

Article

Forecast of Changes in Air Temperatures and Heat Indices in the Sevastopol Region in the 21st Century and Their Impacts on Viticulture

Elena Vyshkvarkova ^{1,*}  and Evgeniy Rybalko ²

¹ Institute of Natural and Technical Systems, 299011 Sevastopol, Russia

² All-Russian National Research Institute of Viticulture and Winemaking ‘Magarach’ RAS, 298600 Yalta, Russia; rybalko_ye_a@mail.ru

* Correspondence: aveiro_7@mail.ru

Abstract: Climate is a limiting factor in viticulture, as it defines favorable areas, grape cultivars, and agrotechnical activities. In the Sevastopol region, viticulture is the main and promising agricultural branch. Using the outputs of the regional climate models from the CORDEX project, the projections of agroclimatic conditions in the Sevastopol region for two future periods (2021–2045 and 2046–2070) under two representative concentration pathways (RCP4.5 and RCP8.5) were obtained. The results in our study show the trend of temperature indices rise (average growing season temperature, effective heat sum, Winkler and Huglin indices) and the region’s transition to higher classes, especially during the second future period (2046–2070). However, despite the higher temperature indices, the Sevastopol region will remain suitable for the growing of grapes cultivars with all ripening periods.

Keywords: viticulture; climate change; projections; Sevastopol region



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1. Introduction

Climate has a great impact on the vineyard productivity [1,2]. Increasing air temperature in connection with climate change impacts the grapes yield and composition and, consequently, wine organoleptic properties [3–6]. The expected rise in air temperature by approximately 1.0–3.7 °C [7] by the end of the 21st century will significantly change the geographic distribution and status of a grape production [8]. The climatic changes will likely affect all wine-producing regions at in one form or another [9].

In the future, the issue of grapes adaptation to the changing temperatures and moisture conditions should be addressed for the Mediterranean region, making up 40% of the global vineyard area [10,11]. The reduced production of table and wine grapes is expected for Southern Europe due to the future increase in the aggregate heat stress and dryness during a growing season [12–14]. In addition, the forecasted reduction in precipitation and a higher evapotranspiration rate due to a warm climate will probably cause the increased demand for water. In such regions as Greece (located in a warmer part of the Mediterranean Basin), a need may arise to move vineyards to the locations of higher elevation depending on the global warming rate and range [15]. In the future, wine making in Greece and Croatia is expected to experience additional pressure because of the shift of the grapes ripening phase toward warmer summer days. This could negatively affect the composition of grapes and, eventually, the wine quality [16,17]. On the other hand, high-quality territories for viticulture will significantly extend to the north of Western and Central Europe [12,18–23]. The change of grapes cultivars will be necessary even in those European areas that remain suitable for viticulture in future (by 2050) [21]. The most suitable viticulture areas are forecast to reduce (41–83% reduction) by 2070 in France under the scenarios RCP4.5 and RCP6.0 [24] are dependent on the current vineyard location.

Numerous studies of the potential climate change impact on viticulture have been conducted in North and South America. It is expected that a warmer and more humid climate

of winemaking regions in Canada will extend the growing season, increase the growth potential, reduce the risk of damage caused by cold temperatures in winter; however, it will intensify summer heat stress [25,26]. The results of climatic projections of the models IPSL-CM5A-MR show a significant displacement of wine-making regions in Argentina toward the southwest and higher locations, mainly in 2075–2099, under the scenario RCP8.5. Correspondingly, the Argentinian viticulture may face both new opportunities and new problems connected with the forecast warmer climatic conditions [27].

The analysis of agroclimatic conditions in the Sevastopol region for a historic period by the data of observations showed the region suitability for the growing of grape cultivars with various ripening seasons (from the very early ones to very late ones) while the observed solar indices illustrate the change in the conditions and the displacement of areas suitable for viticulture [28]. Viticulture is one of the key agricultural branches of the Sevastopol region. The area is projected to expand the area occupied by vineyards to 10,000 hectares by 2030, while the current vineyard area is 4300 ha [29]. Taking into account the economic significance of the viticulture for the region, it is necessary to increase and improve the forecasts on climate change to study their impact on wine-making zoning.

The purpose of this study is to provide predictive estimates for future change of climatic conditions at various representative pathways of greenhouse gases emission (RCP4.5 and RCP8.5) for two future periods (2021–2045 and 2046–2070) with the use of ensemble projections of eight regional climatic models. The results will provide insights into how temperature changes can affect future agroclimatic conditions and facilitate the assessment of the region's suitability for high quality grape production in the mid and long term.

2. Materials and Methods

Meteorological observation data were taken from the station Sevastopol (44.62° N, 33.53° E). The Sevastopol region is located in the southwest of the Crimean peninsula (Figure 1). The analysis of future change in the agroclimatic conditions is made with the help of daily data of the simulation of the mean, minimum and maximum air temperature. The simulation results were taken from the Data Extraction Application for Regional Climate (DEAR-Clima) with open access (<http://meteo3.geo.auth.gr:3838/>, accessed date 21 January 2021) obtained on the basis of the simulated regional climate models from the research program Coordinated Regional Downscaling Experiment (CORDEX). The data of regional climate models (RCM) have a high spatial resolution (0.11°) over the European region and cover a period of 1950–2100. The simulation experiments are a product of various RCMs driven by several Global Climate Models (GCMs).

