

# Prostorsko-časovno modeliranje temperatur: primer vinorodnega okoliša Goriška brda (Slovenija)

## Spatial-temporal temperature modelling: example of Goriška Brda viticultural region (Slovenia)

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UDK: 004.942:536.5(497.473)  
 Klasifikacija prispevka po COBISS.SI: 1.01  
 Prispelo: 4. 6. 2025  
 Sprejeto: 23. 12. 2025

DOI: 10.15292/geodetski-vestnik.2026.01.11-30  
 SCIENTIFIC ARTICLE  
 Received: 4. 6. 2025  
 Accepted: 23. 12. 2025

### IZVLEČEK

Podnebne spremembe vse bolj ogrožajo kmetijstvo in imajo resne posledice (tudi) za vinogradništvo. Zlasti povišanje temperature vpliva na količino pridelka in sestavo grozdja ter kakovost vin. Namen te študije je oceniti prihodnje povišanje temperature v vinorodni regiji Goriška brda (Slovenija). Podatki o izmerjenih temperaturah so bili pridobljeni s treh vremenskih postaj, ki so nameščene na območju oziroma v bližini Goriških brd. Simulacija prihodnjih temperatur za obdobje 2041–2060 je bila ocenjena v okviru scenarijev Reprezentativna pot koncentracije (RCP) 4.5 in 8.5 z uporabo povprečja globalnih podnebnih modelov, Coupled Model Intercomparison Phase 5 (CMIP5). Simulirane temperature so pokazale povprečno zvišanje temperature za približno 2,0°C na vseh treh vremenskih postajah za obdobje 2041–2060 v primerjavi z referenčnim obdobjem 1950–2000. Ocenjeno zvišanje temperatur poudarja potrebo po prilagoditvenih strategijah v Goriških brdih. Ugotovitve študije zagotavljajo podporo vinogradnikom pri izbiranju prilagoditvenih strategij za povečanje odpornosti vinogradništva v kontekstu podnebnih sprememb.

### ABSTRACT

Climate change presents an increasing threat to agricultural, with significant impacts in viticulture. Rising temperatures affect grape yield, grape composition, and wine quality. This study aims to assess future temperature increase at Goriška Brda (Slovenia) viticultural region. Temperature data sets were retrieved from three weather stations located within and in vicinity of Goriška Brda. Future temperature simulation for the period 2041–2060 were evaluated under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios using averages of Coupled Model Intercomparison Phase 5 (CMIP5). The future simulated temperatures showed an average temperature increase of approximately 2.0°C at all three weather stations for 2041–2060 compared to the reference period (1950–2000). The assessed temperature increase highlights the need for adaptation strategies in Goriška Brda. The findings of this study provide valuable insights to support decision-making among winemakers by identifying appropriate adaptation strategies to enhance the resilience of viticulture under future climate change conditions.

### KLJUČNE BESEDE

podnebne spremembe; prilagoditvene strategije; WorldClim; vinogradništvo; RCP 4.5; RCP 8.5

### KEY WORDS

climate change; adaptation strategies; Worldclime; viticulture; RCP 4.5; RCP 8.5

## 1 Introduction

Climate change represents one of the most pressing challenges facing humanity in the 21st century. It is largely driven by anthropogenic greenhouse gas emissions, triggering profound and unprecedented alterations in global climate systems. These include increasing temperatures, shifts in precipitation patterns, and an increased frequency and intensity of extreme weather events (IPCC, 2021), with particularly pronounced effects in the Mediterranean basin (Prada et al., 2024). Such climate changes are also affecting agriculture—a sector fundamentally reliant on predictable and stable environmental conditions. In particular, increased temperatures affect plant phenology and soil moisture dynamics, thereby threatening crop yields and food security (Figari, 2025). Viticulture is among the most climate-sensitive agricultural systems, due to the high climate sensitivity of grapevine and the narrow temperature range suitable for high-quality wine production (Sun et al., 2023).

The most significant consequence of climate change affecting viticulture is the increase in air temperature (van Leeuwen et al., 2024). Rising temperatures have been shown to accelerate grapevine phenological development, resulting in earlier flowering and harvest dates (Jones et al., 2005). These shifts can alter the balance of sugars, acids, and aromatic compounds, thereby affecting wine quality (Jones et al., 2005). Furthermore, elevated temperatures are modifying the climatic suitability of traditional viticultural regions (Neethling et al., 2012), necessitating adaptation strategies to sustain wine quality and, in some instances, to safeguard the continuation of viticultural practices (Quéno, 2014).

The impacts of climate change on viticulture have been extensively studied due to its significant impact in the global agro-food industry (van Leeuwen et al., 2024). Particular attention has been focused on the Mediterranean basin, which has historically provided optimal conditions for grapevine (Lereboullet et al., 2013). Tomasi et al. (2011) analyzed long-term phenological changes in grapevine in north-eastern Italy, west of Goriška Brda. They reported identified significant shifts in grape developmental stages—bloom, veraison, and harvest—occurring 13 to 19 days earlier, along with a 2.3 °C increase in growing-season temperatures between 1964 and 2009. Similarly, Fila (2014) reported advances in budburst of 13.9 to 44.4 days and flowering of 24 to 36.5 days for grapevine variety Chardonnay in the Veneto region (Italy), further underscoring the phenological impacts of rising temperatures.

As climatic conditions in established viticultural regions become less favorable, winemakers are required to adopt adaptive strategies, including the selection of more climate-resilient grapevine varieties, the modification of vineyard management practices and even the relocation of vineyards to more suitable zones (Neethling et al., 2017). Adaptation in viticulture is critical, as grapevine is a perennial crop; thus, selecting varieties suited to both current and future climates is essential (Barbeau et al., 2015). However, successful adaptation is not just about technique; rather, it involves knowing how and when to adapt to constantly changing climatic conditions (Lereboullet et al., 2013). This understanding is based on knowledge of the temporal and spatial dynamics of climatic conditions at the regional level.

Despite growing concerns over the impacts of climate change on viticulture, there is a significant knowledge gap in modelling future climatic effects on viticulture at regional scales. This hampers the development of effective, region-specific adaptation strategies, which are crucial for sustaining viticultural productivity under changing environmental conditions. Enhancing this knowledge is essential to support decision-making in viticulture and to optimize the resilience of viticulture under ongoing climate change. The aim of the study is to provide insights that support the development of adaptation strategies for viticulture in response to

the increasing impact of climate change. The insights are focused on the spatio-temporal progression of temperature at the regional scale in the viticultural region Goriška Brda for the future period 2041–2060.

## 2 Materials and methods

### 2.1 Data collection and case study

To conduct this study, historical temperature data were gathered from three weather stations located within and around the Goriška Brda region, which served as the case study area. Based on the gathered data, future temperature development was modelled using the ensemble mean of global climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), derived from the WorldClim database of cartographic climate data (WorldClim, 2022). Temperature data collection was conducted in four stages: (1) selection of the viticultural region, (2) selection of weather stations, (3) retrieval of temperature data from weather stations, and (4) retrieval of climate model datasets for the locations of the weather stations.

The Goriška Brda viticultural region in western Slovenia was selected because of the availability of climatic data and its significant advancement in high-quality wine production during the last decades. It is a viticultural region of 72 km<sup>2</sup> in western Slovenia, characterized by a series of hilly ridges (Figure 1). Due to the diverse terrain and the influence of warm, humid air masses from the south—often resulting in fog in the valleys—combined with exposure to the north-easterly Burja wind, the study area experiences high microclimatic variability (Fikfak et al., 2017). Goriška Brda is characterized by a mild Mediterranean climate, classified as ‘Cfa’ in the Köppen–Geiger classification (Peel et al., 2006).



Figure 1: Location of the study area, Goriška Brda, and the three weather stations used in this study. The area of Goriška Brda is depicted in red colour. “Vremenska postaja” refers to a weather station, “državna meja” refers to the national border, and “Jadransko morje” refers to the Adriatic Sea.

