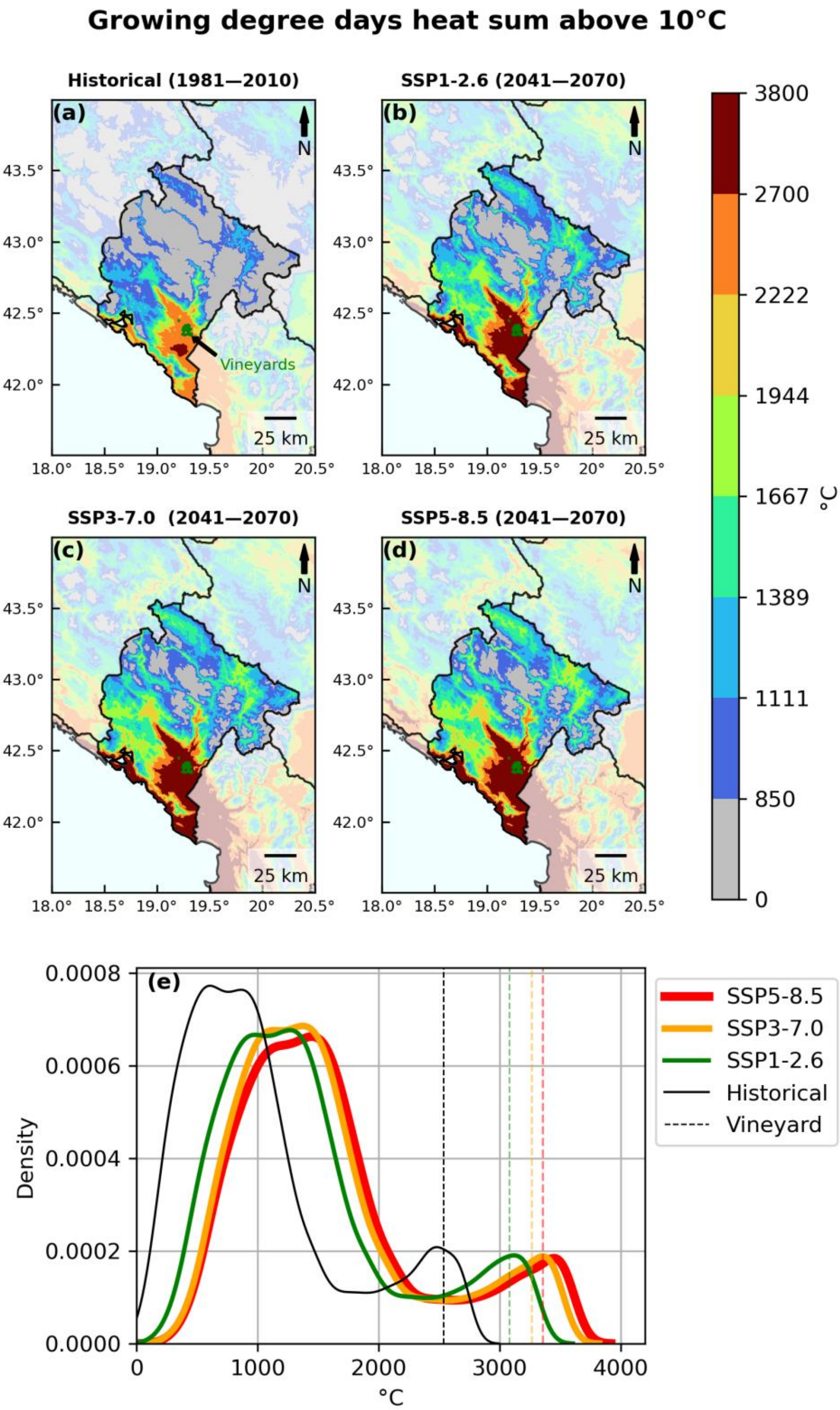

Figure 7. Climate mean growing degree days heat sum above 10 °C for Montenegro according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070) under (**b**) SSP1-2.6, (**c**) SSP3-7.0 and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were estimated by the ensemble median from 5 climate models.