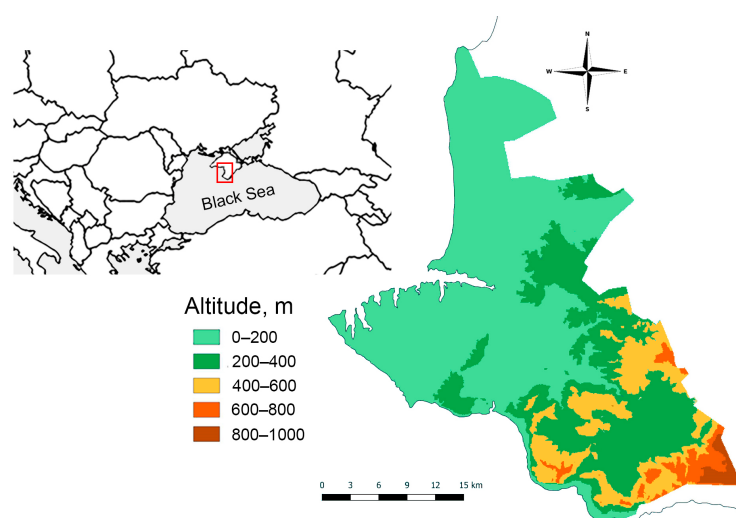


Figure 1. Location of the Sevastopol region.

The results for a future period have been obtained under the impact of three representative concentration pathways (RCP) adopted by IPCC in the fifth assessment report (AR5)—rcp26, rcp45, and rcp85 [7]. The paper uses the calculated data under the scenarios RCP4.5 (moderately optimistic) and RCP8.5 (pessimistic). As a base period, the authors selected the period of 1981–2005 as well as two future periods: 2021–2045 and 2046–2070. The selection of these particular periods in the future is explained by the duration of vineyard renewal, which is 25–30 years. The ensemble of eight climate models from the simulation results is calculated for each meteorological parameter. The application of the model results' ensemble facilitates reducing the uncertainty relating to any separate model [30]. The list of regional models used in the research paper is provided in Table 1.

Table 1. Global and regional climate models used by the research.

Driving GCM	RCM
ICHEC-EC-EARTH	KNMI-RACMO22E
MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009 CLMcom-CCLM4-8-17
CNRM-CERFACS-CNRM-CM5	CNRM-ALADIN53 CLMcom-CCLM4-8-17 SMHI-RCA4
IPSL-IPSL-CM5A-MR	IPSL-INNERIS-WRF331F SMHI-RCA4

To assess the agroclimatic conditions in the Sevastopol region, the authors used the following indicators and indices:

- The mean annual air temperature;
- The average growing season temperature (April–October) [4,19,31];
- The Huglin heliothermal index is used to define the suitability of cultivars for the region and to classify wine-making regions [32]. The index is calculated on the basis of such factors as the mean duration of daylight and biologically effective temperatures for 1 April–30 September in the Northern hemisphere [31];
- The Winkler index provides information on the temperatures necessary to ensure the vine growth and grape ripening [33,34]. It is based on daily minimum and maximum air temperatures where one degree-day is equal to the excess of the mean daily temperature 10 °C;
- The sum of active air temperatures above 10 °C.

The materials applied were a vector map of the Crimean Peninsula, a digital model of the terrain SRTM-3, and a climatic model Worldclim 2.0. The simulation of spatial distribution of heat supply conditions was conducted by the Sofroni–Entenzon formula considering the corrections suggested for the territory of the Crimean Peninsula [35]. The authors applied ArcGIS to simulate agroclimatic indices and visualize the results on the Sevastopol region territory with a high resolution (approximately 80 m).

3. Results

Comparison of the average air temperature for the growing season according to the observational data and the data of the ensemble of regional climate models made it possible to assess the reproducibility of the initial data by the ensemble of models. Average values, linear trends, and their statistical significance showed a high similarity, which made it possible to further use the modeling data to calculate the base and future values of agroclimatic indices.

Air temperature is key for all wine-making aspects [36,37]. Temperatures affect the grapes' physiology, vegetation, and reproductive cycles as well as the quality of the grapes harvested [5,38]. Traditionally, the distribution of wine-making regions in the world is limited by the isotherms 13 °C and 22–24 °C of average growing season temperature [39].

For Russia, temperature is a key factor limiting the growth and development of agricultural crop types [40], including grapes.

The mean annual air temperature for a base period was equal to 12.8 °C. For the first future period under both RCP scenarios, the mean temperature will probably increase up to 13.8 °C. For the second future period, the mean temperature will keep growing to 14.4 °C first under RCP4.5 and up to 15.0 °C under RCP8.5.

In compliance with the data of model ensemble calculations, the average growing season temperature will increase during the first and second future periods (Figure 2). This indicator is used for defining the latitudinal borders of vineyard areas and assessing the ripeness of vine grape cultivars [4,41]. During the base period (1981–2005), a quarter of the regional territory belongs to the intermediate class (15–17 °C) in terms of the average growing season temperature (southeast, foothill part), while the remaining 75% of the areas are located in the warm class zone (17–19 °C). For the first future period under both RCPs, the average growing season temperature falls within the range 17–19 °C, which corresponds to a warm class [4,42] over almost a whole area of the region under study. For the second future period under the moderately optimistic scenario (RCP4.5), the region is divided into two equal subzones: the north and west coastal lands will transit to a hot class (19–21 °C), while the southeast foothill part will remain within the warm class range. Under RCP8.5, 84% of the regional area will be within the territory of the hot class zone, including the values of the average growing season temperature.