For the purpose of spatial analysis of temperature variability, three weather stations were selected. One station is located between the coastal area and the Goriška Brda (Bilje), one within the study area (Vedrijan), and the third in the continental interior relative to Goriška Brda (Vojsko). Station elevation was not considered in the selection process. The available observed temperature data for the corresponding time periods (Table 1) were obtained from the archive of the Slovenian Environment Agency (ARSO, 2022). Weather stations recorded air temperature daily at 7.00, 14:00 and 21:00 hrs. From the three-daily temperature data, minimum temperature (Tmin\_o) and maximum temperature (Tmax\_o) were identified and used for further analysis. Future temperature conditions were assessed by using the ensemble mean of global climate models CMIP5 (WorldClim, 2022).

Table 1: Availability of temperature datasets and their corresponding identifiers from weather stations, including the geographic coordinates and elevation above sea level of the respective weather stations. Tmin stands for minimum and Tmax for maximum temperature. The letter 'o' in the identifier stands for observation dataset and 'm' for modelled datasets. The number 45 stands for the RCP 4.5 scenario and 85 stands for the RCP 8.5 scenario.

Temperature datasets	Corresponding identifiers	Weather stations		
		Bilje	Vojsko	Vedrijan
Observation data period	Tmin_o and Tmax_o	1962–2000	1961–2000	1960–1990
Modelled data reference period	Tmin_m and Tmax_m		1950–2000	
Modelled data future period	Tmin_m_45 and Tmax_m_45 Tmin_m_85 and Tmax_m_85	2041–2060	2041–2060	2041–2060
Latitude (°)		45.8867	46.0206	46.0120
Longitude (°)		13.6364	13.9080	13.5503
Elevation above sea level (m)		52	1083	248

In this study, the ensemble mean of global climate models from CMIP5 (WorldClim, 2022) was used due to its high spatial resolution (1 km<sup>2</sup>) compared to other models. Accordingly, for each weather station, the corresponding grid cell was identified, and modelled temperature data were retrieved from that specific cell to ensure spatial alignment with the observation dataset. The modelled data consist of two components: (1) dataset for the reference period 1950–2000, represented by average monthly minimum and maximum temperatures (Tmin\_m and Tmax\_m), and (2) future dataset for the future period 2041–2060, provided as average monthly values under two Representative Concentration Pathways (RCPs): RCP 4.5 and RCP 8.5. These datasets are denoted as Tmin\_m\_45, Tmax\_m\_45 (for RCP 4.5), and Tmin\_m\_85, Tmax\_m\_85 (for RCP 8.5) (Table 1). The RCP 4.5 scenario represents a stabilization pathway in which radiative forcing is stabilized by 2100 (optimistic scenario), whereas RCP 8.5 is characterized as a high-emission or 'business-as-usual' scenario (Wayne, 2013). A comparable research by Prada et al. (2024), studying the impacts of climate change on viticulture in the Mediterranean basin, used the same RCPs.

## 2.2 Future simulated temperature calculations

Simulated future temperatures for the period 2041–2060 were calculated using the ensemble mean of CMIP5 global climate models (WorldClim, 2022). The simulated temperatures are indicated as Tmin\_s\_45, Tmax\_s\_45 (for RCP 4.5), and Tmin\_s\_85, Tmax\_s\_85 (for RCP 8.5). To calculate the simulated temperatures at each weather station for the period 2041–2060 under RCP 4.5 and RCP 8.5 scenarios, the correction factor (Kf) was added to the observed average monthly (Tmin\_o and Tmax\_o).

The Kf for each weather station was defined as the difference between the modelled monthly temperature for 2041–2060 and the modelled monthly temperature for the reference period 1950–2000. For the simulated temperatures under RCP 4.5, modelled temperature data for the period 2041–2060 corresponding to the RCP 4.5 scenario were used; the same approach was applied for RCP 8.5. As an example, the calculation of the simulated average maximum temperature for April under RCP 4.5 ( $T_{max\_s\_45}$ ) at the Vojsko weather station is presented in the Table 2.

Table 2: Example of the calculation of the simulated average ( $T_{max\_s\_45}$ ) for April under RCP 4.5 for the period 2041–2060 at the Vojsko weather station. Identifiers are explained in the first paragraph of Chapter 2.2.

Identifier	Temperature parameter	Source	Value (°C)
$T_{max\_o}$	Observer monthly average Tmax for April (1962–2000)	(ARSO, 2022)	8.8
$T_{max\_m}$	Modelled monthly average Tmax (1950–2000)	(WorldClim, 2022)	10.1
$T_{max\_m\_45}$	Modelled monthly average Tmax (2041–2060) under RCP 4.5	(WorldClim, 2022)	11.1
Kf	Correction factor	$T_{max\_m\_45} - T_{max\_m}$	1.0
$T_{max\_s\_45}$	Simulated monthly average Tmax (2041–2060) under RCP 4.5	$\sum T_{max\_o}$ in Kf	9.8

The overall workflow, including used datasets and analysis procedure, is divided into three sections: data gathering, analysis and outcome (Figure 2). This schematic depicted on Figure 2 provides a comprehensive overview of the methodological approach applied in the study.

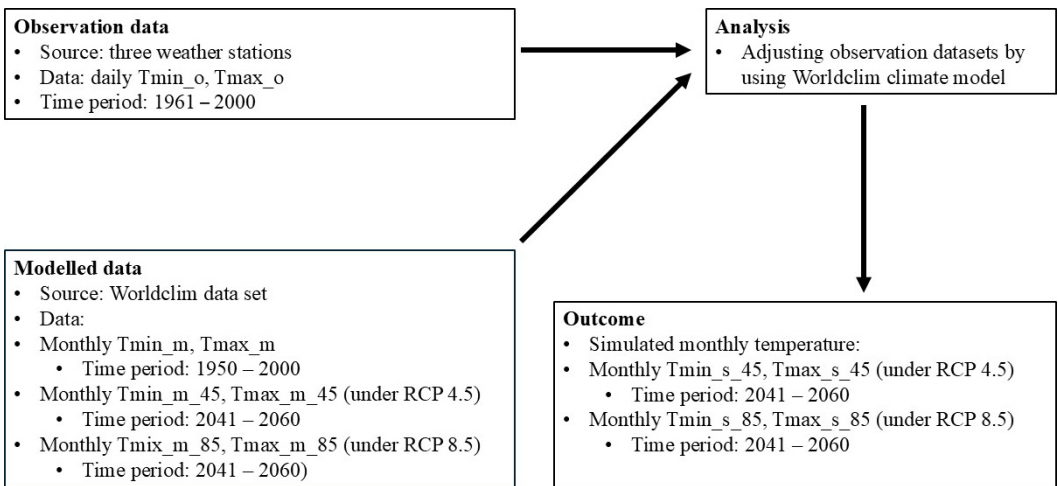


Figure 2: Schematics of the materials, methodology, and outcomes.

### 3 Results and discussion

#### 3.1 Observed and modelled temperature (1950–2000)

Average observed and modelled temperatures for the reference period (1960–2000) showed differences across the three weather stations, reflecting variability in topographical conditions at the study site (Figure 1 and Table 3). Most modelled temperatures were lower than the observed values, with two notable exceptions: at Bilje, the modelled minimum temperature ( $T_{min\_m}$ ) was 2.5 °C higher than the observed temperature, and at Vojsko, the modelled maximum temperature ( $T_{max\_m}$ ) exceeded the

observed temperature by 1.0 °C. The highest difference between observed and modelled temperatures was observed at Bilje for minimum temperature (2.5 °C), while the lowest difference was recorded for maximum temperature at Vedrijan (0.1 °C).

Table 3: Temperature datasets for the reference period (1961–2000); identifiers for temperature parameters are explained in the Materials and methods section (Chapter 2).