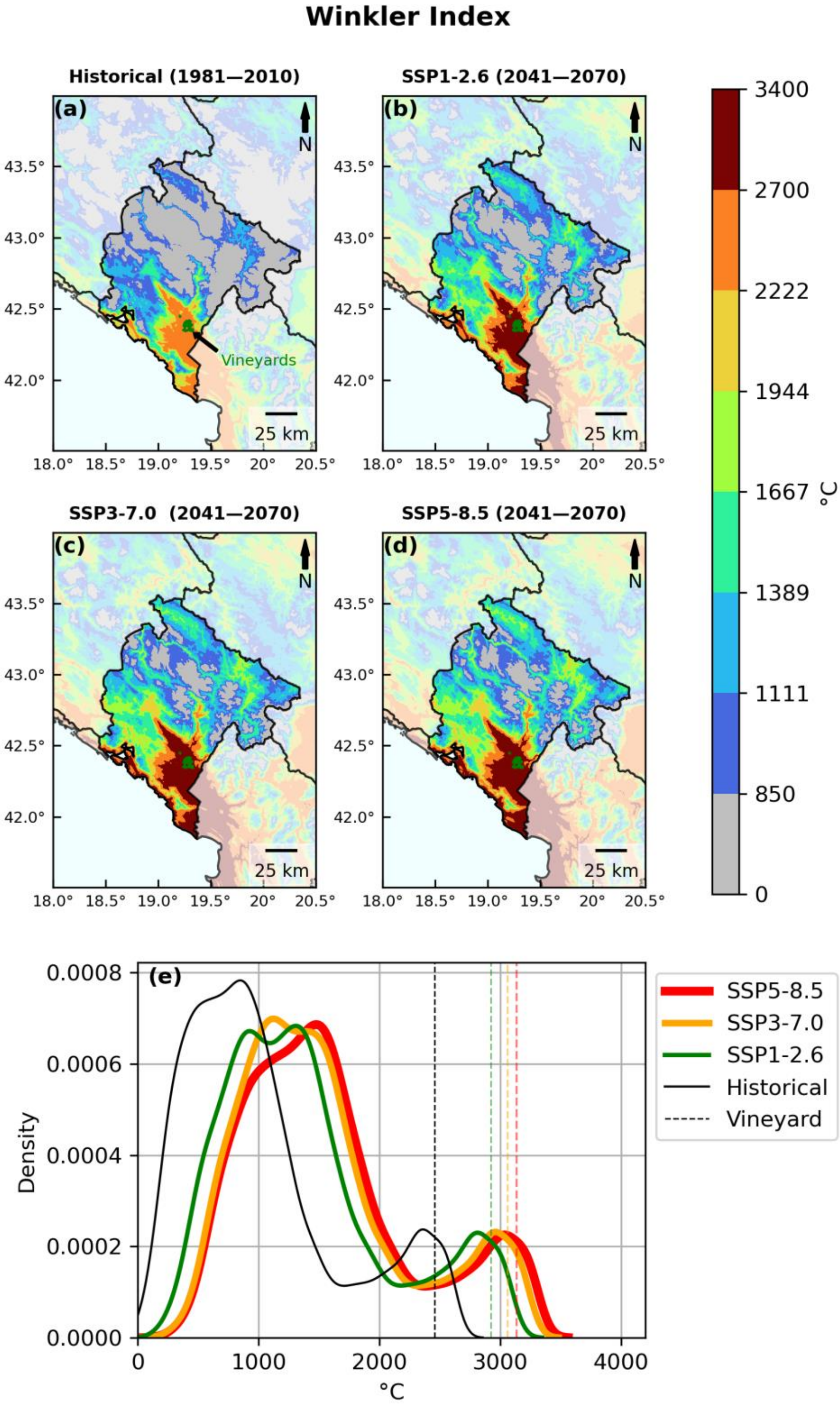

Figure 8. Climate annual mean of Winkler index for Montenegro according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070) under (**b**) SSP1-2.6, (**c**) SSP3-7.0 and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were estimated by the ensemble median from 5 climate models.

