Acta geographica Slovenica, 65-1, 2025, 63–76

PROJECTIONS OF FUTURE SOIL TEMPERATURE IN THE WESTERN PART OF THE SOUTHEASTERN ANATOLIA PROJECT REGION, TÜRKİYE

İlyas Sadık Tekkanat

MEHMET EMİN TUDUN

Planting green beans with a planter at a soil depth of 5 cm in the village of Şekerli, Siverek, Türkiye, in June, when sufficient soil temperatures are reached.

DOI: https://doi.org/10.3986/AGS.13831
UDC: 631.4:551.525.2(560.8)

İlyas Sadık Tekkanat[1]

Projections of future soil temperature in the western part of the Southeastern Anatolia Project region, Türkiye

ABSTRACT: Soil temperature (Ts) is crucial for land use and soil management. It has gained importance in climate change research as it reflects the interactions between the atmosphere and biosphere. This study evaluates Ts changes at depths of 5, 10, 20, 50, and 100 cm in the western part of the Southeastern Anatolia Project (W-SAP) region of Türkiye, which has a Mediterranean and hot semi-arid climate, for the period 2030–2090 compared to 1981–2010. The Soil Temperature and Moisture Model (STM^2) is used to generate Ts estimates. A temperature increase of 0.7–3.0 °C (RCP4.5) and 0.9–5.5 °C (RCP8.5) is predicted for the 21st century. Extreme Ts values in late-century summers may hinder crop planning. The research provides the first future Ts projections in W-SAP and offers important agro-climatic insights.

KEYWORDS: soil temperature, projection, STM^2, Southeastern Anatolia Project, Türkiye

Projekcije prihodnjih temperatur prsti v zahodnem delu območja projekta jugovzhodne Anatolije v Turčiji

POVZETEK: Temperatura prsti je ključna za rabo zemljišč in upravljanje tal. V raziskavah podnebnih sprememb postaja čedalje pomembnejša, saj odraža interakcije med ozračjem in biosfero. V članku so proučene spremembe v temperaturi tal v globinah 5, 10, 20, 50 in 100 cm v zahodnem delu območja projekta jugovzhodne Anatolije v Turčiji, ki ima sredozemsko in vroče polsuho podnebje, in sicer za obdobje 2030–2090 v primerjavi z obdobjem 1981–2010. Za oceno temperatur prsti je uporabljen model temperature in vlage prsti (STM^2). Za 21. stoletje je napovedano zvišanje temperature za 0,7–3,0 °C (RCP4.5) in 0,9–5,5 °C (RCP8.5). Ekstremne temperature prsti v poletnih mesecih proti koncu stoletja bi lahko otežile načrtovanje pridelkov. Predstavljena raziskava podaja prve projekcije prihodnjih temperatur prsti na proučevanem območju in pomembna agroklimatska spoznanja.

KLJUČNE BESEDE: temperatura prsti, projekcija, STM^2, projekt jugovzhodne Anatolije, Turčija

The article was submitted for publication on June 27th, 2024.
Uredništvo je prejelo prispevek 27. junija 2024.

[1] Çankırı Karatekin University, Çankırı, Türkiye
ilyastekkanat@karatekin.edu.tr (https://orcid.org/0000-0003-4338-684X)

1 Introduction

Soil temperature (Ts) is an important agronomic, agrometeorological and ecological parameter for soil classification, soil use and sustainability of ecosystem health (Araghi et al. 2017; Bradford et al. 2019). Moreover, Ts is an integrative indicator that best reflects the impact of climate change on the biosphere (Chang 1957). Ts is directly affected by climate change and land cover/land use changes and may even change its regime. This interaction may increase soil vulnerability to extreme soil temperatures and has negative impacts on natural and social systems (Sviličić et al. 2016; Tekkanat and Öztürk 2022a; Tekkanat and Öztürk 2022b).

In the 19th century, Ts measurements were conducted worldwide, particularly in the USA, China, Russia, and England. Short-term records were used to derive descriptive statistics and analyze annual changes in Ts with respect to depth (Rambaut 1901; Abbe 1905; Bouyoucos 1916). Subsequently, the warming process in the climate, driven by increasing human-induced greenhouse gas emissions from the industrial revolution, increased the need for research on air temperature (Ta) changes. However, studies on Ts have typically been insufficient in both quality and quantity. The primary reasons for this are as follows: firstly, a general lack of Ts observations and insufficient Ts proxies; secondly, Ts decreases exponentially with increasing depth and exhibits greater resistance to change than the atmosphere due to the time lag in its response to Ta; thirdly, Ts can be controlled locally, especially in agricultural areas. Finally, the spatio-temporal uncertainty and complexity of interactions between rhizosphere and plant development complicate the understanding of soil temperature dynamics.

While research on Ts estimation based on Ta observations, soil temperature trends, and soil temperature regimes has gained weight after the 2000s, ecosystem-based Ts studies and projections of future soil temperatures are more recent and scarce. So far, results on projections of soil temperature have been reported for Asia (Araghi et al. 2019; Tekkanat 2023), Europe (Oni et al. 2017; Górniak 2023), and various regions of North America (Houle et al. 2012), but there is a gap in knowledge about other regions. Ts are increasing due to global warming, and it is becoming increasingly important to analyze how soils have responded in the past and how they will respond in the future under changing climate conditions (Qian et al. 2011; Houle et al. 2012; Araghi et al. 2017; Oni et al. 2017; Araghi et al. 2019; Górniak 2023; Tekkanat 2023). For example, under the A1B emission scenario and 15 regional climate models (RCMs), Ts increases of 1.7 °C, 1.5 °C, and 1.3 °C are projected on average for the upper (10 cm), middle (20 cm), and bottom (60 cm) layers in the riparian zone in Svartberget, northern Sweden for the period 2061–2090, respectively. These projected Ts increases were 1.3 °C, 1.3 °C, and 1.1 °C in the highlands, respectively. Another region in northern latitudes (Canada, southern Québec, three forested areas) exhibits higher projected temperature increases in the 70 cm soil layer, especially during 2070–2099. Compared to the 1971–2000 reference period, the projected increase in Ts in the 2040–2069 period ranged from 1.1 to 1.9 °C, while this range was calculated as 1.9 to 3.3 °C in the 2070–2099 period. In a study conducted with three weather stations in northeastern Iran, characterized by an arid and semi-arid climate, it was found that Ts is projected to increase by 0.8 to 1.5 °C and 2.4 to 4.4 °C under the RCP4.5 and RCP8.5 scenarios, respectively (Araghi et al. 2019). Similarly, a Ts projection study in the northwestern region of Türkiye, specifically in the Meriç-Ergene River Basin (MERB), analyzed 17 sets of Global Climate Models (GCMs) at depths ranging from 5 to 100 cm (Tekkanat 2023). This study indicated temperature changes between –0.6 °C to 3.0 °C and –0.5 °C to 5.6 °C under the RCP4.5 and RCP8.5 scenarios, respectively. Furthermore, it has been suggested that the Ts regime in northeastern Poland is also changing due to global warming, with anticipated increases of over 2 °C and approximately 1.5 °C by the end of the 21st century in the 0–20 cm and 50 cm layers, respectively, according to the RCP8.5 scenario (Górniak 2023).