Observed and modelled temperatures with their corresponding time periods in brackets	Weather stations		
	Bilje	Vojsko	Vedrijan
Tmin_o (1961–2000)	6.5 °C	3.1 °C	9.1 °C
Tmin_m (1950–2000)	9.0 °C	2.6 °C	7.7 °C
Tmin_o – Tmin_m	-2.5 °C	0.5 °C	1.4 °C
Tmax_o (1961–2000)	17.9 °C	9.8 °C	16.8 °C
Tmax_m (1950–2000)	17.6 °C	10.8 °C	16.7 °C
Tmax_o – Tmax_m	0.3 °C	-1.0 °C	0.1 °C

The results showed variability in observed temperatures across weather stations, due to differences in station locations (Table 1) and the topographical conditions at the weather stations (Figure 1). Similar variability is also evident in the modelled datasets. Furthermore, discrepancies between observed and modelled datasets are evident across weather stations during the reference period. The most probable reason for the difference between modelled and observed temperatures is the spatial resolution of the climate model: the accuracy of WorldClim data is not as high as that of direct observational data from weather stations. Observed data were gathered from three specific locations (weather stations); however, the climate model data were generated through the interpolation of average monthly data from weather stations on a 1 km<sup>2</sup> resolution grid (WorldClim, 2022). Another possible reason is the variation in observation periods across weather stations from which the data were retrieved (Table 1). The results of a previous study examining the impacts of climate change on viticulture in Goriška Brda showed similar results (Sirnik, 2019). The difference between modelled and observed temperatures was less than 1 °C. Both studies used the same weather stations (Bilje, Vojsko, and Vedrijan); however, the study by Sirnik (2019) employed regional climate models from the Euro-CORDEX project with a spatial resolution of 12.5 km × 12.5 km (Jacob et al., 2014).

### 3.2 Future temperature trends (2041–2060)

Averages of simulated temperatures for the future period 2041–2060 showed high variability across weather stations (Table 4). Among the three weather stations, Bilje exhibited the highest simulated maximum temperature (Tmax\_s\_85), reaching 20.1 °C. The lowest simulated minimum temperature (Tmin\_s\_45) was calculated for Vojsko under the RCP 4.5 scenario (4.9 °C).

Table 4: Averages of (future) simulated temperatures for the period 2041–2060 at all three weather stations. (4.9 °C).

Simulated temperatures for the future period 2041–2060	Weather stations		
	Bilje	Vojsko	Vedrijan
Tmin_s_45	8.3 °C	4.9 °C	10.9 °C
Tmin_s_85	8.9 °C	5.1 °C	11.5 °C
Tmax_s_45	19.6 °C	11.5 °C	18.5 °C
Tmax_s_85	20.1 °C	12.0 °C	19.0 °C

The results showed a temperature increase (up to 2.0 °C) between the reference period (1950–2000) and the future period (2041–2060) at all weather stations (Table 5). This warming trend is consistent with the findings of Jones et al. (2005), who reported an average temperature rise of 2.0 °C across major viticultural regions during the second half of the 21st century, relative to the first half. The temperature increase for the future period, compared to the reference period, showed the same temperature increase across weather stations, with one exception: the increase in minimum temperature under RCP 8.5 at Vojsko was 0.5 °C lower compared to the other two weather stations. This is likely due to Vojsko being the weather station most directly influenced by the Mediterranean Sea among the three weather stations. In contrast, the other two stations, Vedrijan and Bilje, are situated at lower elevations (< 300 m) and are separated from the Mediterranean Sea by natural topographic barriers that limit direct maritime influence. This is consistent with the findings of Cirigliano et al. (2024), confirming that direct maritime exposure mitigates warming trends.

Table 5: Increase in temperature during the period 2041–2060 compared with the period 1950–2000 at all three weather stations under the RCP 4.5 and RCP 8.5 scenarios.

Temperature categories	Temperature increase from 1950–2000 to 2041–2060 at weather stations		
	Bilje	Vojsko	Vedrijan
T <sub>min</sub> under RCP 4.5	1.8 °C	1.8 °C	1.8 °C
T <sub>min</sub> under RCP 8.5	2.4 °C	2.0 °C	2.4 °C
T <sub>max</sub> under RCP 4.5	1.7 °C	1.7 °C	1.7 °C
T <sub>max</sub> under RCP 8.5	2.2 °C	2.2 °C	2.2 °C

The average monthly temperature (T<sub>mean</sub>) for each studied period showed variability across all four temperature categories (T<sub>mean\_o</sub>, T<sub>mean\_m</sub>, T<sub>mean\_s\_45</sub>, and T<sub>mean\_s\_85</sub>) (Figure 3). The observed (T<sub>mean\_o</sub>) and modelled (T<sub>mean\_m</sub>) mean temperatures for the reference period (1950–2000) were lower than the simulated temperatures for the future period (2041–2060). Furthermore, as expected given the nature of the climate scenarios (Van Vuuren et al., 2011), the temperatures under the RCP 8.5 scenario were significantly higher than those projected under RCP 4.5. The results also revealed that the hottest month was July and the coldest was January. November exhibited the highest increase in mean temperature from the reference period to the future period under the RCP 8.5 scenario, with a rise of 2.6 °C. In contrast, the lowest increase was recorded in April under the RCP 4.5 scenario, with a temperature rise of 1.1 °C.

The mean observed temperature (T<sub>mean\_o</sub>) for the reference period was, on average, 0.2 °C higher than the modelled temperature for the same period (1950–2000). The difference between future modelled (e.g. T<sub>mean\_s\_45</sub>) and observed temperatures indicated even higher difference. The average annual future modelled T<sub>mean</sub> values of 1.7 °C and 2.0 °C under RCP 4.5 and RCP 8.5, respectively, are higher compared to the observed annual average T<sub>mean</sub>. The results are consistent with the findings of Prada et al. (2024), reporting a temperature increase of up to 3.6 °C (under RCP 8.5) in the Mediterranean basin, based on a comparison between the reference period 1981–2010 and the future period 2041–2070. The higher temperature increase reported by Prada et al. (2024) may be attributed to the later reference period (1981–2010), a different climate model, and the broader spatial scope of their analysis.

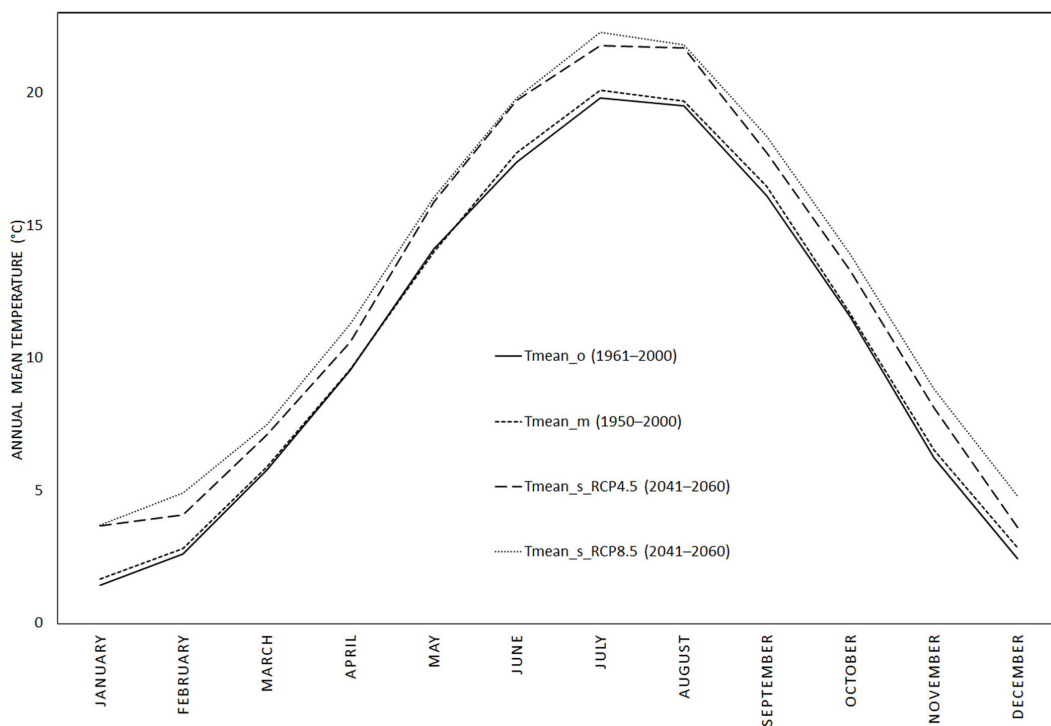


Figure 3: Monthly mean observed and modelled temperatures for the respective periods under the RCP 4.5 and RCP 8.5 scenarios.

