Italian Journal of Agrometeorology
Rivista Italiana di Agrometeorologia

Firenze University Press
https://riviste.fupress.net/index.php/IJAm

Citation: Deveci, H., Önler, B., & Erdem, T. (2025). Estimation of irrigation water requirements of sunflower under the context of climate change in TR21 Thrace Region. *Italian Journal of Agrometeorology* (2): 39-52. doi: 10.36253/ijam-2920

Received: August 24, 2024

Accepted: September 12, 2025

Published: December 31, 2025

Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Competing Interests: The Author(s) declare(s) no conflict of interest.

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Estimation of irrigation water requirements of sunflower under the context of climate change in TR21 Thrace Region

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Abstract. In order to use water resources efficiently and sustainably, it is very important to determine the impact of climate change on water resources accurately. For this purpose, reference evapotranspiration (ET_0), crop evapotranspiration (ET_c), irrigation water requirement (IWR) was determined with CROPWAT 8.0 using climate data obtained from HadGEM2-ES and MPI-ESM-MR model reference period (1971-2000) and future short (2031-2040) and long (2051-2060) periods RCP4.5 and RCP8.5 scenario outputs for sunflower in TR21 Thrace Region. Afterwards, the results obtained for the reference period and future periods are compared and evaluated. As a result, it is estimated that ET_0 values will increase by 6.3%-13.2% and 4.9%-26.9% in the upcoming short (2031-2040) and long (2051-2060) periods, respectively, compared to the reference period (1971-2000), and by 6.0%-13.0% and 3.4%-17.9% in the sunflower development period. ET_c is predicted to increase by 3.5%-12.0% in the short term and 2.4%-16.9% in the long term, compared to the reference period, and IWR values are predicted to vary between 0.3%-19.9% in the short term and -7.0%-20.8% in the long term. In the TR21 Thrace Region, it is estimated that the annual average ET_0, ET_0 during the sunflower development period, and sunflower water consumption will be negatively affected by climate change in the future periods (2031-2040, 2051-2060) and will increase compared to the reference period. It is anticipated that there will be increases and decreases in irrigation water demand; however, the general trend is towards an increase, and it has been determined that these increases will be greater than the decreases. This study will guide producers, managers, and decision makers in carrying out adaptation activities against the impact of climate change on water resources.

Keywords: CROPWAT 8.0, Crop water requirement, Reference evapotranspiration, Irrigation water requirement, *Helianthus annuus* L., Penman-Monteith.

1. INTRODUCTION

The impact of climate change on water resources is primarily due to changes in climate parameters, specifically changes in precipitation regimes and temperatures. Changes in temperatures affect crop evapotranspiration

(ET_c) rate, cloud characteristics, soil moisture, storm intensity, and snowfall and melting regimes. These changes occurring due to climate change can have very important consequences for the water cycle and water resources (RTMAFGDWM, 2020).

According to projections from various climate models based on different greenhouse gas emission scenarios, significant decreases in precipitation, water resources, and flows are expected over the next century, particularly for North Africa, the Mediterranean Basin, Türkiye, and the Middle East. There may be significant increases in surface air temperatures and evapotranspiration as well as extreme weather and climate events (Türkeş et al., 2013). Climate change reduces the availability and accessibility of water resources, increasing vulnerability and causing negative impacts on water-dependent sectors. Since Türkiye is in a semi-arid climate zone, it is of great importance to improve water quality, increase the amount of usable water, and ensure the sustainability of conservation and utilization balance (RTMEUCC, 2024).

Evaporation is an important component of the hydrological cycle, and knowing the water losses caused by evaporation within the scope of the hydrological cycle is an important issue in terms of water management and planning (Azlak, 2015). Evapotranspiration (ET) or ET_c, one of the most important parameters of the hydrological cycle, is used extensively in the project design of irrigation systems, preparation of irrigation programs, and hydrological studies. Therefore, accurate estimation of ET_c is important for water balance, environmental protection, design of irrigation systems, and water resources management. Insufficient and excessive irrigation in crop production negatively affects the soil, product, agricultural production input, and yield. In order to obtain quality and high-yield products, the most appropriate irrigation program must be created by taking into account plant water consumption (Bircan and Kızıl, 2021). Especially in Türkiye, which has an economy based on agriculture and where 70-75% of the water demand is generated by the agricultural sector, the management and planning of water is very important (Azlak, 2015).

Sunflower is one of the important agricultural products grown in Türkiye. Sunflower oil is the most common oilseed plant in Türkiye, as its share holds around 80-85% in vegetable oil consumption and 40% of its oil content. It should be increased to reduce the vegetable oil deficit. In Türkiye, sunflower oil is mainly produced in the Thrace Region and Konya. According to TURKSTAT (Turkish Statistical Institute) data, Tekirdağ (20.5%), Edirne (13.2%), Kırklareli (11.2%), Konya (10.5%), and Adana (8%) account for 63.5% of the oil sunflower cultivation area as of the 2021/2022 season. In terms of production, Tekirdağ ranks first with 18%, Konya 14.7%, Edirne 12.9%, Kırklareli 10.2%, and Adana 9.1% (Bozer, 2023). Therefore, the TR21 Thrace Region is a very potential region in terms of sunflower cultivation.

Some studies are using various models and Representative Concentration Pathways (RCP) scenarios for climate change predictions in Türkiye. These studies were conducted using HadGEM2-ES and MPI-ESM-MR models and RCP4.5 and RCP8.5 scenarios. These models were run using the RegCM4.3 Regional Climate Model, and outputs were produced with the RCP4.5 and RCP8.5 scenarios at ten-kilometer resolution (Akçakaya et al., 2013; Akçakaya et al., 2015; GDWM, 2016). Many studies have been conducted using these outputs. One of these is the "Impacts of Climate Change and Adaptation Strategies in TR21 Thrace Region" project carried out in the TR21 Thrace Region (Anonymous, 2019). With these outputs, climate predictions specific to the TR21 Thrace Region were made in ten-year periods, and evaluations were made for the region. At the same time, Deveci (2025) determined a great agreement between the monthly average temperature values obtained from the HadGEM2-ES, MPI-ESM-MR models, RCP4.5 and RCP8.5 scenario results, and the observed meteorological data, especially for the temperature data in the TR21 Thrace Region in the period 1915-2024. Therefore, these models and scenarios were preferred because they demonstrated consistency in the region and could be evaluated together with the studies conducted.