The projections of future Ts in Türkiye were first conducted by Tekkanat (2023) in the MERB, with no studies having been carried out on Ts changes in other regions. This study presents, for the first time, the short-term (2030), medium-term (2050), and long-term (2070 and 2090) future Ts changes in the western part of the Southeastern Anatolia Project (W-SAP) region of Türkiye. The agrometeorological and agroclimatological data provide valuable information for planning and may alter our understanding of local climate change, water management, agriculture, and food security, particularly in regions like the Southeastern Anatolian Project and the Euphrates Basin. This study provides important and useful information for other regions with similar Mediterranean and hot semi-arid (steppe) climates, such as Southern Europe, North Africa, and the Middle East, where agricultural practices and water resources management are critical under climate change scenarios.

2 Study area, data and methods

2.1 Study area

The study area is situated in the western part of the Southeastern Anatolia Project (W-SAP) region. For this research, two stations were selected in the plains of Siverek and Birecik, as shown in Figure 1. These stations are primarily located within the Euphrates River basin and represent the W-SAP. The region spans an area of 34,835.25 km². According to Koç (2013), the elevation in this area ranges from 0 to 1,000 meters, with extensive agricultural land predominantly found at elevations between 0 and 250 meters. The average slope of the terrain is 4%, consisting of flat, hilly, and gently sloping plains. The cities of Şanlıurfa, Siverek, and Birecik are the major urban centers in the W-SAP.

The W-SAP is characterized by a Mediterranean climate (Csa) and a hot semi-arid climate (Bsh). Influenced by the migratory Cyprus low, which can cause thunderstorms (Kadioğlu 2000), the area experiences a transitional precipitation regime, with rainfall occurring both frontally and convectively. The climate displays traits of a modified Mediterranean climate, featuring a precipitation peak in December and moderate precipitation levels overall (Sariş et al. 2010). Additional geographical information about the meteorological stations can be found in Table 1.

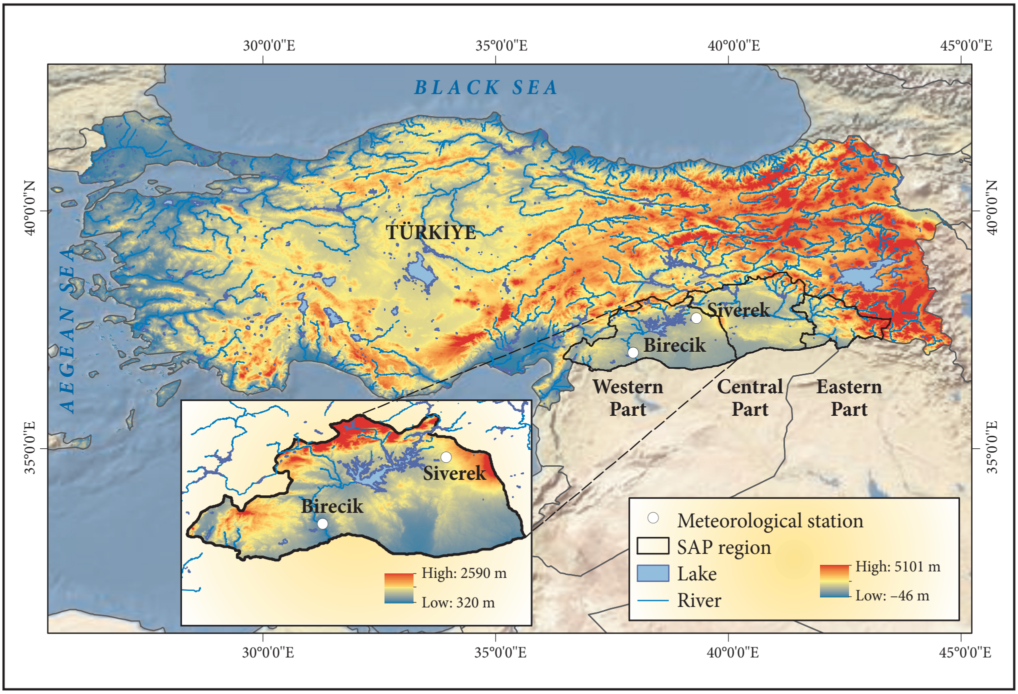

Figure 1: Locations of meteorological stations and the study area.

Table 1: Geographical information of meteorological stations used in this study.

Basin	Station	Lat(°)	Lon(°)	Elevation (m)	Annual precipitation (mm)	Mean annual air temperature (°C)	Beaufort wind scale
Euphrates Basin	Siverek	37.7522	39.3291	801	570	16.63	Light breeze
	Birecik	37.3103	37.9638	347	360	17.94	Light air

In the W-SAP, the soil characteristics in Siverek are as follows. In the topsoil (0–30 cm), the organic carbon content is 1.22% by weight and the pH is 6.3. In the subsoil (30–100 cm), the organic carbon content decreases to 0.58%, while the pH increases slightly to 6.4. Based on the FAO74 soil classification, the dominant soil type in this area is Chromic Luvisols. The proportions of clay, silt and sand in Siverek are 22.5%, 51.9%, and 25.6% respectively, indicating a dominant clay texture.

In contrast, the soil properties in Birecik differ considerably. In the topsoil (0–30 cm), the organic carbon content is 0.6% with a pH of 8.0. In the subsoil (30–100 cm), the organic carbon content decreases further to 0.4%, while the pH increases to 8.1. According to the FAO74 classification, the dominant soil type in Birecik is Eutric Fluvisols. The clay, silt, and sand proportions in Birecik are 36.4%, 18.0%, and 45.6% respectively, resulting in a loamy texture.