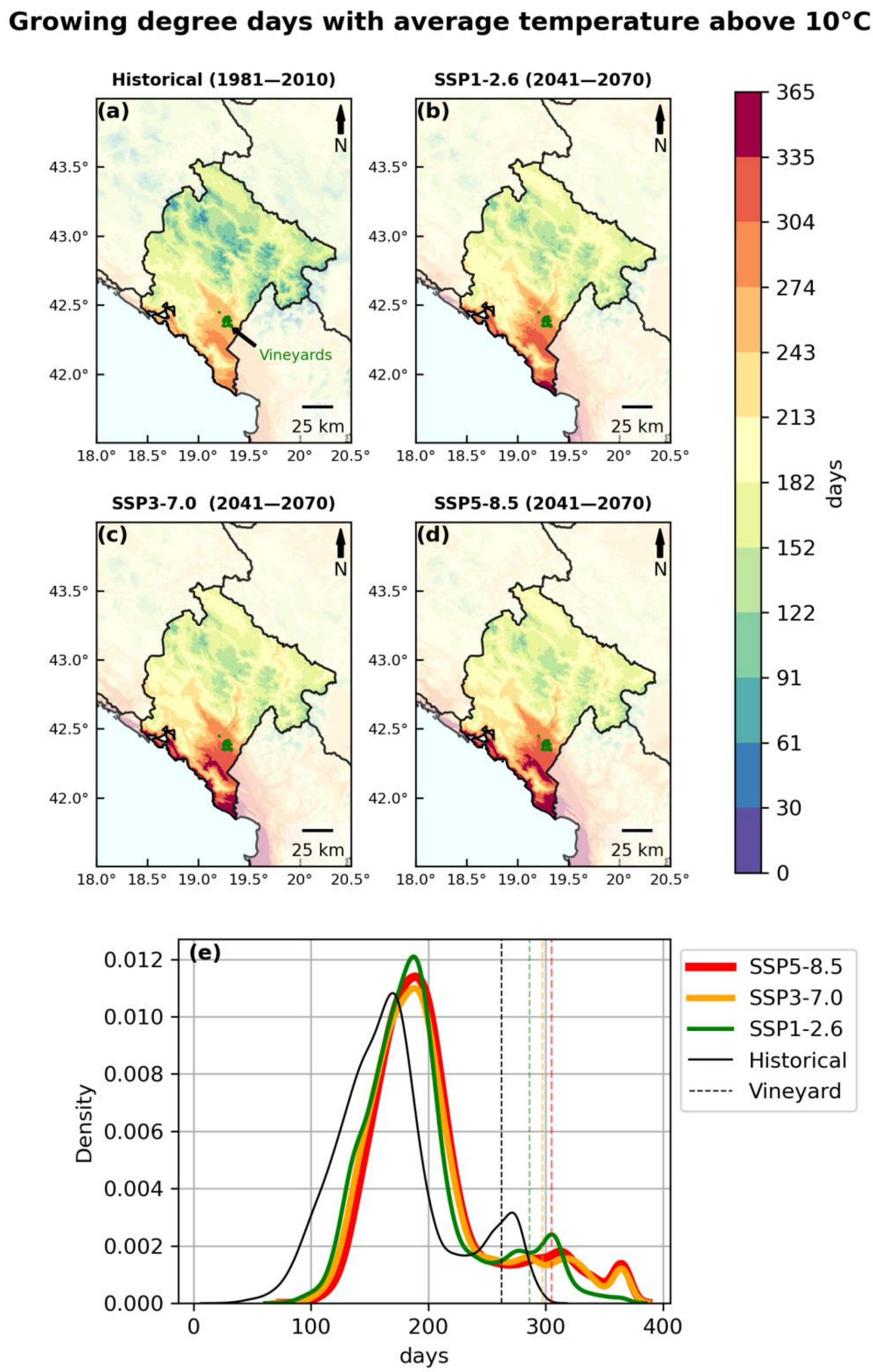

Figure 9. Climate mean of growing degree days with an average daily temperature higher than 10 °C for Montenegro, according to the CHELSA dataset (**a**) over the historical period (1981–2010) and the future period (2041–2070), under (**b**) SSP1-2.6, (**c**) SSP3-7.0 and (**d**) SSP5-8.5. (**e**) Corresponding Kernel density plot of the spatial variability in (**a**–**d**). The median value in the vineyard area is shown as a vertical dashed line. Projections were estimated by the ensemble median from 5 climate models.

In Montenegro, the average temperature from April to October ranges from 5.4 °C up to 22.1 °C (Figure 4). For the future period (Figure 4b–d) it is expected to shift to 7.5 °C and 25.6 °C, respectively, depending on the future scenario. In general, a temperature increase above 2 °C is estimated across all scenarios. Hence, MVA temperature is expected to increase by a similar amount. The warmest quarter is typically dated from June to August [100] as illustrated in Podgorica's weather data (Figure 1e). During these months, in the historical period, the temperature ranges from 9.2 °C up to 26.1 °C. Regardless of the SSP scenario, the warmest quarter temperatures across Montenegro are expected to increase to a range from 11.6 °C up to 29.9 °C (Figure 5).

According to Figure 5e, MVAs warmest quarter temperatures may increase by at least 2.5 °C. In contrast, median annual temperatures of the MVAs (Figure S2e) are expected to increase by a lesser amount of at least 1.7 °C. Hence, the temperature increase will be higher during the summer period and lower for the colder months. This inhomogeneous temperature increase leads to a stronger temperature seasonality (Figure 6). From 1981 to 2010, temperature seasonality was lower in the coastal region, down to 5.7 °C, and it increases with the distance to the shore of the Adriatic Sea, reaching 7 °C. Bjelopavlici Valley [101] faces the highest temperature seasonality, of up to 7.4 °C, also due to the hot summers, as in Podgorica [45]. Like for the other temperature indices, the spatial pattern of temperature seasonality (Figure 6) is similar across the historical period and future projections. In contrast to temperature (Figures 4e, 5e and S2), temperature seasonality for SSP3-7.0 is closer to SSP1-2.6, while SSP5-8.5 reaches higher seasonality (Figure 6e).

The temperature seasonality for the period 2041–2070 is not of major concern, but the increase in temperatures brings challenges to Montenegro's crops [102] by advancing phenological development [35], and decreasing crop productivity and also quality [103]. For a better understanding of the temperature effects, specific bioclimatic indices suitable for viticulture, GDD10, WI, and NGD10 for a base temperature of 10 °C [104] were also analysed. Both the annual (GDD10, Figure 7) and growing season (WI, Figure 8) heat sums significantly increase under the selected SSPs. In Montenegro, GDD10 during the historical period ranges from 6 °C to 2723 °C, and the range is anticipated to increase to between 142 °C and 3601 °C. Particularly for the MVAs, a GDD10 increase of at least 500 °C is expected. During the growing season (Figure 8), the MVAs heat sum is 2457 °C, slightly lower than the annual, but is anticipated to reach values above 3000 °C under climate change. In Montenegro, NGD10 goes from 26 days in the high-altitude areas up to 298 days on the coast. In the MVAs, the median number of days is 262, and this is projected to extend by over 30 days (Figure 6e). The results reveal that there are no distinct differences between SSP3-7.0 and SSP5-8.5 regarding GDD10, WI, and NGD10 (Figure 7e, Figure 8e, and Figure 9e, respectively).

According to Burić et al. [59], annual precipitation across Montenegro ranges from 768 mm up to 4650 mm, while according to the CHESLA dataset, it ranges from 831 mm to 3827 mm. According to the future projections, it is expected that there will be no distinct changes in annual precipitation (Figure S3) since precipitation in future scenarios (all) is close to precipitation in the historical period. During the growing season, in Figure S4, precipitation decreases in all projections. The projected precipitations for SSP3-7.0 and SSP5-8.5 are quite the same, and the SSP1-2.6 scenario is closer to the precipitation for the historical period. Consequently, precipitation will increase in the colder months.

3.3. Climate Change in Vineyards

The present section reports the bioclimatic indices for the historical period in Podgorica's WS, Figure 10, and also the analysis of the climate change in the vineyards: Figure 11 for temperature bios, and Figure S6 for precipitation. Here, the climate change data is accessed through all model data pooled together instead of considering ensemble metrics. Median values can be found in Table S1.