Several studies have been conducted around the world to determine the impact of climate change on reference evapotranspiration (ET_0) (Chaouche et al., 2010; Irmak et al., 2012; Fan et al., 2016; Dinpashoh et al., 2019; Ma et al., 2019; Sun et al., 2020; Li et al., 2022; Reta et al., 2024; Youssef et al., 2024). In Türkiye, reassessment of existing irrigation projects with FAO (Food and Agriculture Organization of the United Nations) criteria (Koç and Güner, 2005), the effect of climate change on seasonal plant water consumption (Bayramoğlu E., 2013), the effect of climate change on evaporation (Azlak, 2015), establishing an irrigation water program for eggplant (Kartal et al., 2019), determining the spatial variation of ET_0 (Yıldırım et al., 2019), development of an android-based application to be used in ET_0 calculation (Bircan and Kızıl, 2021), assessment of crop water requirements by using CROPWAT for sustainable water resources management in agriculture (Aydın-Kandemir and Yıldız, 2022), determining the impact of climate change on maize irrigation water requirements (Şen, 2023; Yetik and Şen, 2023) have been studied. In addition, studies have been carried out on determining the impact of climate change on ET_0 in the Thrace Region (Deveci, 2015; Yıldırım, 2023; Yıldırım and Erdem, 2023; Deveci and Konukcu, 2024). These studies although the modeled region is the same, the reference period climate data, climate models' prediction scenarios, and predicted futures are different, and thus, different calculation methods were used. In addition to the previous studies conducted in the Thrace Region, these studies have diversified by predicting ET_0 in the future years with different climate models. In addition, the most important point that distinguishes this study from other studies is that, for the first time, the irrigation requirements of sunflower have been estimated for the future periods.

This study aims to estimate the change of ET_0, ET_c, and IWR in the future short (2031-2040) and long (2051-2060) periods compared to the reference period (1971-2000) by using HadGEM2-ES and MPI-ESM-MR model RCP4.5 and RCP8.5 scenario outputs for sunflower with CROPWAT 8.0 in TR21 Thrace Region. With the results obtained, the effect of climate change on irrigation water requirements in sunflower cultivation can be evaluated. Therefore, this study will guide producers, managers, and decision makers to carry out adaptation activities against the effects of climate change on water resources.

2. MATERIAL AND METHODS

2.1. Material

2.1.1. Study area

The research area is located in Türkiye. TR21 Thrace Region covers the provinces of Tekirdağ (TR211), Edirne (TR212), and Kırklareli (TR213). The surface area of the region (excluding lakes) is 18.665 km^2. Agricultural activities are intensively carried out in the region, and the proportion of land suitable for agriculture is quite high (TDA, 2010). The study area is shown in Figure 1.

2.1.2. Climate of the research area

A continental climate prevails in the inner part of the TR21 Thrace Region. The Marmara Sea coastline is under the influence of the Black Sea-Mediterranean climate. Winters are cool and rainy; summers are dry and hot. Long-term climate data of the research area are shown in Table 1. Accordingly, the province with the highest (19.8°C) and lowest (8.5°C) average temperature is Edirne. The highest total annual rainfall (601 mm) is also seen in Edirne.

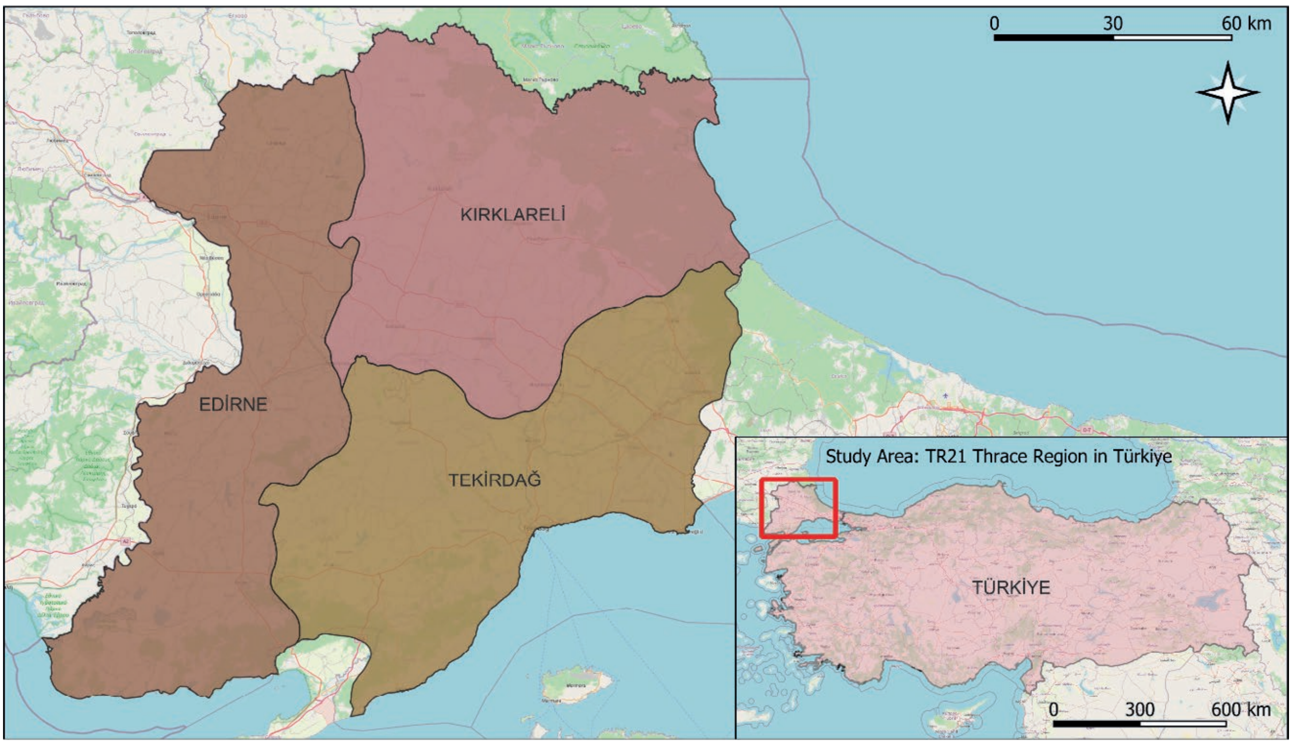

Figure 1. Geographical location of the study area (TR21 Thrace Region).