### 3.3 Limitations

The results of this study may have been influenced by methodological and data-related limitations. Specifically, three key limitations associated with data availability and the methodological approach were identified. (1) This study employed averages of the global climate models CMIP5, which, despite their widespread use, introduce certain uncertainties due to the simplified representation of future climatic conditions (Lucas-Picher et al., 2021). The probability of temperature changes projected by the ensemble of global climate models from CMIP5 ranges from 66 % to 100 % (IPCC, 2013). Future studies would benefit from the use of more recent and higher-quality climate models (Palmer et al., 2023). (2) The spatial resolution of the analysis was limited to 1 km<sup>2</sup> (WorldClim, 2022). The use of a climate model with higher spatial resolution would likely improve the accuracy of the results and reduce uncertainties. Nevertheless, the WorldClim dataset provides global coverage, enabling the methodological approach to be replicated across different regions worldwide. Future research could benefit from comparing maps of mean temperatures for different time periods (e.g., 1951–1980, 1991–2020, and 2041–2060) and incorporating temperature thresholds specific to individual grapevine varieties, thereby allowing a spatial assessment of the suitability of regions for viticulture under future climatic conditions. (3) The availability of observational data was limited by the length of the observation periods of the selected weather stations (Table 1). Access to longer historical datasets would allow analysis of extended temperature series and improve comparison analysis over longer

time periods. Future research should prioritize the quality improvement of climate models by incorporating a broader set of models and conducting validation studies of adaptation strategies. Despite mentioned methodological limitations, the results are consistent with existing studies (e.g., Prada et al., 2024; Sirnik, 2019).

### 3.4 Implications of the findings

Adaptation in viticulture is essential and should be based on future climate models (Naulleau et al., 2021). In particular, understanding temperature trends is critical, as temperature affects grape phenology and consequently the quality of grapes (van Leeuwen & Darriet, 2016). In response to anticipated temperature increases, winemakers in the Goriška Brda region might consider adaptation strategies such as: (1) Using heat-tolerant grapevine varieties to delay ripeness without changing wine typicity (Morales-Castilla et al., 2020; van Leeuwen & Darriet, 2016). (2) Modifying the training system to delay grape phenology (Pieri & Gaudillère, 2003). For example, late pruning can delay bud break and consequently phenological stages. (3) Planning earlier harvest date, to achieve moderate sugar levels and adequate acidity (Santos et al., 2020). Winemakers might also consider long-term adaptation strategies, due to the probable continuation of temperature increases in the future (Prada et al., 2024). Long-term adaptation could include reducing inter-row length, adapting vineyards' spatial orientation (Prada et al., 2024), and moving vineyards to higher altitudes (van Leeuwen & Darriet, 2016). The findings of this study may also be used to guide adaptation strategies in other viticulture regions characterized by comparable climatic and topographic conditions.

## 4 Conclusion

Understanding the spatial-temporal progression of temperature is crucial for enabling winemakers to implement effective adaptation strategies in viticulture. This research provided a spatial-temporal analysis of the climate change impact in the Goriška Brda viticultural region, located in the Mediterranean basin. The results showed that the temperature trend in Goriška Brda is expected to increase during the period 2041–2060 compared to the reference period (1950–2000), by 1.7 °C and 2.0 °C under RCP 4.5 and RCP 8.5, respectively. However, the results revealed discrepancies between observed and modelled temperatures for the same time period. The future simulated temperatures showed a higher temperature increase under the RCP 8.5 scenario compared to RCP 4.5, with the minimum temperature rising more significantly than the maximum temperature. The average simulated future monthly temperature for November showed the highest annual increase (under the RCP 8.5 scenario).

Considering the spatial variability of different climate scenarios across studied three weather stations, the influence of the Mediterranean Sea was detected at the station closer to the coast, where a more moderate temperature increase was observed compared to the other two weather stations. According to the spatio-temporal temperature trends at the Goriška Brda site for the present and future periods, it is recommended to use short-term adaptation techniques (e.g., harvest management, winemaking techniques) and potentially gradually introduce long-term adaptation techniques (e.g., changes in the training system, reduced inter-row length, and the use of heat-tolerant grapevine varieties). The results of this study provide essential data for selecting appropriate adaptation strategies in response to climate

change, with benefits extending beyond viticulture to other vegetation types and ecosystems. Moreover, the applied methodology is transferable to other regions worldwide by using the ensemble mean of global climate models CMIP5 and can also be used for studying adaptation strategies beyond viticulture. The findings of this study provide valuable insights for winemakers and policymakers in the Goriška Brda, supporting the development of effective adaptation strategies to optimize the resilience of viticulture under ongoing climate change.

## Acknowledgments

The research was partially conducted within the framework of the research programme P2-0406: Opazovanje Zemlje in geoinformatika, funded by the Slovenian Research and Innovation Agency through the national budget of the Republic of Slovenia. The author also wishes to thank colleagues and friends for their professional contributions to this study: Solen Le Clech, Hervé Quénol, Miguel Ángel Jiménez Bello, Juan Manzano, Homero Marconi Penteadó, and Gašper Vindišar.

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# Prostorsko-časovno modeliranje temperatur: primer vinorodnega okoliša Goriška brda (Slovenija)

OSNOVNE INFORMACIJE O ČLANKU

GLEJ STRAN 11

## 1 Uvod

Podnebne spremembe so eden najresnejših izzivov človeštva v 21. stoletju. Eden od pomembnih povzročiteljev so antropogene emisije toplogrednih plinov, ki sprožajo izrazite spremembe v globalnih podnebnih sistemih. Te vključujejo naraščajoče temperature, spremembe v padavinskih vzorcih ter večjo pogostost in intenzivnost ekstremnih vremenskih dogodkov (IPCC, 2021), pri čemer so učinki še posebej izraziti v sredozemskem bazenu (Prada et al., 2024). Takšne podnebne spremembe pomembno vplivajo tudi na kmetijstvo – panogo, ki je močno odvisna od predvidljivih in stabilnih okoljskih razmer. Povečanje temperatur vpliva na fenologijo rastlin in dinamiko talne vlage, kar ogroža kmetijske pridelke in prehransko varnost (Figari, 2025). Vinogradništvo je med podnebno najbolj občutljivimi kmetijskimi sistemi, saj je grozdje izrazito občutljivo za podnebne razmere, visokokakovostna pridelava vina pa je mogoča le v ozkem temperaturnem razponu (Sun et al., 2023).

Najpomembnejša posledica podnebnih sprememb za vinogradništvo je naraščanje temperatur zraka (van Leeuwen et al., 2024). Višje temperature pospešujejo fenološki razvoj vinske trte, kar se kaže v zgodnejšem cvetenju in trgatvi (Jones et al., 2005). Te spremembe lahko vplivajo na ravnovesje sladkorjev, kislin in aromatičnih spojin ter s tem na kakovost vina (Jones et al., 2005). Poleg tega višje temperature spreminjajo podnebno primernost tradicionalnih vinorodnih območij (Neethling et al., 2012), kar narekuje potrebo po prilagoditvenih strategijah za ohranjanje kakovosti vina in nemoteno nadaljevanje vinogradniške dejavnosti (Quénol, 2014).

Zaradi vpliva podnebnih sprememb na svetovno agroživilsko industrijo so bili njihovi učinki na vinogradništvo predmet številnih raziskav (van Leeuwen et al., 2024). Posebna pozornost je bila namenjena Sredozemlju, ki tradicionalno zagotavlja optimalne razmere za pridelavo grozdja (Lereboullet et al., 2013). Tomasi et al. (2011) so v svoji študiji analizirali dolgoročne fenološke spremembe v severovzhodni Italiji v obdobju 1964–2009 ter ugotovili časovne premike v razvojnih fazah vinske trte. Faze, kot so cvetenje, barvanje jagod in trgatve, so se v tem obdobju pomaknile za 13 do 19 dni proti zgodnejšim datumom, medtem ko se je povprečna temperatura v rastni dobi povečala za 2,3 °C. Podobno je Fila (2014) za sorto grozdja *chardonnay* v deželi Benečiji poročal o pospešenem brstenju in cvetenju vinske trte, kar dodatno potrjuje vpliv naraščajočih temperatur na fenologijo trte.