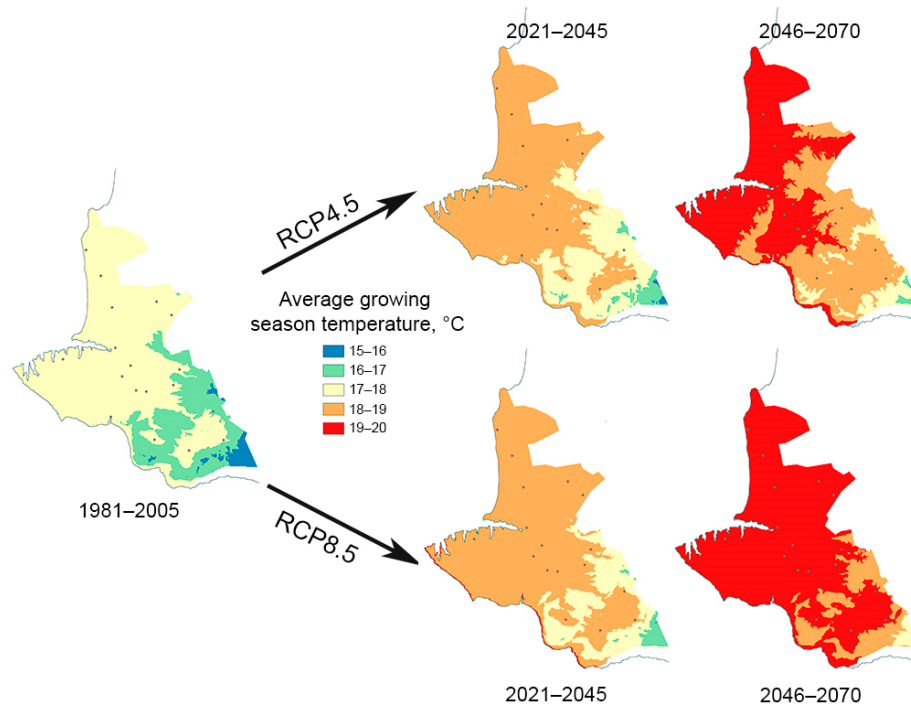


Figure 2. Spatial distribution of the average growing season temperature (°C) over the Sevastopol region obtained by the ensemble of RCMs for the base (1981–2005) and two future periods (2021–2045 and 2046–2070).

Taking into consideration the terrain morphometric characteristics (above sea level, exposition, and slope angle) as well as the territory geographical latitude and solar elevation at the apparent noon, we obtained the maps of distribution of regional heat supply, i.e., the sum of active temperatures above 10 °C by the results of ensemble calculations for base and two future periods. The change in the areas belonging to various classes during future periods under various scenarios is provided in Figure 3. In the territory of the Sevastopol region, the authors identified seven heat supply zones in compliance with the gradation of requirements of various grape cultivars to this indicator [43] (Table 2). During the base

period, approximately 70% of the area has a sum of active temperatures being higher than 3500 °C. Such conditions facilitate growing the grapes cultivars from the very early to the very late ripening periods. During the first future period under RCP4.5, the share of the area with a sum of active temperatures being higher than 3500 °C increases up to 85%; under RCP8.5, it increases up to 88%. By the end of the second future period (2046–2070), the share of the Sevastopol region area, having the conditions for the growing of cultivars with all ripening terms, will probably increase up to 92% and 96% under RCP4.5 and RCP8.5, respectively. The heat supply growth forecast by the end of the second future period may negatively affect the quality of table wines, which will require the change of the grapes application (for example, manufacture of sweet wines).