Podgorica WS is crucial for this study, as it is the closest WS to the main vineyard area, thus reliably representing its mesoclimate. When comparing the vineyard's median temperature-based indices during the historical period (Figures 10 and 11) with the Podgorica WS data (Figure 10), the thermal conditions are very similar. In Podgorica WS, the mean growing season temperature is 21.5 $\pm$ 0.8 °C (average and standard deviation), with temperatures in the warmest quarter at 26.0 ± 1.1 °C and the annual mean at 15.9 ± 0.6 °C; while, in the vineyards, the median according to the CHELSA dataset is 21.5 °C, 25.4 °C, and 16.2 °C, respectively. When it comes to the temperature seasonality in Podgorica WS, it is 7.7 ± 0.4 °C, which is close to the seasonality in vineyards, at 7.2 °C. The GDD10 in Podgorica is 2574 ± 181 °C, and so it is close to the vineyards' 2530 °C. For the WI, it is also clear that Podgorica has the same heat sum during the growing season as the vineyards, as in Podgorica it is 2457 ± 168 °C, and in the vineyards, it is 2457 °C. Moreover, the NGD10 in Podgorica (257 ± 12) is close to the number of days in the vineyards, which is 262 days.

According to Figure S5, for the WSs, the annual precipitation is 1637 ± 308 mm, while it is 2047 mm in the vineyards according to CHELSA (Figure S3). Precipitation during the growing season is 688 ± 175 mm in Podgorica (Figure S5), and in the vineyards (according to the CHELSA dataset) it is 872 mm (Figure S4). Therefore, the weather station precipitation data is fairly close to the CHELSA observational precipitation in the vineyards. The precipitation patterns (Figure S6) do not change over the years. As for projections (Figures S3 and S4), our results reveal that future precipitation may not change substantially and may slightly decrease during the growing season. Other authors also did not perceive significant changes in Podgorica [42,52]. At this point, it is worth noting that precipitation levels might not undergo any significant changes, though the hydric safety of vineyards can become at-risk due to the increasing temperature, which will lead to higher evapotranspiration [105], and so the water demand will increase [31]. In this sense, it is necessary to develop hydrological modelling studies and compile future scenarios, to perceive if water availability will be a threat to viticulture.

From Figure 11, temperatures are projected to increase in the MVAs. These results are in agreement with the increasing trend in Podgorica (Figure 10). Mean temperature during the growing season has increased in the last 30 years (Figure 10a), at a rate of 0.5 °C per decade, which is equivalent to the increase in the annual mean (Figure 10c). However, the increase is higher in the warmest quarter, i.e., 0.8 °C per decade (Figure 11b). Bačević et al. [106] have already mentioned the temperature increase between 1947 and 2018 (72 years), revealing an increase of 1.4 °C in average temperature. When analysing the increase in summer air temperature from 1951 to 2010, Doderović and Burić [44] estimated an increase of 0.27 °C per decade, which is discordant with Figure 10c. Possibly, this is due to the average temperature decreasing trend from 1961 to 1980, and increasing trend during 1981–2010, as the results from Bačević et al. [106] show, which was also noted for Serbia [107]. All the results reveal an increase in temperature; thus, the city's climate is becoming more arid and extreme [42]. For the vineyards, the results show that the mean annual temperature could increase up to 4.9 °C, according to the UKESM1-0-LL model (Figure 11, Table S1). These estimations seem to deviate from other models, resulting in the outliers shown in Figure 11a–c,e–g. As Sellar et al. [92] have mentioned, this model portrays high climate sensitivity, compared to other models. In this regard, the median value from the 5 climate models is considered by the authors as the representative future value. In this order, is expected that (in MVAs), the mean annual temperature will increase from 16.2 °C, up to a temperature between 18 °C and 19 °C. At first sight, the increase in mean annual temperature is not severe, since according to Schultz and Jones [108] a mean annual temperature between 10 °C and 20 °C is suitable for viticulture. During the growing season, the mean temperature of 21.5 °C is estimated to increase up to a value between 23.6 °C and 24.6 °C, which is high for successful grape growing, as the suitable mean temperature during the growing season ranges from 12 to 22 °C [108]. In Montenegro's vineyards, the growing season temperature is already at the limit of the threshold, and the increasing trend might exceed it by at least 2.6 °C. For the warmest quarter, the temperature (25.4 °C) could increase to 28.0 °C or, in the worst-case scenario, up to 29.2 °C. Future consequences seem to compromise viticulture suitability, which is a shared trend in the southern Mediterranean regions of Europe [109,110].