Ker postajajo podnebne razmere na uveljavljenih vinorodnih območjih vse manj ugodne, so vinogradniki primorani k uporabi prilagoditvenih strategij, kot so izbor podnebno bolj odpornih sort grozdja, spremembe v upravljanju vinogradov ali celo preselitev vinogradov na primernejša območja (Neethling et al., 2017). Prilagajanje v vinogradništvu je še posebej pomembno, saj je vinska trta trajnica, zato je izbor sort, primernih za sedanje in prihodnje podnebne razmere, ključen (Barbeau

et al., 2015). Uspešno prilagajanje pa ni le tehnično vprašanje, temveč zahteva tudi razumevanje, kdaj in kako se prilagajati nenehno spreminjajočim se podnebnim razmeram (Lereboullet et al., 2013). To razumevanje temelji na poznavanju časovne in prostorske dinamike podnebnih razmer na regionalni ravni.

Kljub naraščajoči zaskrbljenosti glede vpliva podnebnih sprememb na vinogradništvo še vedno obstaja znanstvena vrzel v poznavanju prihodnjih podnebnih vplivov na regionalni ravni. Ta vrzel ovira razvoj učinkovitih regijskih strategij prilagajanja, ki so ključne za ohranjanje vinogradniške produktivnosti v spremenjenih okoljskih razmerah. Obvladovanje tovrstnega znanja je bistveno za podporo odločanju v vinogradništvu in za optimizacijo odpornosti sektorja proti podnebnim spremembam. Namen prispevka je ponuditi vpogled, ki bodo podpirali razvoj prilagoditvenih strategij za vinogradništvo kot odziv na naraščajoče vplive podnebnih sprememb. Ti vpogledi se osredotočajo na prostorsko-časovni potek temperatur na regionalni ravni v vinorodnem območju Goriška brda za obdobje 2041–2060.

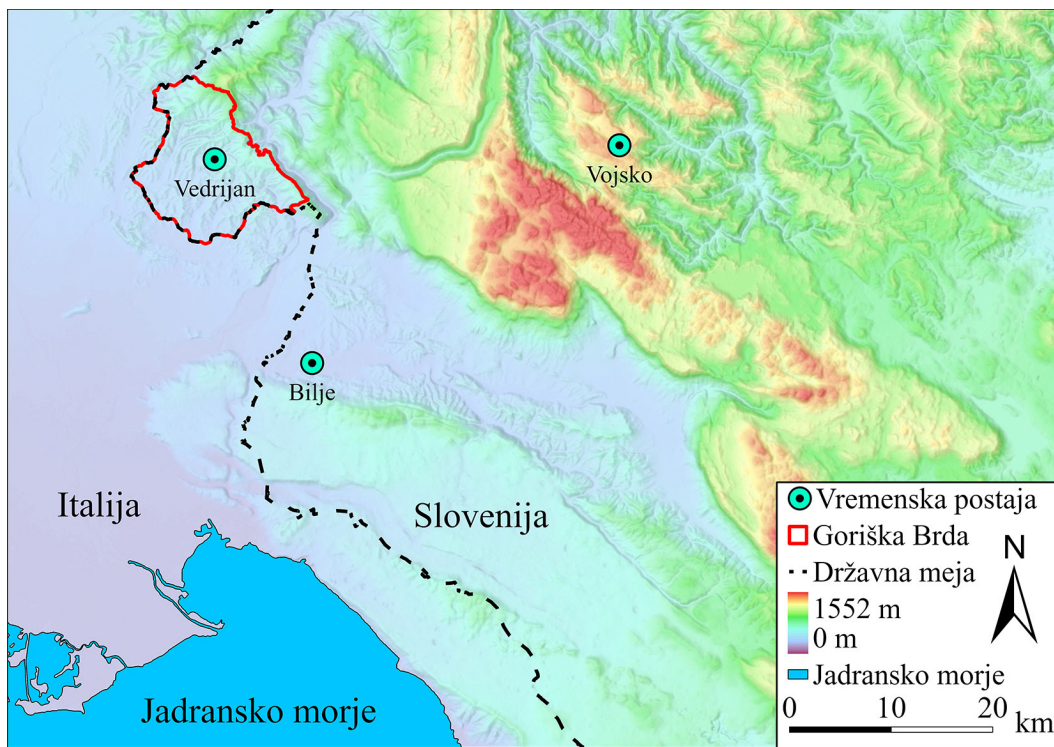
## 2 Metode in materiali

### 2.1 Zbiranje podatkov in predstavitev študijskega območja

Za izvedbo študije smo zbrali zgodovinske podatke o temperaturah s treh vremenskih postaj, ki stojijo v regiji Goriška brda, izbrani za študijsko območje, in njeni okolici. Na podlagi podatkov in povprečja globalnih podnebnih modelov Coupled Model Intercomparison Phase 5 (CMIP5) iz baze kartografskih podatkov WorldClim (WorldClim, 2022) smo modelirali prihodnji temperaturni razvoj. Zbiranje temperaturnih podatkov je potekalo v štirih fazah: (1) izbor vinorodnega okoliša, (2) izbor vremenskih postaj, (3) pridobivanje podatkov o izmerjenih temperaturah na vremenskih postajah in (4) pridobivanje napovedanih temperaturnih podatkov podnebnega modela za lokacije vremenskih postaj.

Za študijo je bil zaradi razpoložljivosti podnebnih podatkov ter njegovega pomembnega napredka v proizvodnji vrhunskih vin v zadnjih desetletjih izbran vinorodni okoliš Goriška brda v zahodni Sloveniji. Vinorodno območje ima površino 72 km<sup>2</sup> in se razteza po gričevnatem reliefu skrajnega dela zahodne Slovenije (slika 1). Zaradi razgibanega terena in izpostavljenosti vplivu toplih in vlažnih zračnih mas z juga, ki pogosto povzročajo meglo v dolinah – v kombinaciji z izpostavljenostjo severovzhodnemu vetru oziroma burji – je za območje raziskave značilna izrazita mikroklimatska raznolikost (Fikfak et al., 2017). Goriška brda so v območju milega sredozemskega podnebja, ki je po Köppen-Geigerjevi klasifikaciji opredeljeno kot »Cfa« (Peel et al., 2006).

Za potrebe prostorske analize spremenljivosti temperature so bile izbrane tri vremenske postaje. Ena stoji med obalnim območjem in Goriškimi brdi (Bilje), ena na območju raziskave (Vedrijan), tretja pa v notranjosti celine glede na Goriška brda (Vojsko). Pri izboru postaj nadmorska višina ni bila upoštevana. Pridobljeni razpoložljivi podatki o opazovanih temperaturah za ustrezna časovna obdobja (preglednica 1) izvirajo iz arhiva Agencije Republike Slovenije za okolje (ARSO, 2022). Vremenske postaje so beležile temperaturo trikrat dnevno, in sicer ob 7:00, 14:00 in 21:00. Na podlagi dnevnih meritev sta bili določeni najnižja ( $T_{min\_o}$ ) in najvišja ( $T_{max\_o}$ ) temperatura. Ti vrednosti sta bili skupaj s podnebnim modelom uporabljeni za nadaljnjo analizo temperature.



Slika 1: Lega študijskega območja Goriška brda in treh vremenskih postaj, uporabljenih v študiji. Območje Goriških brd je prikazano z rdečo barvo.

Preglednica 1: Razpoložljivost temperaturnih naborov podatkov in njihovih pripadajočih identifikatorjev z vremenskih postaj, vključno z geografskimi koordinatami in nadmorsko višino posameznih vremenskih postaj. Tmin pomeni minimalno, Tmax pa maksimalno temperaturo. Črka »o« v identifikatorju označuje opazovane podatke, »m« pa modeliran nabor podatkov. Številka 45 pomeni scenarij RCP 4.5, številka 85 pa scenarij RCP 8.5.