2.2 Data

Ts and Ta observations for the period 1981–2010 were obtained from the General Directorate of Meteorology. Daily Ts data from 2003–2006 at different depths were used to correct biases in the Soil Temperature and Moisture Model (STM^2) outputs and to detect future Ts increases or decreases. Additionally, daily average precipitation (mm), and daily maximum and minimum air temperature data, which are the meteorological input parameters required to run STM^2, were obtained from the MarkSim daily weather generator. MarkSim is a third-order Markov precipitation generator that utilizes methods developed by Richardson (1981) to produce weather data for potential future climatology (Jones and Thornton 2013).

The Harmonized World Soil Database (HWSD) is a raster database with a horizontal resolution of 30 arc seconds (approximately 1 km), where each raster grid represents the predominant soil type. The source databases for HWSD include the European Soil Database (ESDB), the Soil Map of China at a scale of 1:1 million, the SOTWIS database, and the Soil Map of the World. Organic matter and soil texture data used in the model were obtained from the HWSD version 1.21 Imager.

2.3 Methods

In this study, the methodology used by Araghi et al. (2019) was applied to predict future Ts changes in the W-SAP. In the first stage, daily stochastic time series of minimum air temperature, maximum air temperature and precipitation were generated for the years 2030, 2050, 2070 and 2090 with 99 replications for the stations to be used in the soil microclimate prediction model – STM^2. These time series were obtained by running 17 Global Circulation Models (GCMs) under the RCP4.5 and RCP8.5 scenarios using the MarkSimGCM tool.

In the second stage, the organic matter and texture information to be used in STM^2 were extracted from the HWSD version 1.21 Imager based on expert opinion. Both texture and organic matter values included in the model represented the average of topsoil (0–30 cm) and subsoil (30–100 cm). Texture was defined according to the USDA Texture Classification, and organic matter was calculated based on organic carbon (% weight) values (Pribyl 2010).

After the data preparation phase, the STM^2 model was run for the years 2030, 2050, 2070, and 2090, as well as for the 2003–2006 period to be used for bias correction.

STM^2 is a one-dimensional model written in Java that predicts soil microclimate conditions using limited inputs along with empirical and physical models (Spokas and Forcella 2009). This model was developed by the U.S. Department of Agriculture Agricultural Research Service (USDA ARS) and serves as a tool for simulating soil temperature and moisture, often used in agrometeorological studies (Spokas and Forcella 2009; Masin et al. 2012; Perreault et al. 2013; Araghi et al. 2019).

Following the STM^2 model run, it was necessary to calibrate the raw Ts model outputs with bias correction (BC) methods to make accurate predictions. Previous studies have reported that linear scaling performs very well at all depths in calibrating STM^2 Ts model outputs (Araghi et al. 2019). Therefore, in this study, the linear scaling method, which is frequently used in the temperature variable, was preferred to eliminate uncertainties and systematic errors in model outputs (Teutschbein and Seibert 2012; Shrestha et al. 2016). Linear scaling is a correction method that addresses bias by adjusting simulated data through a correction factor. This factor is determined by the ratio of observed monthly averages to those simulated by the model (Lenderink et al. 2007; Teutschbein and Seibert 2012).

Bias corrections were applied to the air and soil temperature data using Equation 1 proposed by Shrestha et al. (2016):

$$T_f^* = T_f(d) + \mu_m(T_{obs}(d)) - \mu_m(T_{his}(d)) \quad (1)$$

where *T, his, obs, f, μ, m,* and *d* represent the temperature, historical run, observational data, model future run, average, month, and day, and the symbol * denotes the bias-corrected data sets.

In the final stage of the methodology, a performance evaluation of the STM^2 model at all depths for 2008 was also conducted. In this sense, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), index of agreement (d), and R-squared correlation (R^2) performance measures were utilized.

3 Results

3.1 Performance of STM^2 model

2008 was chosen as a test year to evaluate the performance of the STM^2 model. We significantly reduced the uncertainties by applying linear scaling to the daily temperature values (Ts) of the model for that year. The RMSE values for the raw outputs of the model (no bias correction) ranged from 2.30 to 3.99 °C, while the RMSE values after applying linear scaling for bias correction ranged from 0.76 to 2.41 °C (Tables 2 and 3).

The error rate at the Birecik station was higher than at the Siverek station, particularly at a depth of 5 cm (Tables 2 and 3). In the post-linear scaling model outputs, the average RMSE values were 1.3 °C across all depths at both stations. It is worth noting that the average RMSE values in the 20–100 cm soil layer were below 1 °C.

Additionally, we observed a 60% decrease in mean absolute error (MAE) values after bias correction, compared to the values before bias correction. The reductions were 47.80%, 75.62%, and 80.78% in the shallow (0–20 cm), medium (50 cm), and deep (100 cm) soil layers, respectively. After applying bias correction at all stations and depths, the mean absolute percentage error (MAPE) values ranged from 3% to 22%, with the average MAPE value decreasing by approximately 50%. Following the linear scaling bias correction applied to the STM^2 model outputs, we achieved accurate predictions based on the d and R^2 criteria (Tables 2 and 3).

Table 2: Performance evaluation of the STM^2 model at Siverek station in 2008 using the linear scaling (LS) bias correction (BC) method.

Depth (cm)	Bias Correction (BC)	index of agreement – d (°C)	Root Mean Square Error (°C)	Mean Absolute Error (°C)	Mean Absolute Percentage Error (%)	R^2
5	no BC	0.99	2.77	2.31	infinity	0.97
	LS	0.99	1.84	1.41	22.4	0.98
10	no BC	0.99	2.64	2.25	18.5	0.98
	LS	1.00	1.56	1.27	14.6	0.99
20	no BC	0.99	2.30	1.94	15.8	0.98
	LS	1.00	1.04	0.81	8.1	0.99
50	no BC	0.97	2.76	2.40	15.2	0.95
	LS	1.00	0.79	0.60	4.5	0.99
100	no BC	0.92	3.17	2.74	15.1	0.88
	LS	1.00	0.77	0.62	4.0	0.99

Table 3: Performance evaluation of the STM^2 model at Birecik station in 2008 using the linear scaling (LS) Bias Correction (BC) method.