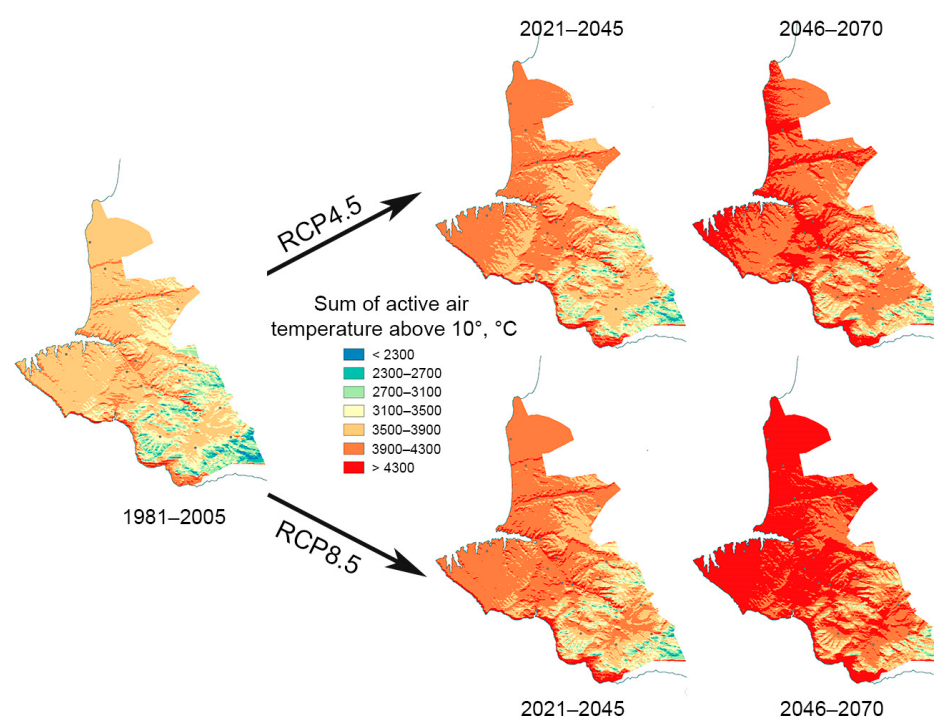


Figure 3. Spatial distribution of the sum of active temperatures above 10 °C over the Sevastopol region obtained by the ensemble of RCMs for the base (1981–2005) and two future periods (2021–2045 and 2046–2070).

Table 2. Distribution of the area (%) of the sum of active temperatures above 10 °C for future periods under various RCP.

Sum of Effective Temperature (°C)	Base Period (1981–2005)	Future Period 1 (2021–2045)		Future Period 2 (2046–2070)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
<2300	0.7	0.2	0.1	0.0	0.0
2300–2700	2.5	1.1	0.7	0.3	0.1
2700–3100	7.6	3.8	2.8	1.8	0.8
3100–3500	18.8	10.1	8.3	5.7	3.0
3500–3900	59.3	32.2	21.7	13.0	8.7
3900–4300	9.8	48.3	58.3	50.9	24.5
>4300	1.2	4.4	8.1	28.3	62.9

By the results of the ensemble calculations of RCMs in the base period (1981–2005), the distribution of the area corresponding to various classes of the Winkler index is characterized by the predominance of the interval Region 2 (1390–1670 units) (approximately 70%) (Table 3, Figure 4). Approximately 15% of the territory belongs to the classes Region 1 and Region 3. For the first future period under various RCP, the distribution of the area by classes is virtually the same. More than 70% of the Sevastopol region territories are located in Region 3 (1670–1940 units). In the period 2046–2070 under RCP4.5, the share of

the Region 4 area increases due to the reduction of the territories belonging to Region 3. The zones with the temperature interval of 1940–2220 units emerge in the north and west of the study region (coastal zone). Under RCP8.5 for the second future period, it is expected that more than 70% of the territory will belong to the class Region 4 (1940–2220 units). This class will cover almost a whole area of the Sevastopol region except for the southeast part (foothill zones).

Table 3. Area (%) corresponding to various classes of the Winkler index for the Sevastopol region for two future periods under different RCP.

WI Classes	Base Period (1981–2005)	Future Period 1 (2021–2045)		Future Period 2 (2046–2070)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
<850 Too cool	0.2	0.0	0.0	0.0	0.0
850–1390 Region 1	15.3	5.1	3.8	1.8	0.4
1390–1670 Region 2	67.1	20.4	16.0	10.3	4.5
1670–1940 Region 3	16.9	70.3	72.7	48.2	18.3
1940–2220 Region 4	0.4	3.9	7.2	38.7	72.4
2220–2700 Region 5	0.0	0.2	0.3	1.1	4.4

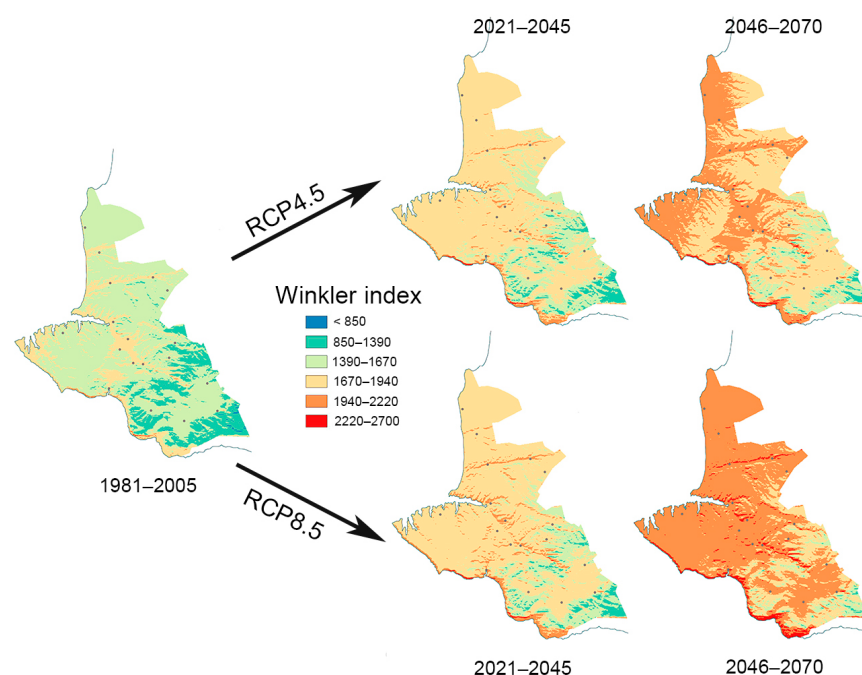
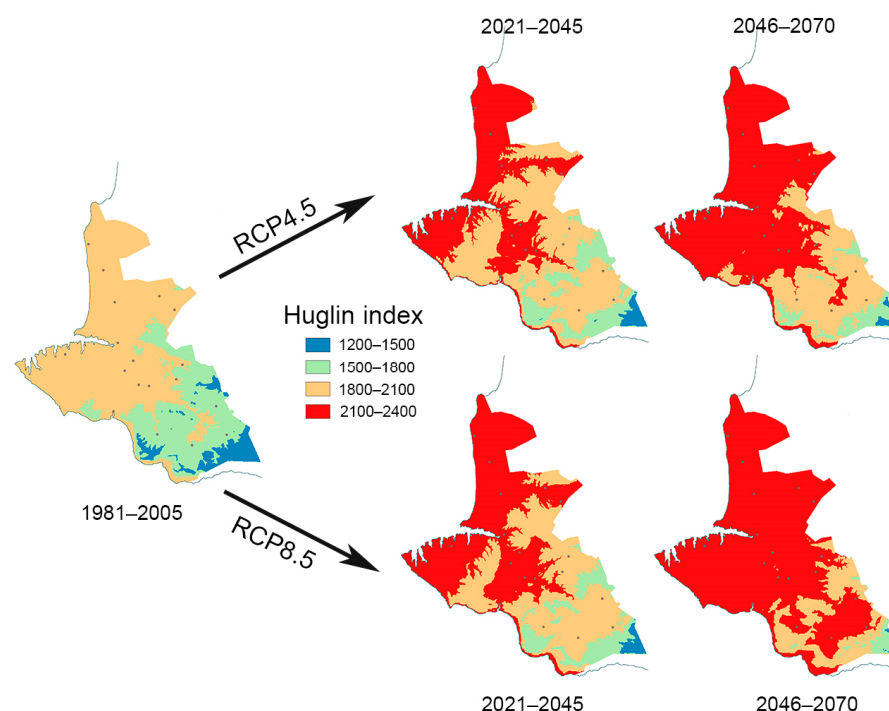