Nabori podatkov o temperaturi	Ustrezni identifikatorji	Vremenske postaje		
		Bilje	Vojsko	Vedrijan
Obdobje opazovanja	Tmin_o in Tmax_o	1962–2000	1961–2000	1960–1990
Referenčno obdobje modeliranih podatkov	Tmin_m in Tmax_m	1950–2000		
Modelirani podatki v prihodnjem obdobju	Tmin_m_45 in Tmax_m_45 Tmin_m_85 in Tmax_m_85	2041–2060	2041–2060	2041–2060
Zemljepisna širina (°)		45.8867	46.0206	46.0120
Zemljepisna dolžina (°)		13.6364	13.9080	13.5503
Nadmorska višina (m)		52	1083	248

V študiji je bilo zaradi visoke prostorske ločljivosti (1 km<sup>2</sup>) v primerjavi z drugimi modeli uporabljeno povprečje globalnih podnebnih modelov CMIP5 (WorldClim, 2022). Za vsako vremensko postajo je bila določena ustrezna mrežna celica, iz katere so bili pridobljeni modelirani podatki o temperaturi, s čimer je bila zagotovljena prostorska usklajenost z opazovalnimi podatki. Modelirani podatki vključujejo dva sklopa: (1) podatke za referenčno obdobje 1950–2000, predstavljene kot povprečne mesečne najnižje in najvišje temperature (Tmin\_m in Tmax\_m), ter (2) podatke za prihodnje obdobje 2041–2060, predstavljene kot

povprečne mesečne vrednosti po dveh scenarijih reprezentativne poti koncentracije (RCP): RCP 4.5 in RCP 8.5 (IPCC, 2021). Ti podatki so označeni kot  $T_{min\_m\_45}$ ,  $T_{max\_m\_45}$  (za RCP 4.5) in  $T_{min\_m\_85}$ ,  $T_{max\_m\_85}$  (za RCP 8.5) (preglednica 1). Scenarij RCP 4.5 predstavlja pot stabilizacije, pri kateri se sevalni prispevek stabilizira do leta 2100 (optimistični scenarij), medtem ko je RCP 8.5 prepoznan kot visokoemisijski oziroma »business as usual« scenarij (Wayne, 2013). V primerljivi raziskavi o vplivih podnebnih sprememb na vinogradništvo v Sredozemlju, ki so jo izvedli Prada et al. (2024), sta bila uporabljena enaka scenarija RCP.

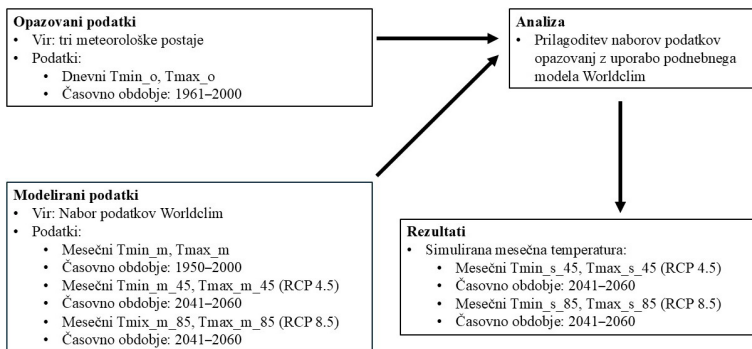
## 2.2 Izračuni prihodnjih temperatur

Simulirane prihodnje temperature za obdobje 2041–2060 so bile izračunane z uporabo povprečja globalnih podnebnih modelov CMIP5. Simulirane temperature so označene kot  $T_{min\_s\_45}$  in  $T_{max\_s\_45}$  (za scenarij RCP 4.5) ter  $T_{min\_s\_85}$  in  $T_{max\_s\_85}$  (za scenarij RCP 8.5). Za izračun simuliranih temperatur na posamezni vremenski postaji za obdobje 2041–2060 po scenarijih RCP4.5 in RCP8.5 je bil k opazovanim povprečnim mesečnim vrednostim ( $T_{min\_o}$  in  $T_{max\_o}$ ) dodan korekcijski faktor (Kf). Kf za posamezno vremensko postajo je bil definiran kot razlika med simulirano mesečno temperaturo za obdobje 2041–2060 in simulirano mesečno temperaturo za referenčno obdobje 1950–2000. Za simulirane temperature po scenariju RCP4.5 so bili uporabljeni simulirani temperaturni podatki za obdobje 2041–2060, ki ustrezajo scenariju RCP4.5; enak pristop je bil uporabljen za scenarij RCP8.5. Kot primer je v preglednici 2 prikazan izračun simulirane povprečne najvišje temperature za april po scenariju RCP 4.5 ( $T_{max\_s\_45}$ ) na vremenski postaji Vojsko.

Preglednica 2: Primer izračuna simuliranega povprečja ( $T_{max\_s\_45}$ ) za april po scenariju RCP4.5 za obdobje 2041-2060 na vremenski postaji Vojsko. Razlaga oznak je podana v prvem odstavku poglavja 2.2.

Oznaka	Temperaturni parametri	Vir	Vrednost (°C)
$T_{max\_o}$	opazovano mesečno povprečje $T_{max}$ za april (1962–2000)	(ARSO, 2022)	8,8
$T_{max\_m}$	modelirano mesečno povprečje $T_{max}$ (1950–2000)	(WorldClim, 2022)	10,1
$T_{max\_m\_45}$	modelirano mesečno povprečje $T_{max}$ (2041–2060) po scenariju RCP 4.5	(WorldClim, 2022)	11,1
Kf	korekcijski faktor	$T_{max\_m\_45} - T_{max\_m}$	1,0
$T_{max\_s\_45}$	simulirana mesečna povprečna $T_{max}$ (2041–2060) po scenariju RCP 4.5	$\Sigma T_{max\_o}$ in Kf	9,8

Celotna procedura, vključno z uporabljenimi nabori podatkov in analizo metodo, je razdeljena na tri sklope: zbiranje podatkov, analizo in izračun rezultatov (slika 2). Shematični prikaz zagotavlja celovit pregled metodološkega pristopa, uporabljenega v študiji.



Slika 2: Shema prikazuje uporabljene podatke, metodologijo in rezultate.

### 3 Rezultati in razprava

#### 3.1 Izmerjena in modelirana temperatura (1950–2000)

Povprečne izmerjene in modelirane temperature za referenčno obdobje (1960–2000) so se med tremi vremenskimi postajami razlikovale, kar odraža raznolikost topografskih razmer na raziskovanem območju (slika 1 in preglednica 3). Večina modeliranih temperatur je bila nižja od izmerjenih vrednosti, z izjemo dveh: v Biljah je bila najnižja modelirana temperatura ( $T_{min\_m}$ ) za 2,5 °C višja od izmerjene, na postaji Vojsko pa je najvišja modelirana temperatura ( $T_{max\_m}$ ) preseгла izmerjeno za 1,0 °C. Največja razlika med izmerjeno in modelirano temperaturo je bila ugotovljena v Biljah za najnižje temperature (2,5 °C), najmanjša pa za najvišje temperature na postaji Vedrijan (0,1 °C).

Preglednica 3: Podatkovni nabori temperatur za referenčno obdobje (1961–2000). Oznake temperaturnih parametrov so pojasnjene v poglavju 2.

Izmerjene in modelirane temperature z ustreznimi časovnimi obdobji v oklepajih	Vremenske postaje		
	Bilje	Vojsko	Vedrijan
$T_{min\_o}$ (1961–2000)	6,5 °C	3,1 °C	9,1 °C
$T_{min\_m}$ (1950–2000)	9,0 °C	2,6 °C	7,7 °C
$T_{min\_o} - T_{min\_m}$	-2,5 °C	0,5 °C	1,4 °C
$T_{max\_o}$ (1961–2000)	17,9 °C	9,8 °C	16,8 °C
$T_{max\_m}$ (1950–2000)	17,6 °C	10,8 °C	16,7 °C
$T_{max\_o} - T_{max\_m}$	0,3 °C	-1,0 °C	0,1 °C

Rezultati so pokazali variabilnost izmerjenih temperatur med vremenskimi postajami, kar je posledica različnih lokacij (preglednica 1) in topografskih značilnosti posameznih vremenskih postaj (slika 1). Podobna variabilnost je opazna v modeliranih podatkovnih nizih. Poleg tega so razlike med izmerjenimi in modeliranimi podatki v referenčnem obdobju izrazite tudi med posameznimi vremenskimi postajami. Najverjetnejši razlog za razlike med modeliranimi in izmerjenimi temperaturami je prostorska ločljivost podnebne modela: natančnost podatkov WorldClim ni primerljiva z neposredno izmerjenimi podatki vremenskih postaj. Opazovalni podatki so bili zbrani na treh točno določenih lokacijah (vremenskih postajah), medtem ko so bili podatki podnebne modela generirani z interpolacijo povprečnih mesečnih podatkov iz vremenskih postaj na mrežo z ločljivostjo 1 km<sup>2</sup> (WorldClim, 2022). Drug mogoč razlog za razlike je različno dolga doba opazovanj na posameznih vremenskih postajah, iz katerih so bili podatki pridobljeni (preglednica 1). Rezultati druge raziskave, s katero so proučevali vpliv podnebnih sprememb na vinogradništvo v Goriških brdih, so pokazali primerljive rezultate (Sirnik, 2019). Razlike med modeliranimi in izmerjenimi temperaturami so bile manjše od 1 °C. V obeh študijah so bile uporabljene iste vremenske postaje (Bilje, Vojsko in Vedrijan), vendar so bili v študiji Sirnik (2019) uporabljeni regionalni podnebni modeli iz projekta Euro-CORDEX z resolucijo 12,5 x 12,5 km (Jacob et al., 2014).