Depth (cm)	Bias Correction (BC)	index of agreement – d (°C)	Root Mean Square Error (°C)	Mean Absolute Error (°C)	Mean Absolute Percentage Error (%)	R^2
5	no BC	0.98	3.58	3.06	19.3	0.97
	LS	0.99	2.41	1.96	17.9	0.97
10	no BC	0.98	3.24	2.65	17.9	0.98
	LS	0.99	1.73	1.39	11.6	0.98
20	no BC	0.98	2.63	2.25	24.7	0.99
	LS	1.00	1.08	0.78	6.6	0.99
50	no BC	0.95	3.49	3.05	20.7	0.94
	LS	1.00	0.98	0.75	5.2	0.99
100	no BC	0.89	3.99	3.35	15.9	0.84
	LS	1.00	0.76	0.59	3.4	0.99

3.2 Projections of future soil temperature

The projections of future changes in soil temperature (Ts) for the period 2030–2090 based on RCP4.5 and RCP8.5 scenarios for stations representing the W-SAP are shown in Figures 4–7. Under the RCP4.5 scenario, soil warming between 0.7 °C and 3.0 °C is projected in the geographical section, with Ts ranging between 0.8–3.0 °C and 0.7–2.6 °C in Siverek and Birecik, respectively. The projected increase in soil temperature in Birecik is about 3% higher than in Siverek. The projected average increase in soil temperature in the W-SAP corresponds to about 1.7 °C, with increases of 1.0 °C, 1.6 °C, and 2.1 °C in the short (2030), medium (2050), and long-term (2070 and 2090), respectively. When RCP8.5 simulation results are analyzed, the projected average increase in Ts in the W-SAP during the 2030–2090 period is 2.8 °C, with soil warming between 0.9 °C and 5.5 °C detected. In 2030, 2050, 2070, and 2090, the projected increases in Ts at 5–100 cm depth vary between 0.9–1.6 °C, 1.6–2.8 °C, 2.4–4.1 °C, and 3.2–5.5 °C. According to the model results, the projected average in the short-, medium-, and long-term Ts increases within the geographical area are 1.2 °C, 2.2 °C, and 3.9 °C, respectively.

In the future, soil temperature at a depth of 5 cm is predicted to be higher than air temperature (Ta) for both scenarios in Siverek, but this change is not observed at other depths. Moreover, the rate of increase in Ts decreases as the depth increases. Conversely, in Birecik, the future trend pattern of Ts is higher than Ta at all depths and under both scenarios, with this trend pattern being more pronounced in the RCP8.5 scenario. However, unlike Siverek, in Birecik, the projected trends of Ts and Ta in the shallow depth layer (5–20 cm) coincide, i.e., they exhibit similar behavior (Figures 2 and 3).

According to the RCP4.5 scenario, the future changes in Ts and Ta in the W-SAP exhibit stronger rates of increase in the medium term, while these increases relatively decrease in the long term. This change observed in Ts and Ta under the RCP4.5 scenario is not reflected in the results under the RCP8.5 scenario, and both Ts and Ta increases exhibit a more linear behavior in the RCP8.5 scenario. Moreover, according to the RCP8.5 scenario, the range of temperature change between depths in the geographical section shows an increasing trend (Figures 2 and 3).

In the RCP4.5 scenario, the simulations in the W-SAP region project an increasing trend in soil temperatures at all depths for this century. The strongest soil warming is expected for September and August at a depth of 50 cm and for October and September at 100 cm. According to the RCP4.5 scenario, a significant increase in the near-surface soil layer (Ts 5 cm) is expected at the Birecik station in September and November. At the Siverek station, the strongest rise in soil temperatures at a depth of 5 cm is projected in July and September of this century. This increase is expected to be more pronounced at higher extreme soil temperatures (≥30 °C and ≥35 °C) at 5 cm, especially from June to September. Slight differences can also be observed on a spatial and temporal level. According to the RCP4.5 scenario, the most significant