Table 1. Long-term monthly averages climate data (Edirne (1930–2023), Kırklareli (1959-2023), Tekirdağ (1940-2023)) (TSMS, 2024a; TSMS, 2024b; TSMS, 2024c).

Climate Parameters	Location	January	February	March	April	May	June	July	August	September	October	November	December	Avg./Tot.
Avg. Mean Temperature (°C)	Edirne	2.7	4.4	7.6	12.8	18.0	22.2	24.7	24.5	20.1	14.5	9.2	4.6	13.8
	Kırklareli	2.9	4.1	6.9	12.0	17.1	21.4	23.8	23.6	19.4	14.1	9.3	5.1	13.3
	Tekirdağ	4.9	5.5	7.3	11.7	16.7	21.1	23.7	23.9	20.3	15.7	11.3	7.3	14.1
Avg. Max. Temperature (°C)	Edirne	6.7	9.4	13.4	19.3	24.8	29.2	32.0	32.0	27.4	20.8	14.2	8.6	19.8
	Kırklareli	6.9	8.6	12.2	17.9	23.5	28.0	30.7	30.7	26.2	20.0	13.9	8.8	19.0
	Tekirdağ	8.1	9.0	11.0	15.7	20.6	25.3	28.1	28.3	24.5	19.5	14.8	10.5	18.0
Avg. Min. Temperature (°C)	Edirne	-0.5	0.5	2.9	7.1	11.7	15.5	17.4	17.3	13.5	9.3	5.3	1.4	8.5
	Kırklareli	0.1	1.0	3.0	7.1	11.6	15.6	17.8	17.8	14.1	9.8	5.9	2.3	8.8
	Tekirdağ	2.0	2.5	4.1	8.1	12.7	16.7	19.1	19.4	16.2	12.1	8.2	4.4	10.5
Avg. Daily Sunshine (hour)	Edirne	2.4	3.6	4.5	6.2	8.0	9.2	10.3	9.8	7.5	5.2	3.2	2.2	6.0
	Kırklareli	2.0	2.5	3.6	4.7	6.3	6.8	7.5	7.5	5.5	3.8	2.7	1.8	4.6
	Tekirdağ	2.8	3.4	4.2	6.0	7.4	8.5	9.4	8.4	6.8	4.9	3.2	2.5	5.6
Precipitation (mm)	Edirne	65.0	52.2	50.1	48.7	52.4	47.1	31.7	23.3	35.9	56.7	67.3	70.6	601.0
	Kırklareli	65.0	51.3	48.7	45.4	49.3	52.6	27.8	21.5	32.8	51.5	66.7	71.1	583.7
	Tekirdağ	68.0	54.5	53.4	42.1	37.2	38.3	23.8	15.5	32.7	60.2	74.3	80.0	580.0

TSMS: Turkish State Meteorological Service.

2.1.3. Climate data

The climate data used in the study include the climate data produced within the scope of the “Impact of Climate Change on Water Resources Project” carried out by the General Directorate of Water Management of the Ministry of Forestry and Water Affairs of the Republic of Türkiye and obtained to be used in the “Climate Change Impacts and Adaptation Strategies in the TR21 Thrace Region” project (GDWM, 2016; Anonymous, 2019). Within the scope of the “Impact of Climate Change on Water Resources Project”, the RegCM4.3 regional climate model was run simultaneously for Türkiye using the outputs of three global models (HadGEM2-ES, MPI-ESM-MR, CNRM-CM5.1) selected from the CMIP5 (Coupled Model Intercomparison Project Phase 5) archive. Since the resolutions of the climate and earth system models reach hundreds of kilometers and there are uncertainties in these model outputs, dynamic downscaling was performed with the RegCM4.3 Regional Climate Model within the scope of the project. The data used in this study are the outputs of the HadGEM2-ES and MPI-ESM-MR models and the RCP4.5 and RCP8.5 scenarios. The period covers the reference period (1971-2000), short (2031-2040), and long (2051-2060) period data.

2.1.4. Plant data

The crop parameters of sunflower were defined in detail for each growth stage to ensure accurate estimation of irrigation water requirements within the CROPWAT 8.0 model. These include growth period durations, crop coefficients (K_c), rooting depth, critical depletion fraction, and yield response factor (k_y). The values were obtained from national agricultural guidelines and FAO sources and applied at the provincial level, allowing for the modeling of regional variability. The crop characteristics of sunflower are presented in Table 2.

2.1.5. Soil data

In the study, a single soil type defined as “medium texture” in the CROPWAT 8.0 database was used to represent average field conditions across the TR21 Region. The selected soil profile reflects loamy soil properties, with moderate water holding capacity and infiltration characteristics, as shown in Table 3.

2.1.6. CROPWAT 8.0 model

CROPWAT 8.0 is developed by the Land and Water Development Division of FAO. It can be downloaded and used free of charge (FAO, 2024b). CROPWAT helps

Table 2. The crop characteristics of sunflower for Edirne, Kırklareli, and Tekirdağ.