#### 3.2 Prihodnje temperaturne razmere (2041–2060)

Povprečne vrednosti simuliranih temperatur za obdobje 2041–2060 so pokazale variabilnost med vremenskimi postajami (preglednica 4). Med vsemi tremi postajami je Bilje izstopala z najvišjo simulirano

najvišjo temperaturo ( $T_{max\_s\_85}$ ), ki je dosegla 20,1 °C. Najnižja simulirana najnižja temperatura ( $T_{min\_s\_45}$ ) je bila izračunana na Vojskem v scenariju RCP 4.5 in je znašala 4,9 °C.

Preglednica 4: Povprečja (prihodnjih) simuliranih temperatur za obdobje 2041–2060 na vseh treh vremenskih postajah.

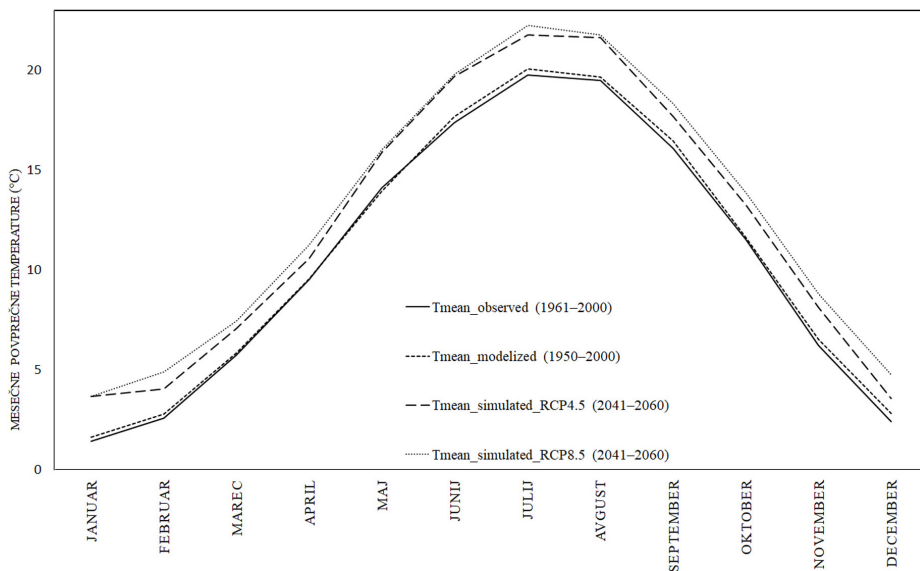
Simulirane temperature za prihodnje obdobje 2041–2060	Vremenske postaje		
	Bilje	Vojsko	Vedrijan
$T_{min\_s\_45}$	8,3 °C	4,9 °C	10,9 °C
$T_{min\_s\_85}$	8,9 °C	5,1 °C	11,5 °C
$T_{max\_s\_45}$	19,6 °C	11,5 °C	18,5 °C
$T_{max\_s\_85}$	20,1 °C	12,0 °C	19,0 °C

Rezultati so pokazali povišanje temperature (do 2,0 °C) med referenčnim obdobjem (1950–2000) in prihodnjim obdobjem (2041–2060) na vseh vremenskih postajah (preglednica 5). Ta trend segrevanja je skladen z ugotovitvami Jonesa et al. (2005), ki so poročali o povprečni rasti temperature za 2,0 °C v vodilnih vinorodnih regijah sveta v drugi polovici 21. stoletja v primerjavi s prvo polovico. Povišanje temperature v prihodnjem obdobju v primerjavi z referenčnim obdobjem je bilo na vseh vremenskih postajah enako, z eno izjemo: povišanje najnižje temperature po scenariju RCP 8.5 na Vojskem je bilo za 0,5 °C manjše kot na preostalih dveh postajah. To je verjetno posledica dejstva, da je vremenska postaja Vojsko med tremi najbolj neposredno izpostavljena vplivom Sredozemskega morja. Nasprotno sta postaji Vedrijan in Bilje na nižjih nadmorskih višinah (< 300 m) in sta od Sredozemskega morja ločeni z naravnimi topografskimi ovirami, ki omejujejo neposreden pomorski vpliv. To je skladno z ugotovitvami Cirigliana et al. (2024), ki potrjujejo, da neposredna pomorska izpostavljenost omili trende segrevanja.

Preglednica 5: Povišanje temperature v obdobju 2041–2060 v primerjavi z obdobjem 1950–2000 na vseh vremenskih postajah po scenarijih RCP4.5 in RCP8.5.

Temperaturne kategorije	Povišanje temperature od obdobja 1950–2000 do obdobja 2041–2060 na vremenskih postajah		
	Bilje	Vojsko	Vedrijan
$T_{min}$ povišanje (RCP4.5)	1,8 °C	1,8 °C	1,8 °C
$T_{min}$ povišanje (RCP8.5)	2,4 °C	2,0 °C	2,4 °C
$T_{max}$ povišanje (RCP4.5)	1,7 °C	1,7 °C	1,7 °C
$T_{max}$ povišanje (RCP8.5)	2,2 °C	2,2 °C	2,2 °C

Povprečna mesečna temperatura ( $T_{mean}$ ) za vsako proučevano obdobje je pokazala variabilnost med vsemi štirimi temperaturnimi kategorijami ( $T_{mean\_o}$ ,  $T_{mean\_m}$ ,  $T_{mean\_s\_45}$  in  $T_{mean\_s\_85}$ ). Variabilnost za vsak mesec posebej prikazuje slika 3. Izmerjene ( $T_{mean\_o}$ ) in modelirane ( $T_{mean\_m}$ ) povprečne temperature za referenčno obdobje 1950–2000 so bile nižje od simuliranih temperatur za prihodnje obdobje 2041–2060. Kot je bilo pričakovano glede na naravo podnebnih scenarijev (Van Vuuren et al., 2011), so bile temperature v scenariju RCP 8.5 občutno višje kot tiste v scenariju RCP 4.5. Rezultati so prav tako pokazali, da je najtoplejši mesec julij, najhladnejši pa januar. Največje povišanje povprečne temperature od referenčnega do prihodnjega obdobja po scenariju RCP 8.5 je bilo ugotovljeno novembra, in sicer za 2,6 °C. Nasprotno je bilo najmanjše povečanje temperature zabeleženo aprila po scenariju RCP 4.5, in sicer za 1,1 °C.



Slika 3: Mesečne povprečne izmerjene in modelirane temperature za ustrezna obdobja in scenarija RCP 4.5 ter RCP 8.5.

Povprečna izmerjena temperatura ( $T_{\text{mean}_o}$ ) za referenčno obdobje je bila v povprečju za  $0,2\text{ }^{\circ}\text{C}$  višja od modelirane temperature za isto obdobje (1950–2000). Še višje temperaturne razlike so pokazale primerjava med prihodnjimi simuliranimi temperaturami ( $T_{\text{mean}_s_{45}}$ ,  $T_{\text{mean}_s_{85}}$ ) in izmerjenimi temperaturami. Povprečne letne prihodnje modelirane vrednosti  $T_{\text{mean}}$  znašajo  $1,7\text{ }^{\circ}\text{C}$  oziroma  $2,0\text{ }^{\circ}\text{C}$  po scenarijih RCP4.5 oziroma RCP8.5, kar v primerjavi z izmerjenim letnim povprečjem  $T_{\text{mean}}$  predstavlja višje vrednosti. Rezultati so skladni z ugotovitvami Prada et al. (2024), ki so na območju Sredozemlja na podlagi primerjave referenčnega obdobja 1981–2010 in prihodnjega obdobja 2041–2070 poročali o temperaturnem dvigu do  $3,6\text{ }^{\circ}\text{C}$  (po scenariju RCP 8.5). Višji temperaturni dvig v študiji Prada et al. (2024) je možna posledica poznejšega referenčnega obdobja (1981–2010), uporabe drugačnega podnebne modela ter širšega prostorskega obsega njihove analize.