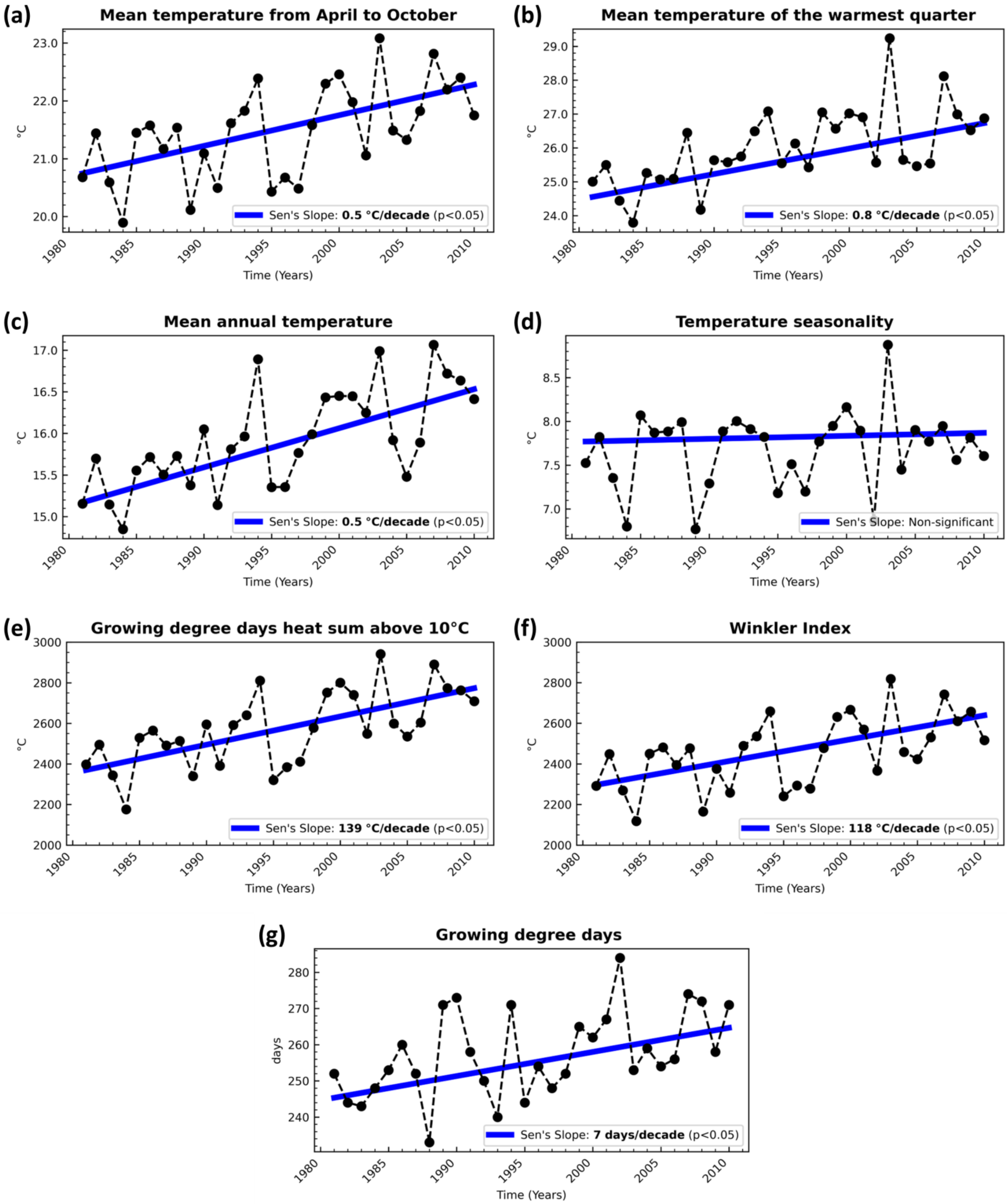

Figure 10. Chronograms of the annual averages of the outlined indices for Podgorica weather station during the historical period (1981–2010). (**a**) Daily mean temperature during the vineyard growing season, from April to October. (**b**) Daily mean temperature during the warmest quarter. (**c**) Daily average temperature. (**d**) Temperature seasonality, the standard deviation of the monthly means. (**e**) Growing degree days heat sum above 10 °C. (**f**) Growing degree days heat sum above 10 °C during the growing season. (**g**) Climate mean of growing degree days with an average daily temperature higher than 10 °C.