Crop Parameters		Edirne	Kırklareli	Tekirdağ	Reference
Crop Development Period (days)	Initial	25	25	25	(RTMAFGDARP, 2017)
	Development	30	30	30	(RTMAFGDARP, 2017)
	Mid-Season	60	60	60	(RTMAFGDARP, 2017)
	Late-Season	30	30	30	(RTMAFGDARP, 2017)
Crop Coefficient (K_c)	Initial	0.38	0.36	0.40	(RTMAFGDARP, 2017)
	Mid-Season	1.14	1.12	1.11	(RTMAFGDARP, 2017)
	Late-Season	0.34	0.32	1.31	(RTMAFGDARP, 2017)
Rooting Depth (m)	Initial	0.30	0.30	0.30	(FAO, 2024a)
	Late-Season	0.90	0.90	0.90	(Erdem, 2001)
Sowing Date		15 April	15 April	15 April	(RTMAFGDARP, 2017)
Vegetation Duration (days)		145	145	145	(RTMAFGDARP, 2017)
Critical Depletion (Fraction)		0.5	0.5	0.5	(Steduto et al., 2012)
Yield Response Factor (k_y)		1.0	1.0	1.0	(Steduto et al., 2012)

RTMAFGDARP: Republic of Türkiye Ministry of Environment, Urbanization and Climate Change.

Table 3. Soil properties.

Soil Parameters	Values
Total available soil moisture (mm/m)	140.0
Maximum rain infiltration rate (mm/day)	40.0
Maximum rooting depth (cm)	900
Initial soil moisture depletion (%)	0

to calculate ET_0, ET_c, IWR, and scheme water demand. It develops irrigation schedules under various management conditions. Furthermore, it estimates rainfed production and drought effects. The program calculates ET_0 using the FAO Penman-Monteith method (Allen et al., 1998).

CROPWAT 8.0 program works using the following climate, plant, and soil parameters:

- Climate parameters (minimum temperature (°C), maximum temperature (°C), humidity (%), rainfall (mm), wind speed (m/sec), sunshine hours (hours),
- Crop parameters (planting date (days), crop development period (days), crop coefficient (K_c), rooting depth (m), critical depletion, yield response factor (k_y),
- Soil parameters (total available soil moisture (mm/m), maximum rain infiltration rate (mm/day), maximum rooting depth (cm), initial soil moisture depletion (%).

2.2. Method

In this study, monthly climate data for the reference period (1971-2000) and two future projection periods (2031-2040 and 2051-2060) were separately entered into the CROPWAT 8.0 software. The data were derived from the HadGEM2-ES and MPI-ESM-MR models under RCP4.5 and RCP8.5 scenarios. This approach allowed the evaluation of potential changes in sunflower irrigation water requirements under varying climate scenarios and time frames.

In CROPWAT 8.0, ET_0 was calculated using the FAO Penman-Monteith method. Based on ET_0 and K_c values defined for each growth stage of sunflower, ET_c was estimated. Effective rainfall (P_{eff}) was calculated using the USDA (United States Department of Agriculture) method, and IWR was determined by subtracting P_{eff} from ET_c (Deveci et al., 2025).

2. RESULTS

In this study, annual average ET_0, ET_0 during the sunflower growing period, ET_c, and IWR were evaluated. For these calculations, climate data obtained from the HadGEM2-ES and MPI-ESM-MR models, reference period (1971-2000) and future short (2031-2040) and long (2051-2060) periods under the RCP4.5 and RCP8.5 scenarios were used.

2.1. Evaluation of annual average ET_0

ET_0 is predicted to increase in three locations in both models and both scenarios compared to the reference period (Edirne (4.9%-26.9%), Kırklareli (5.3%-18.3%), and Tekirdağ (5.7%-17.5%)) (Table 4, Figure 2). The highest ET_0 was predicted in Edirne in the period

Table 4. HadGEM2-ES and MPI-ESM-MR model annual average ET_0 values change for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) in sunflower.

Location	Future Periods	Deviation from the reference period (1971-2000) (%)			
		HadGEM2-ES Model		MPI-ESM-MR Model	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Edirne	2031-2040	8.3	10.9	6.7	7.9
	2051-2060	18.0	26.9	4.9	9.0
Kırklareli	2031-2040	10.2	13.2	7.7	9.5
	2051-2060	14.0	18.3	5.3	9.0
Tekirdağ	2031-2040	9.9	11.7	6.3	9.1
	2051-2060	12.9	17.5	5.7	8.9

2051-2060 (3.54 mm/day) because of the HadGEM2-ES model under the RCP8.5 scenario, and the lowest ET_0 was predicted in Tekirdağ in the period 2051-2060 (2.70 mm/day) because of the MPI-ESM-MR model RCP8.5 scenario (Figure 2). The largest change compared to the reference period was predicted in Edirne in the period 2051-2060 (26.9%) because of the HadGEM2-ES model RCP8.5 scenario, and the smallest change was predicted in Edirne in the period 2051-2060 (4.9%) because of the MPI-ESM-MR model RCP8.5 scenario (Table 4).

In this part of the study, the accuracy of HadGEM2-ES and MPI-ESM-MR model monthly ET_0 values covering 30 years for the reference period 1971-2000 was evaluated. For this purpose, the ET_0 values obtained from the reference period climate data were compared with the ET_0 values calculated and published monthly for each province in Türkiye covering a long period of 30 years in the "Guide to Plant Water Consumption of Irrigated Crops in Türkiye" published by the General Directorate of Agricultural Research and Policies and State Hydraulic Works (RTMAFGDARP, 2017). In this guide, ET_0 values were prepared by using quality-controlled 30-year daily climate data from 259 meteorological stations of the General Directorate of Meteorology throughout Türkiye. Parameters such as minimum, maximum, and average temperature, relative humidity, insolation time, insolation intensity, precipitation, and wind speed were taken into account in the preparation of the guide, missing data were completed by Allen et al. (1998) and solar radiation data were organized according to ASCE-EWRI (2004) principles. In this framework, monthly average ET_0 values covering 30 years for Edirne, Tekirdağ, and Kırklareli provinces were obtained from the guide and compared with the values calculated with 30-year reference data of HadGEM2-ES and MPI-ESM-MR models, and a high level of agreement was found (Figure 3). For