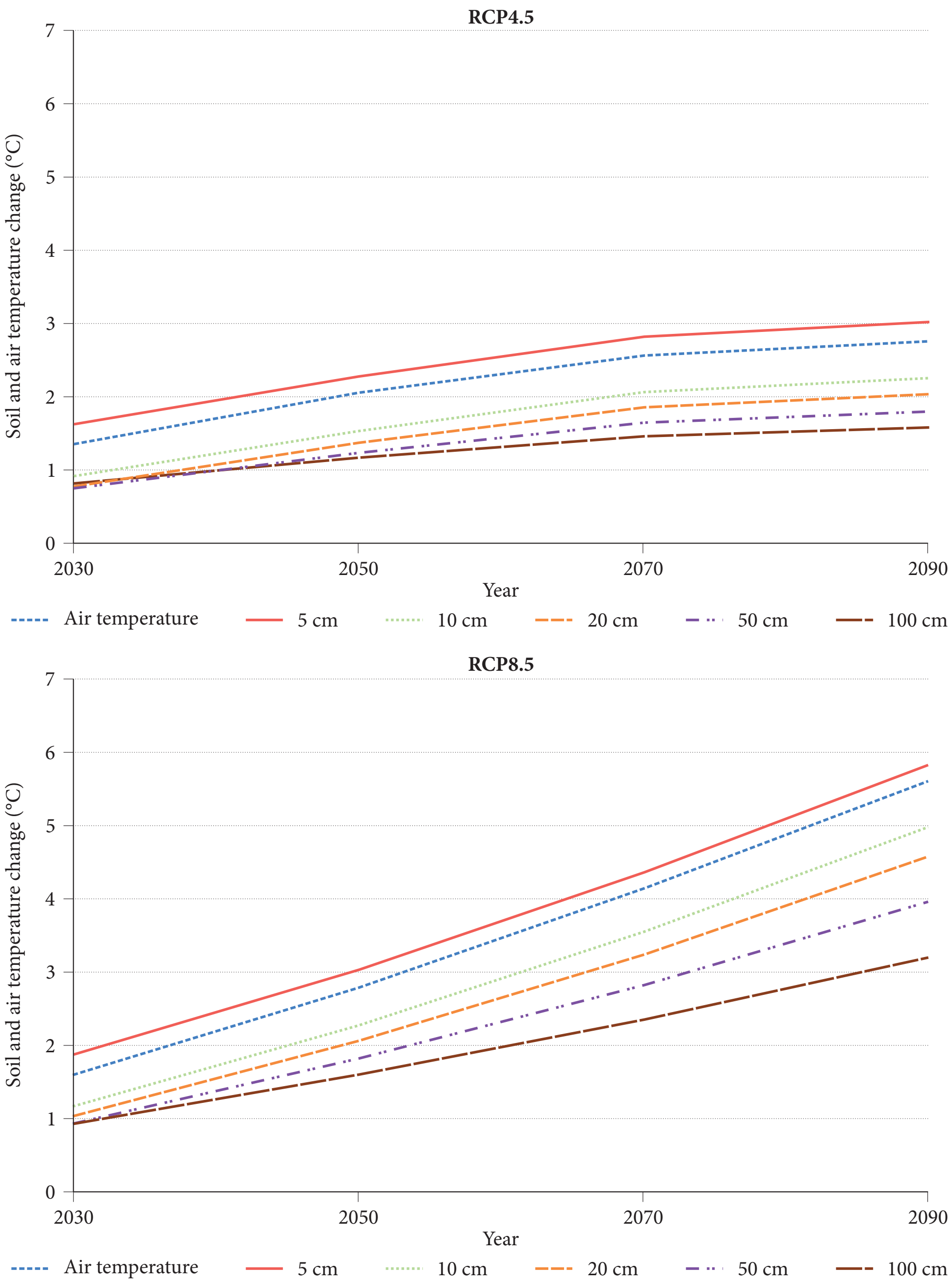

Figure 2: Change of future soil temperature and air temperature projections at Siverek station based on the 1981–2010 standard reference period.

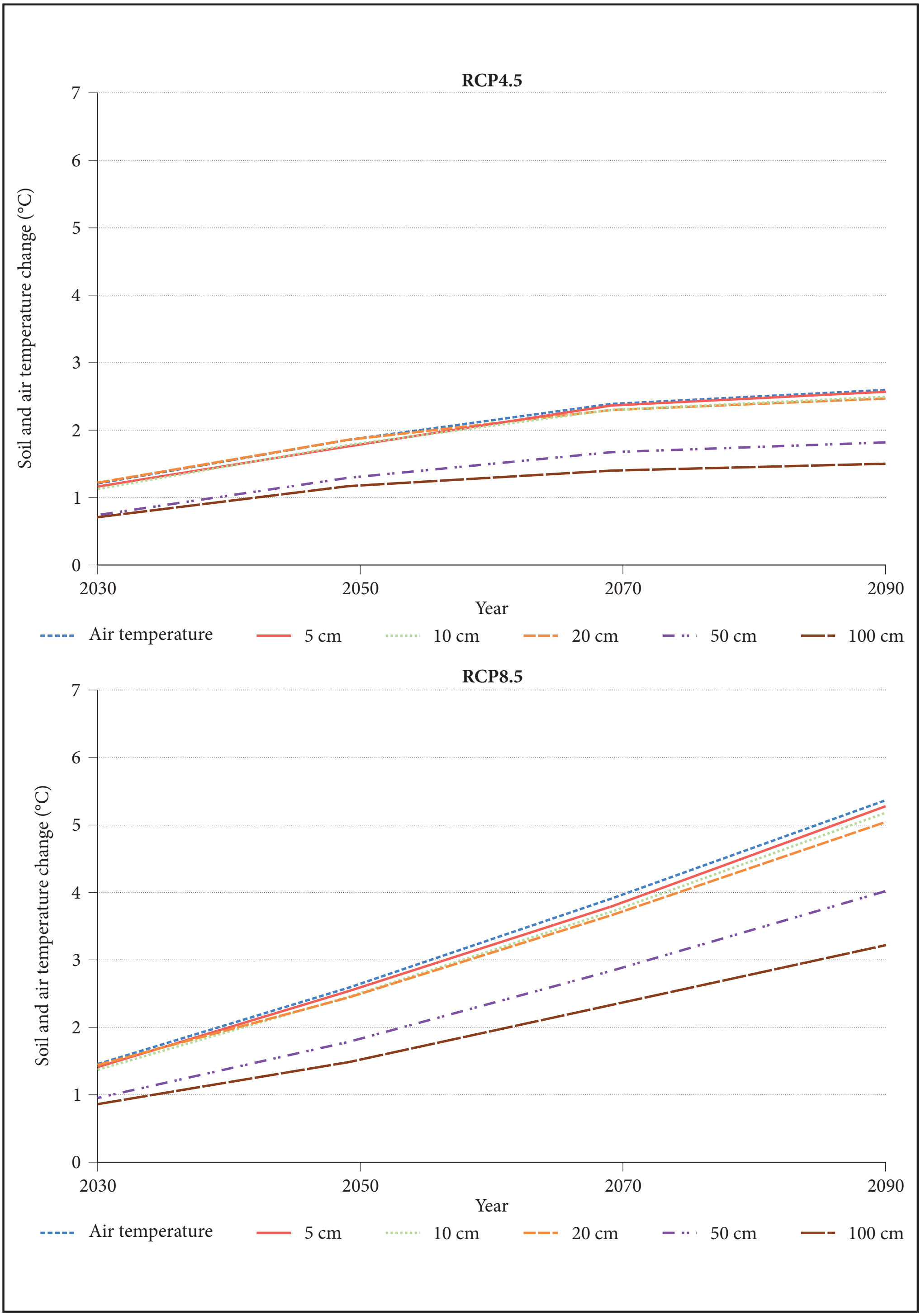

Figure 3: Change of future soil temperature and air temperature projections at Birecik station based on the 1981–2010 standard reference period.

change in soil temperatures at 5 cm depth is the projected increase in the frequency of temperatures above 30 °C in Birecik in the second half of this century. In particular, the frequency of days with soil temperatures of 30°C and above in May is expected to increase significantly in Birecik in the second half of the 21st century. These extreme temperature days will double by 2050 and even quadruple by 2090. In addition, according to the RCP8.5 scenario, a significant increase in extreme soil temperatures is expected in May in both Siverek and Birecik, which will be more pronounced in Birecik in the second half of this century and in Siverek towards the end of the century. At the Birecik station, the frequency of days with extreme soil temperature (≥30°C) in May will double compared to the historical period and will last for one to two weeks in the second half of this century.

4 Discussion

Many researchers have indicated that soil temperatures (Ts) in the 1-meter soil layer in different climate zones will continue to increase in the 21st century (Houle et al. 2012; Araghi et al. 2019; Górniak 2023; Tekkanat 2023). In our research, the western part of the Southeastern Anatolia Project (W-SAP) region, which has a semi-arid climate dominated by irrigation conditions, showed a similar trend. Although the predicted increases in Ts in some areas of the region are lower than air temperature (Ta) increases (Araghi et al. 2019; Tekkanat 2023), the increases in Ts at a depth of 5 cm in some areas, such as Siverek, are relatively higher than Ta. In this sense, the future soil-atmosphere interaction in Siverek is similar to the Edirne station located in the Meriç-Ergene River Basin (MERB), which is situated at the intersection of different climate zones and is characterized by a Mediterranean transitional climate (Tekkanat 2023).