Figure 4. Spatial distribution of the Winkler index over the Sevastopol region obtained by the ensemble of RCMs for the base (1981–2005) and two future periods (2021–2045 and 2046–2070).

The dominant class (about 66%) of the Huglin heliothermal index within the base period is the class HI-1 “moderate” with the range of 1800–2100 units (Table 4). About 30% of the regional territory is covered by the class “cool” HI-2. It is associated with elevated areas (southeast part of the region). For the first future period (2021–2045), the territory is redistributed by index classes: the shares of classes “cool” and “temperate” reduce, the class “warm temperate” emerges; under RCP4.5, the latter class is expected to occupy 40% and 48% under RCP8.5 (Figure 5). For the second future period, the percentage belonging to the class HI + 1 (2100–2400 units) will increase up to 65% and 82% under RCP4.5 and RCP8.5, respectively. Therefore, by the forecast values of the Huglin index in the first and second future periods, there are no heliothermal limitations for the ripening of all cultural grape cultivars on the Sevastopol region territory [44].

Table 4. Area (%) corresponding to various classes of the Huglin index for the Sevastopol region for two future periods under different RCP.

HI Classes	Base Period (1981–2005)	Future Period 1 (2021–2045)		Future Period 2 (2046–2070)	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
1200–1500 Very cool	6.3	1.6	1.4	0.8	0.2
1500–1800 Cool	27.9	12.0	9.9	5.8	2.2
1800–2100 Temperate	65.8	47.3	40.3	28.8	15.9
2100–2400 Warm temperate	0.0	39.0	48.4	64.6	81.7

**Figure 5.** Spatial distribution of the Huglin index over the Sevastopol region obtained by the ensemble of RCMs for the base (1981–2005) and two future periods (2021–2045 and 2046–2070).

4. Discussion and Conclusions

As mentioned above, air temperature is a key parameter affecting the growth and development of grapes, territorial specialization, and harvest [4,42,45]. Temperature variability could be the main factor affecting the quality of wine [46] in the future due to the global warming [47]. The expected growth of the air temperatures by the mid to late 21st century will affect the agroclimatic conditions of the Sevastopol region. In the current climatic conditions, the study region is a viticulture area with a good potential. The analysis of climate projections for the 21st century carried out in the article showed an increase in temperature agroclimatic indices (GST, HI, and WI) for the study region. Similar results were previously obtained for different regions of Europe (e.g., [46,48,49]). By the mid-21st century, the entire Sevastopol region will have optimal conditions under both RCPs by the values of the mean air temperature. In the second future period, the increase in the average growing season temperature (2046–2070) provided the pessimistic scenario RCP8.5, which up to a hot class (higher than 19 °C) will exceed the optimal values for a vegetation period [12]. Such a change can lead to an increase in heat stress on the plants. To reduce heat stress, for example, north-facing slopes for planting vineyards can be chosen [50].

In future periods, the change in the territory distribution by the classes of the Winkler index can change the region suitability for different grape cultivars growing. By the authors' results, in the first future period under both RCPs, a larger part of the Sevastopol region territory will be located in Region 3 that is suitable for the production of standard and high-quality table wines [34]. In the second future period under RCP8.5, the change for

Region 4 is possible with the conditions favorable for high productivity; however, the table wine quality will be at its most acceptable. According to the calculations of the HadCM3 and CSIRO MK3 models until 2050, the Sevastopol region belongs to the areas where the grapevines can potentially grow well both in the present and in the future climate [21].