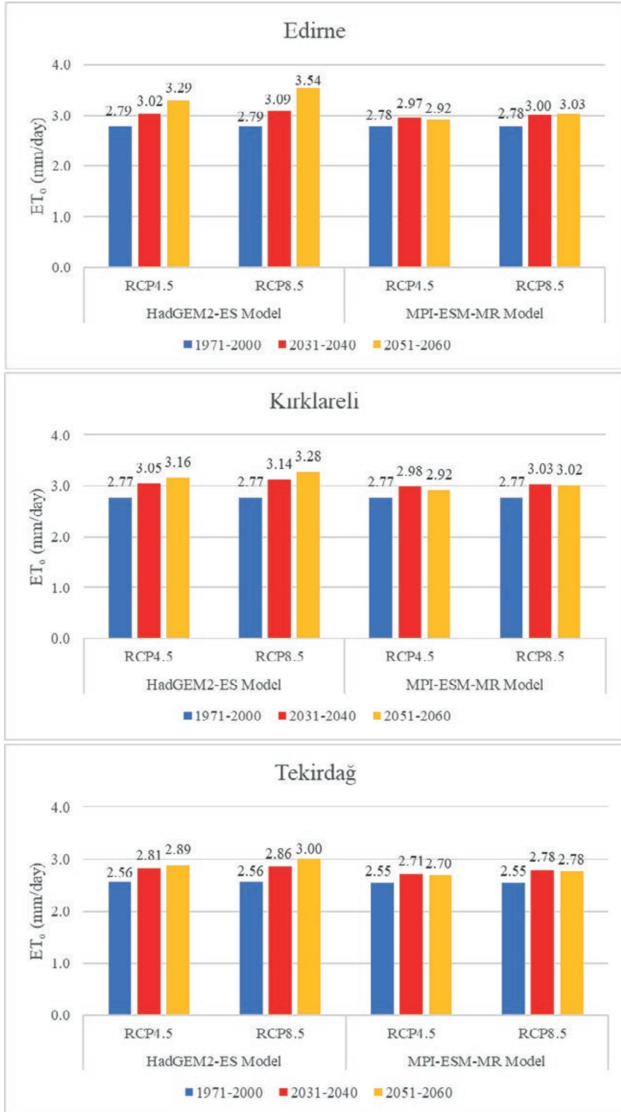

Figure 2. Daily average ET_0 values (mm/day) for the reference (1971-2000) and future periods (2031-2040, 2051-2060) according to HadGEM2-ES and MPI-ESM-MR climate models.

the correlation coefficients, it was calculated as 0.995 for Edirne, 0.987 for Kırklareli, and 0.987 for Tekirdağ in the HadGEM2-ES model. In the MPI-ESM-MR model, it was calculated as 0.995 for Edirne, 0.994 for Kırklareli, and 0.984 for Tekirdağ. In addition, the difference between the annual total ET_0 values was 13.2% (Edirne), 6.6% (Kırklareli), and 4.1% (Tekirdağ) in the HadGEM2-ES model, while it was 13.0% (Edirne), 6.6% (Kırklareli), and 3.8% (Tekirdağ) in the MPI-ESM-MR model. These findings show that both model reference data used in the study overlap to a large extent with the 30-year ET_0 values calculated with measured climate data for the region and that the data obtained from the models can be used reliably.

2.2. Evaluation of ET_0 during the sunflower vegetation period

In general, ET_0 (during the sunflower vegetation period) in the TR21 Thrace Region is projected to increase in both models, scenarios, and periods compared to the reference period (Table 5, Figure 4). This increase was predicted to be between 3.4%-16.7% in Edirne, 3.9%-17.9% in Kırklareli and 4.7%-17.6% in Tekirdağ (Table 5). During the sunflower growing period, the highest ET_0 was predicted in Edirne in the period 2051-2060 (5.06 mm/day) because of the HadGEM2-ES model RCP8.5 scenario, and the lowest ET_0 was predicted in Tekirdağ in the period 2051-2060 (3.97 mm/day) because of MPI-ESM-MR model RCP8.5 scenario (Figure 2). In addition, the largest change compared to the reference period was predicted in Kırklareli in the period 2051-2060 (17.9%) because of HadGEM2-ES model RCP8.5 scenario and the smallest change was predicted in Edirne in the period 2051-2060 (3.4%) because of MPI-ESM-MR model RCP8.5 scenario (Table 5).

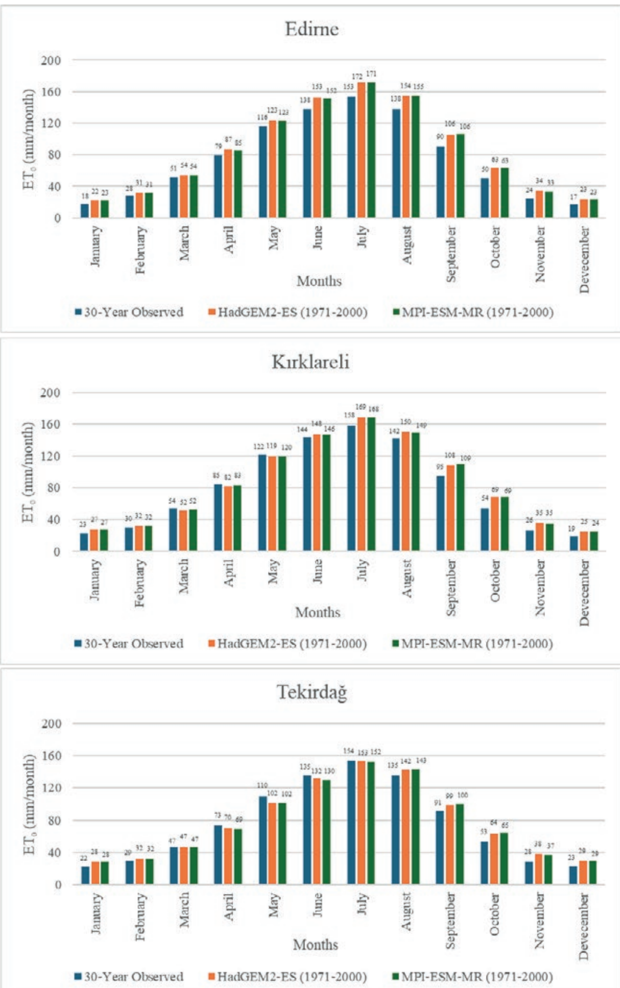

Figure 3. Comparison of monthly ET_0 values obtained from 30-year observed data with HadGEM2-ES and MPI-ESM-MR model reference data.