The W-SAP is an area dominated by the Aridisols soil order, and it has been reported that soil temperatures in this region will never fall below 0°C by the end of the 21st century, as predicted for the global Aridisols order (Soong et al. 2022). According to their results, there is a significant difference between soil temperatures near the surface (5 cm) and in the deep soil layer (100 cm) in the W-SAP, despite the expected uniform warming of all soil patterns on a global scale. The difference between the soil temperatures at the surface and the temperature increase at 100 cm depth is significantly lower than the global estimates. In the region, according to the RCP4.5 scenario, the expected increase in soil temperature at a depth of 5 cm in the 21st century corresponds to the global average values and the projected temperature increase at a depth of 1 cm in the Aridisols. In contrast, soil warming at 100 cm depth is slightly below the global average but within the standard deviation range of projected temperature change. These results indicate that surface temperatures in the W-SAP are above the global average, while a smaller temperature increase is observed in deeper soil layers. Projections based on the RCP8.5 scenario show that the temperature increase in deep soil layers is within the standard deviation of the global averages or the projected increase in the Aridisols. These differences illustrate how local climate and soil conditions deviate from global trends and that regional climate change modeling requires a more sensitive analysis at the local level.

In the Northern Hemisphere, warming in the northern latitudes is considerably higher than in the southern latitudes, with warming in the Arctic being four times faster than in other parts of the world over the period 1971–2021 (43 years) (Rantanen et al. 2022). In this context, Post et al. (2019) have argued that the world has warmed by about 0.8 °C since the late 19th century, while warming in the Arctic has been 2.5 to 4 times this rate. This historical and current situation is also evident in other cross-regional correlations between future Ts and Ta simulations, including the results of the present study (Araghi et al. 2019; Soong et al. 2020; Sahoo 2022; Tekkanat 2023). The projected increases in Ts and Ta in the short, medium, and long term in the W-SAP, dominated by a semi-arid climate, are lower than in northern latitudes and higher than in southern latitudes. The increases in Ts and Ta determined in the research are lower than the outer limit of the subtropical belt, i.e. lower than in the areas with a continental climate in northern latitudes (Jungqvist et al. 2014; Górniak 2023). The fact that the projected increases in Ts and Ta in W-SAP are larger than in MERB, which has a semi-humid climate in northwestern Türkiye, and in northeastern Iran, which has an arid and semi-arid climate under the RCP4.5 scenario (Araghi et al. 2019; Tekkanat 2023), supports the above conclusion.

The variability of projected Ts increases in the W-SAP follows a pattern higher than in northeastern Iran but lower than in the MERB of Türkiye (Araghi et al. 2019; Tekkanat 2023). The increased soil moisture due to irrigation may have a significant impact on the lower Ts variability in the study area compared to the more humid MERB. This is because 19 of the 29 irrigation unions established in the last 30 years under the Southeastern Anatolia Regional Development Plan are located within the W-SAP region. This development is further supported by the opening of 130 thousand hectares of land for irrigation in the Şanlıurfa-Harran Plains as of 2001 (Republic of Türkiye … 2002). GCMs predict that precipitation will increase in the Eastern Anatolia Region in the future. Therefore, the water level of the dams built on the Euphrates and Tigris Rivers is expected to rise. Essentially, these conditions mean that the increase in irrigation unions and the opening of land for irrigation will be encouraged. In conclusion, the combined results of Ts, Ta, and precipitation projections, along with land use/land cover changes in the W-SAP, indicate that Ts variability will decrease further compared to regions with more humid climates. This suggests a shift in the agroclimatology of the region and positive developments in agricultural activities.

It is expected that between 1981 and 2120 the mesic and thermal zones between 45°N–60°N and 45°S–60°S will expand due to global warming. This expansion may lead to a shift in agricultural areas from mesic to thermic and from thermic to hyperthermic areas (Grillakis et al. 2016). In particular, the expansion of the thermal regime zones can also be observed at lower latitudes. In the last ten years, significant changes in soil temperature regimes have been observed in Türkiye due to rising air temperatures. In addition, thermic and hyperthermic zones are expanding significantly and shifting northwards compared to other regimes (Tekkanat and Öztürk 2022a). According to the RCP4.5 and RCP8.5 scenarios, similar changes are expected in the W-SAP in the short, medium, and long term.

The margin of error for the Ts estimated in W-SAP for the 20–100 cm soil layer is smaller and more reliable than at the 5 and 10 cm depths. When considering the average Ts at the 1-meter soil layer, the performance of STM^2 remains within acceptable limits. This result is consistent with the work of Araghi et al. (2019) and Tekkanat (2023), who found that the linear scaling method is the most accurate for correcting biases in Ts model outputs. However, the accuracy of predicted Ts in W-SAP is somewhat lower than in MERB and its immediate vicinity, but better than in the northeast of Iran. Thus, the consistency of STM^2 tends to decrease as continentality increases and the climate becomes drier.

According to the models, the surface air temperature is expected to change by 1.5–4.5 °C by the end of this century compared to the pre-industrial period, with a high probability of global warming of more than 2 °C (Mozaffari 2022). Although we do not have Ts data for the pre-industrial period in the W-SAP, the general warming trend and soil temperature increases over the 1981–2010 standard climate period indicate a similar warming trend in the shallow soil layer. Projections suggest that the 2 °C threshold at a 5 cm depth will be exceeded in the second half of the 21st century according to the RCP4.5 scenario. This finding suggests a regional warming trend, which has previously been observed in MERB and its immediate vicinity (Tekkanat 2023).

The increase in soil temperatures observed in recent years is due to the rise in temperature, especially in summer (Yeşilırmak 2014; Tekkanat 2023). It is expected that this trend will largely continue in the W-SAP in the future. However, in Birecik, a stronger increase in soil temperatures at 5 cm and 10 cm depth was observed in fall compared to summer. In Siverek, soil temperatures are expected to increase significantly in the fall compared to the summer. Although this changes the general trends somewhat, similar changes are predicted for the W-SAP. A higher increase in soil temperatures is expected for the fall compared to the summer, especially at a depth of 5 cm.