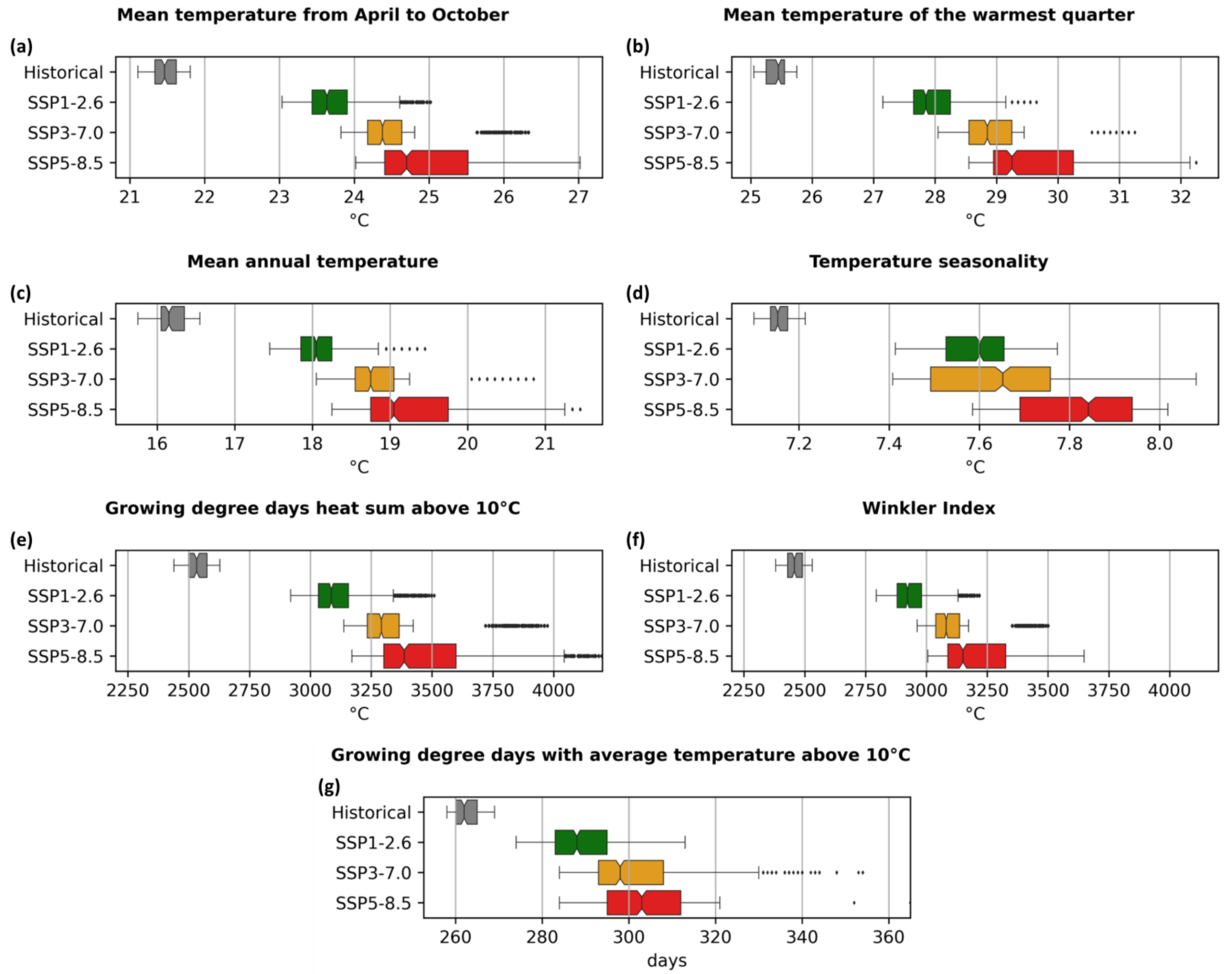

Figure 11. Notch boxplots of the outlined indices from the CHELSA dataset in the vineyard areas of Montenegro, for the historical period (1971–2010) and for the future period (2041–2070) models under SSP1-2.6, SSP3-7.0 and SSP5-8.5. (**a**) Climate means daily average temperature during the vineyard growing season, from April to October. (**b**) Climate means daily average temperature during the warmest quarter. (**c**) Climate annual means daily average temperature. (**d**) Climate means of temperature seasonality, the standard deviation of the monthly means. (**e**) Climate means of GDD10. (**f**) Climate means of WI. (**g**) Climate means of NGD10.

The future increase in temperature during the growing season leads to a higher temperature seasonality. Seasonality tends to remain constant in Podgorica (7.7 ± 0.4 °C, Figure 10). The vineyard's future seasonality could range from 7.5 to 8.0 °C, which are not record-breaking values, even for the worst-case scenario. In Podgorica, the average seasonality is close to the vineyard's future seasonality (Figure 11d). Still, the trend of increase is relatively weak and must be estimated beyond 2070.

The heat sum (Figure 10e,f), and NGD10 (Figure 10g), reveal an increasing trend, in agreement with the future projections (Figure 11e–g). According to the WI scale [111], Podgorica is classified as region V, with a WI of 2457 ± 168 °C, which is equal to that of the vineyards. The WI tends to increase by 118 °C per decade. This trend encompasses the results from (Figure 11f and Table S1), showing that the WI might reach values from 2919 °C up to 3130 °C in vineyards, which are classified as "too hot" [112]. According to historical averages of the WI, there are no regions in Europe with a value higher than

2700 °C, above "Region V", for the historical period [113–115]. When it comes to future projections, Cardell et al. [113] have already shown that multiple regions will surpass the 2700 °C threshold. This heat sum would extend out of the growing season, as the annual heat sum could increase from 2530 °C to up to 3352 °C (Figure 11e). For the historical period, both indexes have similar values. This means that daily average temperatures above 10 °C are mostly found during the growing season. Future scenarios show that the difference between GDD10 and the WI is likely to increase (Figure 11e,f). For SSP1—2.6 the difference is 157 °C, for SSP3-7.0 it is 208 °C and for SSP5-8.5 it is 222 °C; thus, the growing season can start earlier. According to Podgorica WS data Figure 1e, the growing season (>10 °C) starts in the middle of March and extends to the middle of November, 257 ± 12 days. However, is estimated to increase to between 286 and 305 days (Figure 11g), reaching approximately 10 months, and so starting during February and ending in December. For a clear understanding of the possible consequences, it is necessary to apply future projections in phenological models [31,116,117]. Still, the results from Fraga et al. [24], when using a lower resolution dataset, predicted that the budburst, flowering, veraison, and harvest will be anticipated by 20 to 30 days, according to RCP scenarios. Furthermore, the anticipation of phenological events will deeply require management adaptations to hold sustainable yields.

4. Adaptation Strategies

Crops are commonly settled in regions where the climate and soil conditions favour their development. Due to climate change, it is clear for most wine regions that baseline conditions will not prevail in the upcoming decades, thus challenging their viticultural suitability and implying geographical shifts in the optimal/adequate conditions [118]. In the worst-case scenario, the selection of new crops, better adapted to the anticipated conditions, is an answer to ensure socio-economic sustainability. Still, when the option of keeping the same crop is chosen, there are two options left: relocate or adapt on-site.

According to our projections, it is likely that new vineyards will emerge. Savić and Vukotić [61] performed a climate zoning for Montenegro, using climate data from 1950 to 2005. By combining their results with the present study's climate projections, it is possible to identify areas that will have suitable climate conditions for vineyards in Montenegro, keeping the already grown grapevine cultivars [80]. However, to plant new vineyards, soil properties must be considered as well, as they largely determine local terroirs and wine attributes [119]. Montenegro's complex orography challenges the settlement of new vineyards, due to the lack of flat land areas. Viticulture is, however, possible in steep slope landscapes, such as the Douro Wine Region [120] in Portugal, or the Aosta Valley [121] in Italy. New climate conditions will emerge in the future (Figure 8), as well as new suitable regions for viticulture, with a WI mostly ranging from 850 °C to 2000 °C, which are classified as regions Ib, II, III [111]. Region "V", currently located in the Lake Skadar basin, will only prevail on the hillsides of rivers. Upon the SSP1-2.6 scenario, the vicinity of Nikšić city will become region III, but "IV" under SSP3-7.0 or SSP5-8.5, with a growing season average temperature from 16 to 20 °C. Nikšić has already been suggested as a potential future zone for viticulture [68,122]. As such, it is important to perform viticulture zoning under future climates in Montenegro, considering soil and landscape features, and specifically regarding soil erosion in steep slopes [123] and ecological impacts due to land use change [124].