2.3. Evaluation of ET_c of (Sunflower)

ET_c in the TR21 Thrace Region is predicted to increase in both models, both scenarios, and both periods compared to the reference period (Table 6, Figure 5). This increase is projected to be between 2.4%-15.8% in Edirne, 3.1%-16.9% in Kırklareli, and 3.5%-15.6% in Tekirdağ (Table 6). The highest ET_c was predicted in Edirne for the period 2051-2060 (698.4 mm/season) because of the HadGEM2-ES model RCP8.5 scenario, while the lowest ET_c was predicted in Tekirdağ for the period 2051-2060 (533.8 mm/season) because of the MPI-ESM-MR model RCP8.5 scenario (Figure 5). The largest change compared to the reference period was predicted in Kırklareli in the period 2051-2060 (16.9%) because of the HadGEM2-ES model RCP8.5 scenario, and the smallest change was predicted in Edirne in the period 2051-2060 (2.4%) because of the MPI-ESM-MR model RCP8.5 scenario (Table 6).

2.4. Evaluation of IWR

IWR is predicted to increase in the period 2051-2060 in Edirne, Kırklareli, and Tekirdağ in the RCP4.5

Table 5. HadGEM2-ES and MPI-ESM-MR model ET_0 values change for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) in the sunflower vegetation period.

Location	Future Periods	Deviation from the reference period (1971-2000) (%)			
		HadGEM2-ES Model		MPI-ESM-MR Model	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Edirne	2031-2040	7.5	10.5	6.1	7.8
	2051-2060	11.3	16.7	3.4	7.7
Kırklareli	2031-2040	9.5	13.0	7.1	9.1
	2051-2060	14.1	17.9	3.9	8.1
Tekirdağ	2031-2040	9.8	11.6	6.0	9.2
	2051-2060	13.2	17.6	4.7	8.1

Figure 4. HadGEM2-ES and MPI-ESM-MR model ET_0 values for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) for sunflower in the vegetation period.

scenario in the MPI-ESM-MR model. In addition, in Tekirdağ, the same model predicted a decrease in the RCP8.5 scenario for the same period and an increase in all other forecasts (Table 7). This change is projected to be between -5.3%-17.5% in Edirne, -7.0%-20.8% in Kırklareli, and -3.3%-17.9% in Tekirdağ (Table 7). The highest IWR occurred in Edirne in the period 2051-2060 (587.1 mm/season) because of the HadGEM2-ES model RCP8.5 scenario, and the lowest IWR occurred in Tekirdağ in the period 2051-2060 (389.1 mm/season) because of the MPI-ESM-MR model RCP4.5 scenario (Figure 6). In addition, the largest

Table 6. HadGEM2-ES and MPI-ESM-MR model ET_c values change for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) in the sunflower vegetation period.

Location	Future Periods	Deviation from the reference period (1971-2000) (%)			
		HadGEM2-ES Model		MPI-ESM-MR Model	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Edirne	2031-2040	7.3	9.7	3.8	8.1
	2051-2060	11.4	15.8	2.4	6.0
Kırklareli	2031-2040	9.6	12.0	5.2	10.4
	2051-2060	13.8	16.9	3.1	6.3
Tekirdağ	2031-2040	8.4	9.9	3.5	9.4
	2051-2060	12.5	15.6	3.6	6.5

change compared to the reference period was projected in Kırklareli in the period 2051-2060 (20.8%) because of HadGEM2-ES model RCP8.5 scenario and the smallest change was projected in Kırklareli in the period 2051-2060 (-7.0%) because of MPI-ESM-MR model RCP8.5 scenario (Table 7).

3.5. General evaluation

The general evaluation of the results is presented in Table 8. Accordingly, it is predicted that the annual average ET_0 will vary between 2.70-3.54 mm/day in the TR21 Thrace Region, and ET_0 will vary between 3.97-5.06 mm/day during the sunflower growing period. The change in annual average ET_0 compared to the reference period was estimated to be 4.9%-26.9%, and the change in ET_0 compared to the reference period during the sunflower growing period was estimated to be 3.4%-17.9%. ET_c for sunflower was predicted to vary between 533.8-698.4 mm/season in the modeled periods, and this change was predicted to be 2.4%-16.9% compared to the reference period. IWR is predicted to vary between 389.1-587.1 mm/season, and this change is predicted to be -7.0%-20.8% in both models, both scenarios, and both periods compared to the reference period.

In TR21 Thrace Region, annual average ET_0, ET_0 during the sunflower growing period, and sunflower evapotranspiration (ET_c) are estimated to be negatively affected by climate change and to increase compared to the reference period. It is estimated that ET_0 values will increase by 6.3%-13.2% and 4.9%-26.9% in the upcoming short (2031-2040) and long (2051-2060) periods, respectively, compared to the reference period (1971-2000), and by 6.0%-13.0% and 3.4%-17.9% in the sunflower development period, respectively. ET_c is pre-

Figure 5. HadGEM2-ES and MPI-ESM-MR model ET_c values for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) for sunflower.

dicted to increase by 3.5%-12.0% in the short term and 2.4%-16.9% in the long term, compared to the reference period. It is anticipated that there will be increases and decreases in irrigation water demand. Because it has been determined that IWR values will vary between 0.3%-19.9% in the short term and -7.0%-20.8% in the long term. However, the general trend is towards an increase, and it has been determined that these increases will be greater than the decreases.

Table 7. HadGEM2-ES and MPI-ESM-MR model IWR values change for the reference period.