In Türkiye, air temperature has the strongest correlation with soil temperature when compared to other factors (Tonkaz et al. 2007; İçel and Ataol 2013; Yeşilırmak 2014). However, a weak relationship between air temperature and soil temperature at 50 cm depth is observed in the southwestern part of Türkiye and the Şanlıurfa/Birecik region. In the Southeast Anatolia region, the relationship pattern between soil and air temperature is more variable than in the other areas where strong and weak relationships are observed (Tekkanat 2023). This relationship pattern shows high variability in the W-SAP compared to the other areas, as not only air temperature but also vegetation cover and soil moisture have a combined effect on soil temperature changes. Therefore, it can be said that factors such as the construction of irrigation canals and dams as part of the Southeast Anatolia Project and the rise in air temperature will play an important role in future changes in soil temperature in the W-SAP. In addition, the expansion of irrigable land towards steppe areas will also have an impact on soil temperature.

According to the model results, there is no risk of a frost event in the winter months in both the short and medium term, and in the long term, primarily due to soil and air warming. However, according to the RCP4.5 scenario, soil temperatures of 30 °C and above start to be more effective in Siverek starting from June at a depth of 5 cm. These extreme temperatures are predicted to be effective in Birecik in May in the short term and in June in the medium and long term. In the RCP8.5 scenario, these extreme temperatures shift two months earlier in the 21st century and become effective from April. In both scenarios, the time difference decreases in the months in which the soil temperatures reach 35 °C or more. In addition, the occurrence of extreme soil temperatures increases between June and September. These results indicate that the Southeastern Anatolia Region (Tekkanat and Öztürk 2022b), which shows moderate to very high vulnerability to soil temperatures of 35 °C and above at a depth of 5 cm, will reach very high vulnerability in the second half of the 21st century.

The predicted soil and air temperatures contain important phenological information and indicate that a change in the agricultural cropping pattern of the W-SAP will occur. The trend of increasing Ts and Ta widens the sowing window for wheat and favors rapid root development and deep root crowns. Under the RCP4.5 scenario, the earliest planting date for cotton corresponds to the first half of April, shifting about one month earlier than the optimal conditions. However, under the RCP8.5 scenario, the earliest cotton planting in Siverek in the long term (2070 and 2090) shifts about 1.5 months earlier than the optimal date range. For maize, which is sown after the wheat harvest, optimum germination conditions occur halfway through the year at a depth of 5 cm, and increased Ts are projected to support rapid emergence. On the other hand, extreme soil temperatures (≥35 °C) at a depth of 5 cm between the last week of June and the third week of September may threaten crop development. However, the combination of increasing wetlands (natural and artificial lakes) and expanding irrigation activities with the SAP also suggests that the climate will soften in the region. Therefore, it is unlikely that this risk of extreme soil temperatures will negatively affect agricultural development in the future.

5 Conclusion

This study analyzes the projections of future soil temperatures in the western part of the Southeastern Anatolia Project (W-SAP) region under two scenarios: RCP4.5 and RCP8.5. The analysis covers short-term (2030), medium-term (2050), and long-term (2070 and 2090) forecasts. According to the ensemble models based on these scenarios, both Siverek and Birecik exhibit a notable warming trend in the 1-meter soil layer, consistent with global warming. On average, the projected increase in soil temperature for the 21st century is about 1.7 °C for the RCP4.5 scenario and around 2.8 °C for the RCP8.5 scenario. The projected rise in soil temperature (Ts) varies from 0.7 °C to 3.0 °C under RCP4.5 and from 0.9 °C to 5.5 °C under RCP8.5. Consequently, most models indicate that the goal of limiting global warming to below 2 °C will be surpassed in the shallow soil layer by both the medium and long-term forecasts.

These findings can serve as a basis for strategies to adapt to future climate change, particularly for agricultural planning, water resource management, and ecosystem health. A phenological calendar based on soil temperature and moisture could help determine minimum germination temperatures, optimal sowing times, ideal growing seasons, and appropriate crop rotation systems. It could also help create agricultural maps to mitigate the effects of climate change. To improve planning efforts, trend analysis methods such as the Mann-Kendall trend test and Sen's innovative trend test could be used alongside agro-climatological analyses. Extending the methodology to additional meteorological stations in larger river basins would allow the identification of microclimates and provide more accurate data for land use and agricultural crop planning. This approach has great potential for future research and could contribute significantly to developing spatial strategic information for agricultural planning.

ACKNOWLEDGEMENT: The author would like to thank the anonymous reviewers and the editorial board for their constructive feedback, which significantly improved the quality of this article.

RESEARCH DATA: For information on the availability of research data related to the study, please visit the article webpage: https://doi.org/10.3986/AGS.13831.

6 References

Abbe, C. 1905: A first report on the relations between climate and crops. US Government Printing Office.

Araghi, A., Adamowski, J., Martinez, C. J., Olesen, J. E. 2019: Projections of future soil temperature in northeast Iran. *Geoderma* 349. https://doi.org/10.1016/j.geoderma.2019.04.034

Araghi, A., Mousavi-Baygi, M., Adamowski, J. 2017: Detecting soil temperature trends in northeast Iran from 1993 to 2016. *Soil and Tillage Research* 174. https://doi.org/10.1016/j.still.2017.07.010

Bouyoucos, G. J. 1916: Soil temperature. Agricultural Experiment Station. *Technical Bulletin*. Michigan State University.

Bradford, J. B., Schlaepfer, D. R., Lauenroth, W. K., Palmquist, K. A., Chambers, J. C., Maestas, J. D., Campbell, S. B. 2019: Climate-driven shifts in soil temperature and moisture regimes suggest opportunities to enhance assessments of dryland resilience and resistance. *Frontiers in Ecology and Evolution* 7-358. https://doi.org/10.3389/fevo.2019.00358

Chang, J. H. 1957: World patterns of monthly soil temperature distribution. *Annals of the Association of American Geographers* 47-3. https://doi.org/10.1111/j.1467-8306.1957.tb01538.x

Górniak, A. 2023: Recent and future soil temperature regime in the coldest part of Poland. *Journal of Agrometeorology* 25-1. https://doi.org/10.54386/jam.v25i1.1867

Grillakis, M. G., Koutroulis, A. G., Papadimitriou, L. V., Daliakopoulos, I. N., Tsanis, I. K. 2016: Climate-induced shifts in global soil temperature regimes. *Soil Science* 181-6. https://doi.org/10.1097/SS.0000000000000156

Houle, D., Bouffard, A., Duchesne, L., Logan, T., Harvey, R. 2012: Projections of future soil temperature and water content for three southern Quebec Forested Sites. *Journal of Climate* 25-21. https://doi.org/10.1175/JCLI-D-11-00440.1

İçel, G., Ataol, M. 2013: Türkiye'nin yıllık ortalama hava ve 50 cm toprak sıcaklıklarında eğilimler ve hava 50 cm toprak sıcaklıkları arasındaki ilişkiler (1975–2005). In: 6th Atmospheric Science Symposium, Proceedings. İstanbul Technical University.