The increase in the Huglin index values during future periods will facilitate a warmer growing season and the reduction in the number of freezing cases and, consequently, in the reduction in limitations on the fruit ripening of all cultivars [11]. The Huglin index values above 1500 units in the future periods under both RSPs allow concluding that the Sevastopol region has a good potential for wine production [19]. The observed trends toward the change of agroclimatic conditions in the Black Sea zone for the last decades [28,51] generally comply with the forecasts for climate change in the 21st century on the basis of global and regional climate models obtained herein. The results of predictive estimates obtained in the paper correspond to the conclusions drawn by other authors for wine-making areas in Europe [2,12,21]. A shift in bioclimatic indices toward higher classes and areas suitable for growing grapes to the north in the near future are obtained for many wine-growing regions of Europe using different models and scenarios of greenhouse gas emissions: e.g., in France [24], in Portugal [48], in Italy [52], in Mediterranean [11], for a whole Europe [12,21,53,54].

The agroclimatic indices for the future climate were calculated and analyzed for the territory of Sevastopol region in the paper. To accomplish this task, we applied an ensemble consisting of eight regional climate models driven by GCMs from the CORDEX project for two greenhouse gases' representative concentration pathways (RCP4.5 and RCP8.5).

The obtained results for agroclimatic conditions point to a further temperature rise during future periods under both RCPs. Under the current climatic conditions and during the first future period (2021–2046), the territory of the Sevastopol region is a wine-producing area with a good potential. During the second future period, especially under pessimistic RCP8.5, dominating index classes shift toward higher (warm) intervals which will likely cause additional heat stress for plants.

The main recommendation that can be made on the basis of the results obtained on the transition of agroclimatic indices to the upper classes in the future is to replace grape cultivars with more thermophilic ones and to select the optimal areas for these cultivars. Taking into account the plans on increasing the vineyard areas in the Sevastopol region it is also important to consider the climate changes in future. These accurate air temperature projects will help the efficient allocation of grape plantings and the selection of optimal grape cultivars.

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Data Availability Statement: The initial time series of daily data of the average, minimum and maximum air temperature are on the website DEAR-Clima <http://meteo3.geo.auth.gr:3838> (Accessed date 21 January 2021).

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References

1. Van Leeuwen, C.; Friant, P.; Xavier, C.; Tregoat, O.; Koundouras, S.; Dubourdieu, D. Influence of climate, soil, and cultivar on terroir. *Am. J. Enol. Vitic.* **2004**, *55*, 207–217.
2. Santos, J.A.; Fraga, H.; Malheiro, A.C.; Moutinho-Pereira, J.; Dinis, L.-T.; Correia, C.; Moriondo, M.; Leolini, L.; Dibari, C.; Costafreda-Aumedes, S.; et al. A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Appl. Sci.* **2020**, *10*, 3092. [[CrossRef](#)]