Location	Future Periods	Deviation from the reference period (1971-2000) (%)			
		HadGEM2-ES Model		MPI-ESM-MR Model	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Edirne	2031-2040	10.8	10.4	4.0	15.8
	2051-2060	17.1	17.5	-5.3	1.5
Kırklareli	2031-2040	14.1	13.6	6.3	19.9
	2051-2060	20.8	19.2	-7.0	1.5
Tekirdağ	2031-2040	11.3	12.3	0.3	12.3
	2051-2060	17.9	17.0	-3.3	-0.1

3. DISCUSSION

In the “Impacts of Climate Change and Adaptation Strategies in TR21 Thrace Region” project carried out in the region, climate assessments were made in ten-year periods (Anonymous, 2019). Accordingly, it is predicted that there will be temperature increases in both models and scenarios in Edirne, Kırklareli, and Tekirdağ in the short (2031-2040) and long (2051-2060) periods, and periodic increases and decreases in precipitation. Possible temperature increases are projected to vary between 1.08°C and 2.90°C, while the change in precipitation is projected to be between -13.70 and 11.46 mm (Hanedar et al., 2019). In this study, it is predicted that the annual average ET_0 will vary between 2.70 and 3.54 mm/day in the TR21 Thrace Region, and ET_0 will vary between 3.97 and 5.06 mm/day during the sunflower growing period. The change in annual average ET_0 compared to the reference period is estimated to be 4.9%-26.9%, and the change in ET_0 compared to the reference period during the sunflower growing period is estimated to be 3.4%-17.9%. In another study conducted in the region, Deveci and Konukcu (2024) evaluated the reference (1961-1990) and future A2 SRES scenario outputs of the ECHAM5 General Circulation Model in Pınarbaşı Basin in the Thrace Region and predicted an average temperature increase of 0.12°C between 2016-2025, 1.43°C between 2046-2055 and 3.05°C between 2076-2085 compared to the model reference years (1970-1990). It is also predicted that total precipitation will increase by 60 mm between 2016-2025 (9%), total precipitation will decrease by 91 mm between 2046-2055 (14%), and total precipitation will decrease by 78 mm between 2076-2085 (12%). In 2012, an experiment was conducted and it was estimated that while the average ET_0 values were 3.0 mm/day in 2012, they would increase to 3.2 mm/day (+7%) between 2016-2025, 3.6 mm/day (+20%) between 2046-

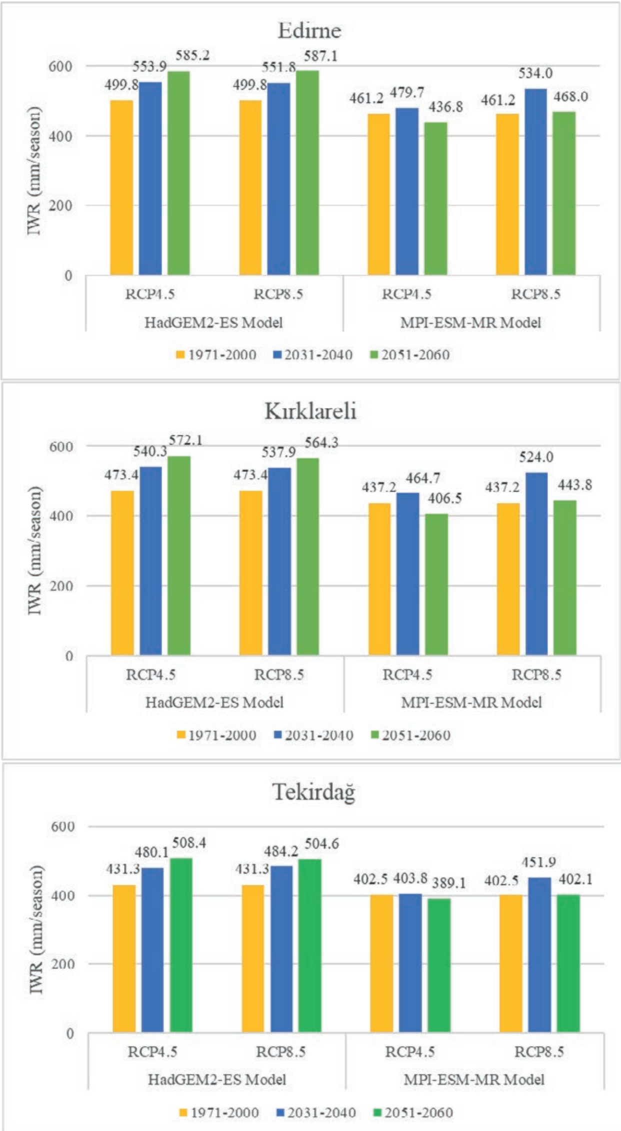

Figure 6. HadGEM2-ES and MPI-ESM-MR model IWR values for the reference period (1971-2000) and future periods (2031-2040, 2051-2060) for sunflower.

2055 and 4.0 mm/day (+33%) between 2076-2085. In addition, when compared with the reference period (1970-1990), ET_0 values change by 9% and 21% in the medium 2046-2055 and long 2076-2085 terms, respectively. Even though the reference periods, future periods, forecast models, and scenarios used in these studies are different, the results of this research support each other. In addition, De Oliveira et al. (2021) stated that the ET_0 value, which is an important component in calculating the water requirement of plants, can be affected by climate change. Arabi and Candoğan (2022) estimated ET_0 values for 18 meteorological stations in the Marmara Region using monthly climate data between 1990 and 2020 and found statistically significant increasing trends in ET_0 values in Edirne, Kırklareli, and Tekirdağ. These results and the results found in this study are in the same direction. When other studies conducted in Türkiye are evaluated, it is estimated that ET_0 increases with temperature increases in the Çukurova Region (Şen, 2023; Yetik and Şen, 2023). In the study conducted by Anlı (2014) for the Southeastern Anatolia region, the change in ET_0 values over time was investigated, and it was determined that there were significant increasing trends in ET_0 values. Selçuk (2021) calculated the monthly ET_0 values for the years 1959-2019 using the FAO Penman-Monteith method, using the climate data of 17 meteorological stations within the borders of Malatya province, and revealed that increasing temperature values increased Malatya ET_0 values by 3%. In the worldwide studies, Irmak et al. (2012) found that at reference (potential) evapotranspiration (ET_{ref}), precipitation, and relative humidity were significantly ($P<0.05$) inversely correlated, while mean temperature, maximum temperature, vapor pressure deficit, solar radiation and net radiation values had significant and positive correlations. Goyal (2004), in his study on long-term climate data for 32 years (1971-2002) in Rajasthan (India), determined that there would be a 14.8% increase in total ET with a 20% increase in temperature (maximum 8°C). As a result, all these studies are in line with the conclusion that the annual average ET_0 and ET_0 values during the sunflower growing period will increase with the predicted climate change in the region.