Jones, P. G., Thornton, P. K. 2013: Generating downscaled weather data from a suite of climate models for agricultural modelling applications. *Agricultural Systems* 114. https://doi.org/10.1016/j.agsy.2012.08.002

Jungqvist, G., Oni, S. K., Teutschbein, C., Futter, M. N. 2014: Effect of climate change on soil temperature in Swedish boreal forests. *PloS one* 9-4. https://doi.org/10.1371/journal.pone.0093957

Kadioğlu, M. 2000: Regional variability of seasonal precipitation over Turkey. *International Journal of Climatology* 20-14. https://doi.org/10.1002/1097-0088(20001130)20:14%3C1743::aid-joc584%3E3.0.co;2-g

Koç, T. 2013: Türkiye'nin morfometrik özellikleri. In: Profesör Doktor İlhan Kayan'a Armağan Kitabı. Ege University.

Lenderink, G., Buishand, A., Van Deursen, W. 2007: Estimates of future discharges of the river Rhine using two scenario methodologies: Direct versus delta approach. *Hydrology and Earth System Sciences* 11-3. https://doi.org/10.5194/hess-11-1145-2007

Masin, R., Loddo, D., Benvenuti, S., Otto, S., Zanin, G. 2012: Modeling weed emergence in Italian maize fields. *Weed Science* 60-2. https://doi.org/10.1614/WS-D-11-00124.1

Mozaffari G. A. 2022: Climate change and its consequences in agriculture. In: The Nature, Causes, Effects and Mitigation of Climate Change on the Environment. IntechOpen. https://doi.org/10.5772/intechopen.101444

Oni, S. K., Mieres, F., Futter, M. N., Laudon, H. 2017: Soil temperature responses to climate change along a gradient of upland–riparian transect in boreal forest. *Climatic Change* 143. https://doi.org/10.1007/s10584-017-1977-1

Perreault, S., Chokmani, K., Nolin, M. C., Bourgeois, G. 2013: Validation of a soil temperature and moisture model in southern Quebec, Canada. *Soil Science Society of America Journal* 77-2. https://doi.org/10.2136/sssaj2012.0311

Post, E., Alley, R. B., Christensen, T. R., Macias-Fauria, M., Forbes, B. C., Gooseff, M. N., Wang, M. et al. 2019: The polar regions in a 2°C warmer world. *Science Advances* 5-12. https://doi.org/10.1126/sciadv.aaw9883

Pribyl, D. W. 2010: A critical review of the conventional SOC to SOM conversion factor. *Geoderma* 156-3,4. https://doi.org/10.1016/j.geoderma.2010.02.003

Qian, B., Gregorich, E. G., Gameda, S., Hopkins, D. W., Wang, X. L. 2011: Observed soil temperature trends associated with climate change in Canada. *Journal of Geophysical Research: Atmospheres* 116. https://doi.org/10.1029/2010JD015012

Rambaut, A. A. 1901: Underground temperature at Oxford in the Year 1899, as determined by five platinum-resistance thermometers. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* 195. https://doi.org/10.1098/rsta.1900.0027

Rantanen, M., Karpechko, Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., Laaksonen, A. 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment* 3-1. https://doi.org/10.1038/s43247-022-00498-3

Republic of Türkiye Southeastern Anatolia Project Regional Development Administration 2002: Southeastern Anatolia Project Regional Development Plan SAP Executive Summary. *Report*. Southeastern Anatolia Project Regional Development Administration.

Richardson, C. W. 1981: Stochastic simulation of daily precipitation, temperature, and solar radiation. *Water Resources Research* 17-1. https://doi.org/10.1029/WR017i001p00182

Sahoo, M. 2022: Winter soil temperature and its effect on soil nitrate Status: A Support Vector Regression-based approach on the projected impacts. *Catena* 211. https://doi.org/10.1016/j.catena.2021.105958

Sariş, F., Hannah, D. M., Eastwood, W. J. 2010: Spatial variability of precipitation regimes over Turkey. *Hydrological Sciences Journal* 55-2. https://doi.org/10.1080/02626660903546142

Shrestha, S., Shrestha, M., Babel, M. S. 2016: Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. *Environmental Earth Sciences* 75-4. https://doi.org/10.1007/s12665-015-5150-8

Soong, J. L., Phillips, C. L., Ledna, C., Koven, C. D., Torn, M. S. 2020: CMIP5 models predict rapid and deep soil warming over the 21st century. *Journal of Geophysical Research: Biogeosciences* 125-2. https://doi.org/10.1029/2019JG005266

Spokas, K., Forcella, F. 2009: Software tools for weed seed germination modeling. *Weed Science* 57-2. https://doi.org/10.1614/WS-08-142.1

Sviličić, P., Vučetić, V., Filić, S., Smolić, A. 2016: Soil temperature regime and vulnerability due to extreme soil temperatures in Croatia. *Theoretical and Applied Climatology* 126-1,2. https://doi.org/10.1007/s00704-015-1558-z

Tekkanat, İ. S. 2023: Türkiye'de toprak sıcaklıklarının değişimi. *Ph.D. thesis.* Çanakkale Onsekiz Mart University.

Tekkanat, İ. S., Öztürk, B. 2022a: The character of soil temperature regime over Turkey. *International Journal of Environment and Geoinformatics* 9-2. https://doi.org/10.30897/ijegeo.985732

Tekkanat, İ. S., Öztürk, B. 2022b: Spatial changes in soil vulnerability to extreme temperatures in Türkiye. In: TÜCAUM 2022 International Geography Symposium Proceedings Book. Ankara University Research Center of Turkish Geography.

Teutschbein, C., Seibert, J. 2012: Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology* 456. https://doi.org/10.1016/j.jhydrol.2012.05.052

Tonkaz, T., Doğan, E., Aydemir, S. 2007: GAP Bölgesi toprak sıcaklıklarının alansal değişimleri ve hava sıcaklığı ile ilişkileri. *Harran Üniversitesi Ziraat Fakültesi Dergisi* 11-1,2.

Yeşilırmak, E. 2014. Soil temperature trends in Büyük Menderes Basin, Turkey. *Meteorological Applications* 21-4. https://doi.org/10.1002/met.1421