3. Schultz, H.R. Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Aust. J. Grape Wine Res.* **2000**, *6*, 2–12. [\[CrossRef\]](#)
4. Jones, G.V.; White, M.A.; Cooper, O.R.; Storchmann, K. Climate change and global wine quality. *Clim. Chang.* **2005**, *73*, 319–343. [\[CrossRef\]](#)
5. De Orduña, R.M. Climate change associated effects on grape and wine quality and production. *Food Res. Int.* **2010**, *43*, 1844–1855. [\[CrossRef\]](#)
6. Ashenfelter, O. Predicting the quality and prices of bordeaux wine. *World Sci. Handb. Financ. Econ. Ser.* **2018**. [\[CrossRef\]](#)
7. IPCC. *Climate Change 2014: Synthesis Report*; Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014; 151p.
8. Fraga, H.; Garcia de Cortazar-Atauri, I.; Malheiro, A.C.; Santos, J.A. Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Glob. Chang. Biol.* **2016**, *22*, 3774–3788. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Webb, L.B.; Watterson, I.; Bhend, J.; Whetton, P.H.; Barlow, E.W.R. Global climate analogues for winegrowing regions in future periods: Projections of temperature and precipitation. *Aust. J. Grape Wine Res.* **2013**, *19*, 331–341. [\[CrossRef\]](#)
10. Hannah, L.; Roehrdanz, P.R.; Ikegami, M.; Shepard, A.V.; Shaw, M.R.; Tabor, G.; Zhi, L.; Marquet, P.A.; Hijmans, R.J. Climate change, wine, and conservation. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 6907–6912. [\[CrossRef\]](#)
11. Santillán, D.; Garrote, L.; Iglesias, A.; Sotes, V. Climate change risks and adaptation: New indicators for Mediterranean viticulture. *Mitig. Adapt. Strateg. Glob. Chang.* **2020**, *25*, 881–899. [\[CrossRef\]](#)
12. Cardell, M.F.; Amengual, A.; Romero, R. Future effects of climate change on the suitability of wine grape production across Europe. *Reg. Environ. Chang.* **2019**, *19*, 2299–2310. [\[CrossRef\]](#)
13. Neethling, E.; Petitjean, T.; Quénel, H.; Barbeau, G. Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change. *Mitig. Adapt. Strat. Glob. Chang.* **2017**, *22*, 777–803. [\[CrossRef\]](#)
14. Fraga, H.; García de Cortázar Atauri, I.; Santos, J.A. Viticultural irrigation demands under climate change scenarios in Portugal. *Agric. Water Manag.* **2018**, *196*, 66–74. [\[CrossRef\]](#)
15. Koufos, G.; Mavromatis, T.; Koundouras, S.; Jones, G.V. Response of viticulture-related climatic indices and zoning to historical and future climate conditions in Greece. *Int. J. Climatol.* **2017**, *38*, 2097–2111. [\[CrossRef\]](#)
16. Koufos, G.C.; Mavromatis, T.; Koundouras, S.; Jones, G.V. Adaptive capacity of winegrape varieties cultivated in Greece to climate change: Current trends and future projections. *OENO One* **2020**, *4*, 1201–1219. [\[CrossRef\]](#)
17. Omazi, B.; Prtenjak, M.T.; Prša, I.; Vozila, A.B.; Vučetić, V.; Karoglan, M.; Kontić, J.K.; Prša, Ž.; Anić, M.; Šimon, S.; et al. Climate change impacts on viticulture in Croatia: Viticultural zoning and future potential. *Int. J. Climatol.* **2020**, 1–22. [\[CrossRef\]](#)
18. Eitzinger, J.; Kubu, G.; Formayer, H.; Gerersdorfer, T. Climatic wine growing potential under future climate scenarios in Austria. In *Sustainable Development and Bioclimate: Reviewed Conference Proceedings*; Slovak Acad Sciences: Bratislava, Slovakia, 2009; pp. 146–147.
19. Malheiro, A.C.; Santos, J.A.; Fraga, H.; Pinto, J.G. Climate change scenarios applied to viticultural zoning in Europe. *Clim. Res.* **2010**, *43*, 163–177. [\[CrossRef\]](#)
20. Gaál, M.; Moriondo, M.; Bindi, M. Modelling the impact of climate change on the Hungarian wine regions using Random Forest. *Appl. Ecol. Environ. Res.* **2012**, *10*, 121–140. [\[CrossRef\]](#)
21. Tóth, J.P.; Végvári, Z. Future of winegrape growing regions in Europe. *Aust. J. Grape Wine Res.* **2016**, *22*, 64–72. [\[CrossRef\]](#)
22. Machar, I.; Vlčková, V.; Buček, A.; Vrublová, K.; Filippovová, J.; Brus, J. Environmental Modelling of Climate Change Impact on Grapevines: Case Study from the Czech Republic. *Pol. J. Environ. Stud. Vol.* **2017**, *26*, 1927–1934. [\[CrossRef\]](#)
23. Trbic, G.; Djurdjevic, V.I.; Mandic, M.V.; Ivanisevic, M.; Cupac, R.; Bajic, D.; Zahirovic, E.; Filipovic, D.; Dekic, R.; Popov, T.; et al. The impact of climate change on grapevines in Bosnia and Herzegovina. *Euro-Mediterr. J. Environ. Integr.* **2021**, *6*, 4. [\[CrossRef\]](#)
24. Mendoza, G.H.; Ramos, C.A.G.; Corral, D.M.H.; Cruz, R.S.; Garbolino, E. Assessing Suitable Areas of Common Grapevine (*Vitis vinifera* L.) for Current and Future Climate Situations: The CDS Toolbox SDM. *Atmosphere* **2020**, *11*, 1201. [\[CrossRef\]](#)
25. Hewer, M.J.; Brunette, M. Climate change impact assessment on grape and wine for Ontario, Canada's appellations of origin. *Reg. Environ. Chang.* **2020**, *20*, 86. [\[CrossRef\]](#)
26. Hewer, M.J.; Gough, W.A. Assessing the impact of projected climate change on the future of grape growth and wine production in the Niagara Peninsula (Canada). *J. Wine Res.* **2020**, *34*, 6–34. [\[CrossRef\]](#)
27. Cabré, F.; Nuñez, M. Impacts of climate change on viticulture in Argentina. *Reg. Environ. Chang.* **2020**, *20*, 12. [\[CrossRef\]](#)
28. Vyshkvarkova, E.V.; Rybalko, E.A.; Baranova, N.V.; Voskresenskaya, E.N. Favorability Level Analysis of the Sevastopol Region's Climate for Viticulture. *Agronomy* **2020**, *10*, 1226. [\[CrossRef\]](#)
29. *Socioeconomic Development Strategy of the City of Sevastopol*; Legislative Assembly of the City of Sevastopol: Sevastopol, Russia, 2017; 171p.
30. Intergovernmental Panel on Climate Change (IPCC). *Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections*; National Center for Atmospheric Research: Boulder, CO, USA, 2010.
31. Shaw, T.B. Climate change and the evolution of the Ontario cool climate wine regions in Canada. *J. Wine Res.* **2016**. [\[CrossRef\]](#)
32. Huglin, P. Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. In *Proceedings of the Symposium International sur l'Ecologie de la Vigne*, Constanta, Romania, 25–29 September 1978; Ministère de l'Agriculture et de l'Industrie Alimentaire: Constanta, Romania, 1978; pp. 89–98.