Şen et al. (2008) predicted a decrease in effective precipitation and thus in water resources in the Seyhan Basin, but an increase in plant water requirements. Although climatic factors are not the sole determinant of sunflower yield, they have significant effects on yield, and according to the results of the analysis, it was determined that temperature and humidity parameters have a significant effect on sunflower yield (Gürkan et al., 2016). In this study, sunflower ET_c was predicted to vary between 533.8-698.4 mm/season during the modeled periods, and this change could be 2.4%-16.9% compared to the reference period. Together with the predicted temperature increases in the region (1.08°C-2.90°C), this situation was considered as probable. Similarly, Deveci et al. (2025) determined that ET_c would increase with temperature increases in wheat and canola in the same region, even though the plants were different.

In this study, IWR was predicted to change between 389.1-587.1 mm/season, and this change was predicted to be -7.0%-20.8% in both models, both scenarios, and both periods compared to the reference period. It is pre-

Table 8. General evaluation of ET_0, ET_0 (sunflower vegetation period), ET_c (sunflower), and IWR.

	Values		Deviation from the reference period (1971-2000) (%)	
	Max.	Min.	Max.	Min.
ET_0 (annual average)	Edirne HadGEM2-ES RCP8.5 2051-2060 3.54 mm/day	Tekirdağ MPI-ESM-MR RCP8.5 2051-2060 2.70 mm/day	Edirne HadGEM2-ES RCP8.5 2051-2060 %26.9	Edirne MPI-ESM-MR RCP8.5 2051-2060 %4.9
ET_0 (sunflower vegetation period)	Edirne HadGEM2-ES RCP8.5 2051-2060 5.06 mm/day	Tekirdağ MPI-ESM-MR RCP8.5 2051-2060 3.97 mm/day	Kırklareli HadGEM2-ES RCP8.5 2051-2060 %17.9	Edirne MPI-ESM-MR RCP8.5 2051-2060 %3.4
ET_c (sunflower)	Edirne HadGEM2-ES RCP8.5 2051-2060 698.4 mm/season	Tekirdağ MPI-ESM-MR RCP8.5 2051-2060 533.8 mm/season	Kırklareli HadGEM2-ES RCP8.5 2051-2060 %16.9	Edirne MPI-ESM-MR RCP8.5 2051-2060 %2.4
IWR	Edirne HadGEM2-ES RCP8.5 2051-2060 587.1 mm/season	Tekirdağ MPI-ESM-MR RCP4.5 2051-2060 389.1 mm/season	Kırklareli HadGEM2-ES RCP8.5 2051-2060 %20.8	Kırklareli MPI-ESM-MR RCP8.5 2051-2060 -%7.0

dicted that there will be increases and decreases in irrigation water demand; the general trend is in the direction of increase, and proportionally, these increases will be more than the amount of decrease. In the MPI-ESM-MR model, it is estimated that there will be a decrease in Edirne (-5.3%), Kırklareli (-7%) and Tekirdağ (-3.3%) in the period 2051-2060 in the RCP4.5 scenario and also in Tekirdağ in the same model, same period RCP8.5 scenario (-0.1%), and an increase in all other forecasts (Table 7). Looking at the 3 situations that draw attention as a decrease, it is estimated that the temperature will increase by 1.36°C in Edirne, 1.34°C in Tekirdağ and 1.34°C in Kırklareli, and precipitation will increase by 5.71 mm in Edirne, 9.75 mm in Tekirdağ and 11.46 mm in Kırklareli (Hanedar et al., 2019). Therefore, it is seen that there is a close change in temperatures. Increases in precipitation were observed during this period. Precipitation is more decisive. Therefore, the decrease in IWR with increases in precipitation was considered normal. In fact, it is interpreted that these precipitations probably occurred during the development period of the plant, and the need for irrigation water is likely to decrease.

The calculated IWR values represent the net water requirement of the crop, independent of the irrigation method and application efficiency. However, the efficiency of irrigation systems used in practice can significantly affect the actual amount of water applied in the field. For instance, while the application efficiency of traditional surface irrigation methods is typically around 30–40%, it may reach 55–70% in furrow irrigation and 90–95% in drip irrigation systems (Qureshi et al., 2015; Yara, 2024). Therefore, even if similar IWR values are estimated for different regions, the total volume of water that needs to be applied in the field can vary depending on the irrigation method used. Similar findings in the literature have emphasized that irrigation methods play a critical role in meeting increased or altered water demands under the influence of climate change (Lakhiar et al., 2024).

Overall, the findings of this study are largely consistent with both regional and national literature, indicating that climate change directly affects irrigation water requirements, and the magnitude of this effect varies depending on local climatic conditions, precipitation patterns, and the irrigation techniques employed.

4. CONCLUSIONS

In this study, the effect of climate change on the irrigation water requirement of sunflower in the TR21 Thrace Region was modeled. As a result, in this study, annual average ET_0, ET_0 during the sunflower growth period, and sunflower evapotranspiration in the TR21 Thrace Region were predicted to be negatively affected by climate change and to increase compared to the reference period. Decreases in IWR are predicted only in the MPI-ESM-MR Model, it is estimated that there will be a decrease in Edirne (-5.3%), Kırklareli (-7%) and Tekirdağ (-3.3%) in the period 2051-2060 in the RCP4.5 scenario and also in Tekirdağ in the same model, same period RCP8.5 scenario (-0.1%), and an increase in all other forecasts and the general trend is upward. Increases in

IWR are expected to proportionally outweigh decreases. Accurately determining the impact of climate change on ET_0, ET_c, and IWR is crucial for designing irrigation systems and preparing irrigation programs. These results suggest that the currently widespread rainfed sunflower cultivation in the TR21 Thrace Region may become insufficient under future climate conditions, potentially necessitating the use of supplementary irrigation. Therefore, the efficient, planned, and sustainable management of regional water resources is of great importance. In this context, the findings may serve as a guide for producers, irrigation planners, and policymakers in developing adaptation strategies to climate change.

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