Changing the crop and relocation are the most extreme adaptation measures in the long-term, which should be adopted in the worst-case scenario [62]. However, long- and short-term adaptation measures on-site should be considered [34]. Adaptation starts with awareness, which is the first step to delineate successful strategies. For Montenegro, the results from Ćeranić et al. [125] suggested that it is necessary to raise climate change awareness among Montenegrin citizens. This is the first and most important adaptation strategy, to foster a proactive stance from winemakers and decision-makers to reverse the negative effects of climate change on wine production [126]. Adaptation to the necessity is not a good practice, as this reduces the range of options for short-term measures. This is a common choice for winegrowers, while long-term measures are taken as a last resort [127]. Nevertheless, to guarantee future viticultural sustainability and profitability, the key is to combine short- and long-term strategies [36]. To maintain viticulture on the same site, short-term strategies focus on measures like irrigation, soil management, canopy management, pest and disease control, and harvest management, whereas long-term strategies comprise developing adequate farm strategies, selection of plant material, or adjusting the vineyard design [31,34,36,62].

For the studied vineyards, the water supply for irrigation comes from groundwater extraction from intergranular aquifers [128]. Water supply is not a current concern for MVA as there are no reported concerns about water availability in the vineyards, and also because precipitation patterns will not change significantly, However, water availability might become a future problem, since evapotranspiration will increase and, with it, the water demand. From this perspective, the improvement and optimization of irrigation systems is an unavoidable necessity in Montenegro's vineyards, which might need to be supported by the construction of water storage structures. In the scope of precision viticulture, sensors in Montenegrin vineyards measuring soil moisture at different depths are already being implemented [77–79].

Based on the received data obtained through the installed equipment, soil moisture content is determined and complemented with meteorological data, thus supporting smart irrigation [77–79]. Due to the inherent uncertainties of climate change and weather irregularity, sensors are indeed critical for precision viticulture, enhancing short-term predictions (e.g., based on weather forecasting) to optimise canopy and harvest management. For pest control, digital pheromone traps are being used in Montenegro for monitoring the presence and abundance of pests to ensure the optimal use of protective agents based on the presence and number of pests.

In Montenegro, autochthonous and locally adapted grapevine varieties have survived because age-old natural selection represents a source of genetic variety and diversity, and this enables them to have a greater ability to adapt to climate change. Enviable results were achieved in the work on the genetics and genomics of autochthonous and domestic varieties [80], as well as in the clonal selection of the Vranac variety [79], the dominant grapevine variety for the production of red wines in Montenegro. Montenegrin wine is mainly produced with Vranac, which is a variety adapted to warm conditions [129,130]. In this sense, Podgorica winegrowers are already implementing the usage of late-ripening varieties, which is a key long-term adaptation strategy [131]. However, vineyards are already placed in the warmest regions, which will become "too-hot" regions according to the Winkler scale. Moreover, as Vranac is a late-ripening grape variety, it ripens in the middle of September, according to the agroecological conditions of Montenegro [132]. Therefore, later-ripening varieties are mandatory in this location, as well as, possibly, varieties even more resistant to climate change.

From a long-term perspective, research is being performed to find old grape native neglected varieties, which are likely more resistant to climate change [80]. This brings the need for another adaptation measure, i.e., the adaptation of the consumers and markets [133]. Changing varieties will bring a new challenge, as new flavours might not be easily accepted. As the typical vineyard lifespan is around 25–30 years [134], the replacement of old varieties with new ones should be undertaken gradually, enabling a smooth consumer adaptation. Apart from Podgorica's vineyards, there is a small section of vineyards scattered across Montenegro that produce foreign white wine varieties, and also red wine varieties. As the temperature increase across Montenegro is inevitable, these small vineyards might need to change their farm strategy, increasing wine diversification and, e.g., planting red wine varieties. Overall, warmer climates tend to be better for red varieties [135,136].

When it comes to rootstocks, in the newer vineyards the dominant rootstocks are 1103 P, R110, R140 and 41B, while in the older plantings, the rootstocks Kober 5BB and SO4 were used more often. Vine rootstock Teleki 5C and 161-49 are also used in smaller areas. According to the metanalysis from Santesteban et al. [137] 161-49 C and 41-B MGt are suitable for climate change, allowing grapes to attain a moderate sugar accumulation and pH, while Ruggeri 140 and Kober 5BB provide high yields, but higher acidity and sugar content. Among the used ones, Paulsen 1103 and Richter 110, the most used are highly resistant to water stress [31,138]. Overall, the most used rootstocks in Montenegro, 1103 Paulsen, 110 Richter, and 140-Ruggeri, are suitable for climate change, as they are among the best options for hot climates [139,140], and so this is already an implemented long-term strategy.

The state-of-the-art of Montenegrin viticulture in climate change adaptation requires further research incorporating more local data for a better selection and the fine-tuning of adaptation measures. Here, the biggest challenge is to implement long-term adaptation measures. For short-term adaptation, soil and canopy management require further research. Moreover, collecting data on the perception and adoption of measures by viticulturists and winemakers is essential to foster an avant-garde stance, break away from older practices, and embracing new suitable practices.