33. Amerine, M.A.; Winkler, A.J. Composition and quality of musts and wines of California grapes. *Hilgardia* **1944**, *15*, 493–675. [[CrossRef](#)]
34. Winkler, A.J.; Cook, J.A.; Kliwer, W.M.; Lider, L.A. *General Viticulture*; University of California Press: Berkeley, CA, USA, 1974.
35. Rybalko, E.A. Adaptation of the mathematical model of the spatial distribution of heat supply in the territory in order to efficiently place industrial vineyards on the territory of the Crimean Peninsula. *Vinograd. Vinodel.* **2014**, *2*, 10–11.
36. Gladstones, J. *Wine, Terroir and Climate Change*; Wakefield Press: Mile End, Australia, 2011; 279p.
37. Poni, S.; Gatti, M.; Palliotti, A.; Dai, Z.; Duchêne, E.; Truong, T.-T.; Ferrara, G.; Matarrese, A.M.S.; Gallotta, A.; Bellincontro, A.; et al. Grapevine quality: A multiple choice issue. *Sci. Hortic.* **2018**, *234*, 445–462. [[CrossRef](#)]
38. Venios, X.; Korkas, E.; Nisiotou, A.; Banilas, G. Grapevine Responses to Heat Stress and Global Warming. *Plants* **2020**, *9*, 1754. [[CrossRef](#)] [[PubMed](#)]
39. Schultz, H.R.; Jones, G.V. Climate induced historic and future changes in viticulture. *J. Wine Res.* **2010**, *21*, 137–145. [[CrossRef](#)]
40. Novikova, L.Y.; Naumova, L.G. Dependence of Fresh Grapes and Wine Taste Scores on the Origin of Varieties and Weather Conditions of the Harvest Year in the Northern Zone of Industrial Viticulture in Russia. *Agronomy* **2020**, *10*, 1613. [[CrossRef](#)]
41. Jones, G.V. Climate and terroir: Impacts of climate variability and change on wine. In *Fine Wine and Terroir—The Geoscience Perspective*; Meinert, L.D., Ed.; Geoscience Canada, Geological Association of Canada: St. John's, NL, Canada, 2006; pp. 1–14.
42. Nesbitt, A.; Kemp, B.; Steele, C.; Lovett, A.; Dorling, S. Impact of recent climate change and weather variability on the viability of UK viticulture—combining weather and climate records with producers' perspectives. *Aust. J. Grape Wine Res.* **2016**, *22*, 324–335. [[CrossRef](#)]
43. Davitaya, F.F. *Basic Principles of Zoning of Grape Culture//Physiology of Grapes and the Basics of Its Cultivation*; Bulgaria Academy Sofia: Sofia, Bulgaria, 1981; pp. 27–52.
44. Tonietto, J.; Carbonneau, A.A. Multicriteria climatic classification system for grape growing regions worldwide. *Agric. For. Meteorol.* **2004**, *124*, 81–97. [[CrossRef](#)]
45. Keller, M. *The Science of Grapevines: Anatomy and Physiology*; Elsevier, Inc.: New York, NY, USA, 2010; p. 400.
46. Biasi, R.; Brunori, E.; Ferrara, C.; Salvati, L. Assessing impacts of climate change on phenology and quality traits on *Vitis vinifera*, L.: The contribution of local knowledge. *Plants* **2019**, *8*, 121. [[CrossRef](#)]
47. Molitor, D.; Junk, J.; Evers, D.; Hoffmann, L.; Beyer, M. A high-resolution cumulative degree day-based model to simulate phenological development of grapevine. *Am. J. Enol. Vitic.* **2014**, *65*, 72–80. [[CrossRef](#)]
48. Fraga, H.; Santos, J.A.; Malheiro, A.C.; Oliveira, A.A.; Moutinho-Pereira, J.; Jones, G.V. Climatic suitability of Portuguese grapevine varieties and climate change adaptation. *Int. J. Climatol.* **2015**, *36*, 1–12. [[CrossRef](#)]
49. Pina-Rey, A.; Gonzalez-Fernandez, E.; Fernandez-Gonzalez, M.; Lorenzo, M.N.; Rodriguez-Rajo, F.J. Climate Change impacts assessment on wine-growing bioclimatic transition areas. *Agriculture* **2020**, *10*, 605. [[CrossRef](#)]
50. Nesbit, A.; Dorling, S.; Lovett, A. A suitability model for viticulture in England and Wales: Opportunities for investment, sector growth and increased climate resilience. *J. Land Use Sci.* **2018**, *13*, 414–438. [[CrossRef](#)]
51. Petrov, V.S.; Aleynikova, G.Y.; Novikova, L.Y.; Naumova, L.G.; Lukyanova, A.A. The influence of climate changes on the grape phenology. *Fruit Grow. Vitic. South Russ.* **2019**, *57*, 29–50. [[CrossRef](#)]
52. Caffarra, A.; Eccel, E. Projecting the impacts of climate change on the phenology of grapevine in a mountain area. *Aust. J. Grape Wine Res.* **2011**, *17*, 52–61. [[CrossRef](#)]
53. Moriondo, M.; Jones, G.V.; Bois, B.; Dibari, C.; Ferrise, R.; Trombi, G.; Bindi, M. Projected shifts of wine regions in response of climate change. *Clim. Chang.* **2013**, *119*, 825–839. [[CrossRef](#)]
54. Ponti, L.; Gutierrez, A.P.; Boggia, A.; Neteler, M. Analysis of grape production in the face of climate change. *Climate* **2018**, *6*, 20. [[CrossRef](#)]