### 3.3 Omejitve

Na rezultate te študije so lahko vplivale nekatere metodološke in podatkovne omejitve. Natančneje, ugotovljene so bile tri ključne omejitve, povezane z razpoložljivostjo podatkov in metodološkim pristopom. (1) V tej študiji so bila uporabljena povprečja globalnih podnebnih modelov CMIP5, ki kljub svoji široki uporabi prinaša nekaj negotovosti zaradi poenostavljene predstavitve prihodnjih podnebnih razmer (Lucas-Picher et al., 2021). Verjetnost temperaturnih sprememb pri povprečju globalnih podnebnih modelov CMIP5 je 66–100 % (IPPC, 2013). V prihodnjih raziskavah bi bilo smiselno uporabiti novejšje in kakovostnejše podnebne modele (Palmer et al., 2023). (2) Prostorska ločljivost analize je bila omejena na  $1\text{ km}^2$  (WorldClim, 2022). Pri uporabi podnebne modela z višjo prostorsko ločljivostjo bi se verjetno izboljšala natančnost rezultatov in zmanjšale negotovosti. Kljub temu pa nabor podatkov WorldClim omogoča globalno pokritost, kar omogoča ponovljivost metodoloških pristopov v različnih regijah po svetu. V prihodnjih raziskavah bi bilo smiselno uporabiti primerjavo zemljevidov s povprečnimi

temperaturami za različna časovna obdobja (npr. 1951–1980, 1991–2020 in 2041–2060) ter vključiti temperaturne pragove posameznih sort grozdja, da bi prostorsko ovrednotili primernost območja za vinogradništvo v prihodnosti.

(3) Razpoložljivost opazovalnih podatkov je omejena z dolžino opazovalnih obdobj izbranih vremenskih postaj (preglednica 1). Dostop do daljših zgodovinskih naborov podatkov bi omogočil analize daljših temperaturnih nizov in izboljšal primerjave v daljših časovnih obdobjih. Prihodnje raziskave bi se morale osredotočiti na izboljšanje podnebne modeliranja z vključitvijo širšega nabora modelov ter validacijskih študij prilagoditvenih strategij. Kljub nekaterim omejitvam pristopa so rezultati skladni z obstoječimi študijami (npr. Prada et al., 2024; Sirnik, 2019). (4) V prihodnjih raziskavah bi bilo smiselno izvesti primerjavo kart povprečnih temperatur za različna časovna obdobja (npr. 1951–1980, 1991–2020 in 2041–2060). Poleg tega bi bilo priporočljivo vključiti temperaturne pragove posameznih sort grozdja, da bi se prostorsko ovrednotila njihova primernost za prihodnje vinogradniške razmere.

### 3.3 Implikacije rezultatov

Prilagajanje v vinogradništvu je ključno in bi moralo temeljiti na prihodnjih podnebnih modelih (Nau- lleau idr., 2021). Zaradi vpliva temperature na fenologijo vinske trte in posledično na kakovost grozdja (van Leeuwen & Darriet, 2016) je zlasti pomembno razumevanje temperaturnih trendov. Kot odziv na pričakovano povišanje temperatur bi vinogradniki v Goriških brdih lahko razmislili o naslednjih strate- gijah prilagajanja: (1) Uporaba sort vinske trte, odpornih proti vročini, ki omogočajo zamik dozorevanja, ne da bi pri tem spremenili tipičnost vina (Morales-Castilla idr., 2020; van Leeuwen & Darriet, 2016). (2) Prilagoditev obrezovanja trte (npr. pozno obrezovanje) lahko vpliva na zamik fenoloških faz (Pieri & Gaudillère, 2003). (3) Z zgodnejšo trgatvijo lahko dosežemo zmerno vsebnost sladkorja in ustrezno kislost (Santos idr., 2020). Vinogradniki bi lahko razmislili tudi o dolgoročnih prilagoditvenih strate- gijah, saj se bo trend naraščanja temperature verjetno nadaljeval tudi v prihodnosti (Prada idr., 2024). Med dolgoročne ukrepe spadajo skrajšanje dolžine vrst v vinogradu, prilagoditev prostorske usmerjenosti vinogradov (Prada idr., 2024) ter premestitev vinogradov na višje nadmorske višine (van Leeuwen & Darriet, 2016). Ugotovitve te študije lahko služijo tudi kot podlaga za oblikovanje strategij prilagajanja v drugih vinorodnih okoliših, za katere so značilne podobne podnebne in topografske razmere.

### 4 Ugotovitve

Razumevanje prostorsko-časovne dinamike temperature je ključno za omogočanje učinkovitega pri- lagajanja vinogradnikov na podnebne spremembe. V tej raziskavi je bila izvedena prostorsko-časovna analiza vpliva podnebnih sprememb v vinorodni regiji Goriška brda, ki je v Sredozemlju. Rezultati so pokazali, da se bo temperaturni trend v Goriških brdih v obdobju 2041–2060 v primerjavi z referenčnim obdobjem (1950–2000) povečal za približno 1,7 °C po scenariju RCP 4.5 in za približno 2,0 °C po scenariju RCP 8.5. So pa rezultati razkrili neskladja med opazovanimi in modeliranimi temperaturami v referenčnem obdobju. Simulirane prihodnje temperature so pokazale večje povišanje temperature po scenariju RCP 8.5 v primerjavi z RCP 4.5, pri čemer se je minimalna temperatura zvišala izraziteje kot maksimalna. Največje letno povprečno povišanje simulirane (prihodnje) mesečne temperature je bilo zaznано v novembru (po scenariju RCP 8.5).

Glede na prostorsko variabilnost različnih podnebnih scenarijev za posamezne vremenske postaje je bil zaznan vpliv Sredozemskega morja pri postaji bližje obali, kjer je bilo opaziti zmernejše povišanje temperature v primerjavi z drugima dvema vremenskima postajama. Na podlagi napredovanja prostorsko-časovnih temperaturnih trendov na območju Goriških brd v prihodnosti se priporoča uporaba kratkoročnih prilagoditvenih ukrepov (npr. uporaba sort vinske trte, odpornih proti vročini) ter postopno vključevanje dolgoročnih prilagoditvenih pristopov (npr. prilagoditev prostorske usmerjenosti vinogradov). Rezultati te študije zagotavljajo ključne podatke za izbiro ustreznih prilagoditvenih strategij kot odziv na podnebne spremembe, pri čemer korist ne zadeva zgolj vinogradništva, temveč tudi druge tipe vegetacije in ekosisteme. Uporabljen metodologija je prenosljiva na druge regije po svetu z uporabo povprečja globalnih podnebnih modelov CMIP5 in je uporabna tudi za preučevanje prilagoditvenih strategij za druge vrste pridelkov. Ugotovitve zagotavljajo dragocene podatke za vinogradnike in oblikovalce politik v vinorodni regiji Goriška brda, saj podpirajo razvoj učinkovitih prilagoditvenih strategij za optimizacijo odpornosti vinogradništva v času podnebnih sprememb.

## Zahvala

Raziskovalno delo je bilo delno opravljeno v okviru raziskovalnega programa *P2-0406: Opazovanje Zemlje in geoinformatika*, ki ga financira Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije iz državnega proračuna. Zahvala za strokovni prispevek k študiji gre tudi mojim kolegom in prijateljem: Solenu Le Clechu, Hervéju Quénu, Miguelu Ángelu, Jiménezu Bellu, Juanu Manzanu, Homeru Marconiju Penteadu in Gašperju Vindišarju.

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Geodetski vestnik, 70 (1), 11-30.

DOI: <https://doi.org/geodetski-vestnik.2026.01.11-30>

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