Further studies should be devoted to the quantification of the adaptative potential of these strategies in response to climate change and risk reduction, to select the best to adopt, knowing that the usage of a single adaptation measure might not be enough, as the results from Fraga et al. [141] suggest. It is also important to downscale available climate datasets to a spatial resolution of <1 km in some targeted vineyard sites over complex orography [142,143]. The impacts of increasing temperature can thereby be better quantified by modelling, e.g., phenology, yield, or wine quality. Future research should also address the impacts of climate change on soil for viticulture. Soil properties are essential for any cultivation and certainly soil quality is vulnerable to climate change [144]. Increasing temperatures accelerate biological processes in soil, altering the nutrient cycles and also the soil microbiome [145]. With increased evapotranspiration, soil moisture is expected to decrease and aridity to increase. This leads to the loss of soil's carbon content, an increase in erosion, and a decrease in water and nutrient holding capacities, and so soils become less fertile [146]. Consequently, grass cover cropping in vineyards becomes harder to maintain, which is essential to limit erosion, stimulate microbial activity, and, among other factors, promote soil health and carbon sequestration as a mitigation measure [147].

The present study outcomes provide a foundation for the improvement and adaptation of Montenegrin viticulture amidst the challenges posed by climate change. Climate change projections suggest significant consequences for Montenegrin viticulture, regardless of the SSP scenario. Even in the best-case scenario, besides adaptation, the implementation of mitigation measures should be fostered, as the effectiveness of the adaptation measures strongly depends on the intensity of climate change impacts. Adaptation measures have a higher chance of success under SSP1-2.6, for which baseline conditions are slightly exceeded. Under SSP5-8.5, the exceedance is superior, and it is uncertain that most adaptation measures would preserve Montenegrin viticulture heritage.

5. Conclusions

The future climate of Montenegrin viticulture was accessed in the present study, using the CHELSA dataset and a representative weather station located in the vicinity of the vineyards, in Podgorica. Three SSPs were used, and the results showed that regardless of the scenario, Montenegrin viticulture will be challenged by climate change impacts driven by increases in temperature.

Our results revealed that precipitation might decrease, but not below a concerning point. Nevertheless, the optimisation of the irrigation system will have to be conducted for vineyards to adequately cope with higher evapotranspiration rates in the future, and guarantee water availability.

In Podgorica's vineyards, the mean annual temperature of 16.2 °C is estimated to increase up to 19.0 °C. During the growing season, the average temperature could reach between 23.6 to 24.6 °C. Increasing temperatures will be also felt in the colder season, at a point where the growing season might expand to over 1 month, and so the advancement of phenological development is expected, along with other consequences.

Montenegro is already applying adaptation measures, including the application of precision viticulture, usage of late-ripening varieties, and rootstocks tolerant to higher temperatures. Furthermore, additional adaptation measures must be taken for the expected climate changes from 2041 to 2070 to maintain the viticultural heritage.

Our results also revealed the suitability of new locations for the settlement of vineyards, which opens up new opportunities for the development of viticulture, bringing new wines to the market.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijgi13080270/s1, Figures S1–S6 and Table S1.

Author Contributions: Conceptualization, António Fernandes, Nataša Kovač, Marko Simeunović, Kruna Ratković, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos; Data curation, António Fernandes, Nataša Kovač and André Fonseca; Formal analysis, António Fernandes, Nataša Kovač, Hélder Fraga, André Fonseca and João A. Santos; Funding acquisition, Nataša Kovač, Marko Simeunović and Kruna Ratković; Investigation, António Fernandes, Nataša Kovač, Hélder Fraga, André Fonseca, Sanja Šućur Radonjić, Christoph Menz and João A. Santos; Methodology, António Fernandes, Nataša Kovač, Marko Simeunović, Kruna Ratković, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos; Project administration, Nataša Kovač, Marko Simeunović and Kruna Ratković; Resources, Kruna Ratković and João A. Santos; Software, António Fernandes, Nataša Kovač, Hélder Fraga and André Fonseca; Supervision, Nataša Kovač, Marko Simeunović, Kruna Ratković and João A. Santos; Validation, António Fernandes, Nataša Kovač, Hélder Fraga, André Fonseca, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos; Visualization, António Fernandes, Hélder Fraga, André Fonseca, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos; Writing—original draft, António Fernandes, Nataša Kovač, Hélder Fraga, André Fonseca, Sanja Šućur Radonjić, Marko Simeunović, Kruna Ratković, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos; Writing—review & editing, António Fernandes, Nataša Kovač, Hélder Fraga, André Fonseca, Sanja Šućur Radonjić, Marko Simeunović, Kruna Ratković, Christoph Menz, Sergi Costafreda-Aumedes and João A. Santos. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the MONTEVITIS project "Integrating a comprehensive European approach for climate change mitigation and adaptation in Montenegro viticulture", funded by the European Union's Horizon Europe—the Framework Programme for Research and Innovation (2021–2027)—under grant agreement nº 101059461 (https://doi.org/10.3030/101059461).

Data Availability Statement: Weather station observations data belong to State Institute for Hydrometeorology and Seismology of Montenegro (IHMSM), available on IHMSM request. The original data from E-OBS is available at: https://www.ecad.eu/download/ensembles/download.php, accessed on 10 July 2023. The original data from ERA5-Land is available at: https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=form, accessed on 10 July 2023. The original data from ERA5-Land is available at https://chelsa-climate.org/cmip6/, accessed on 14 August 2023.

Acknowledgments: Authors thank the Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020 (https://doi.org/10.54499/UIDB/04033/2020) and LA/P/0126/2020 (https://doi.org/10.54499/LA/P/0126/2020).

Conflicts of Interest: The authors declare no conflicts of interest.

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