



# Climate model projections of aridity patterns in Türkiye: A comprehensive analysis using CMIP6 models and three aridity indices

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## Abstract

Climate change can alter the spatial and temporal distribution of aridity around the world through a combination of factors such as reduced precipitation, rising temperatures and decreased evapotranspiration. Especially the Mediterranean region has been identified as vulnerable to anthropogenic climate change due to a significant reduction in precipitation compared to other land regions in all climate models operated under different scenarios. Despite numerous studies on aridity trends, few have focused specifically on Türkiye and considered a comprehensive range of aridity indices and scenarios. This study aims to fill this research gap by providing a more detailed understanding of future aridity trends in Türkiye under various climate change scenarios and using multiple aridity indices. A novelty of this study lies in the simultaneous examination of three aridity indices (PCI, EAI and UNEP AI) for Türkiye, allowing for a more comprehensive assessment of future aridity trends. Furthermore, this study considers three future time periods (2011–2040, 2041–2070 and 2071–2100) and three shared socioeconomic pathways (SSPs) to evaluate the potential range of climate change impacts on aridity in Türkiye. Therefore, in this study, we aimed to determine the changes in aridity conditions in Türkiye until the end of the 21st century. We used three aridity indices: the Pinna combinative index, the Erinç aridity index and the UNEP aridity index. These indices were calculated for the baseline period of 1981–2010 using gridded data (CHELSA) and for the periods of 2011–2040, 2041–2070 and 2071–2100 using three climate models (GFDL-ESM4, MRI-ESM2-0 and IPSL-CM6A-LR) and multi-model means with three SSPs to represent different future scenarios. The results showed that all three indices indicate an increase in dry climate conditions in Türkiye after 2041, with particularly notable increases expected in Central Anatolia, Southeastern Anatolia and parts of the Eastern Mediterranean, as well as eastern parts of Eastern Anatolia and the inner Aegean region. Under the SSP3-7.0 scenario, the expansion of semi-arid and arid areas is predicted to cover more than 30% of the

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country by the end of the century (2071–2100). This increase in aridity could increase the region's vulnerability to climate change and the risk of desertification, which should be taken into consideration in national water management and planning.

#### KEYWORDS

aridity index, CHELSA, CMIP6, Erinç aridity index, Pinna combinative index, Türkiye, UNEP aridity index

#### JEL CLASSIFICATION

Q540, Q580

## 1 | INTRODUCTION

Both observations and modelling studies show increasing meteorological drought and climatic aridity over many land areas, leading to changes in the areal extent of drylands and their subtypes (Chiang et al., 2021; Huang et al., 2016; Prävãlie et al., 2019; Ullah et al., 2022). Increased droughts and aridity not only contribute to the expansion of global drylands but also create soil moisture depletion, exacerbating land degradation, decreasing carbon uptake at land ecosystems, amplifying extreme temperature conditions and contributing to heat waves and forest fires (Huang et al., 2016; Shi et al., 2021).

There are evidences to suggest a shift towards semi-arid or arid conditions globally due to the combined effect of decreasing precipitation and warming (Kalyan et al., 2021; Li et al., 2019; Spinoni et al., 2021). For example, drylands increased by 3.1% globally between 1980 and 2008, compared to 1948–1979. The expansion of drylands has accelerated, particularly over the past 40 years (Li et al., 2019). A diachronic analysis of two major global drought databases showed that arid areas have expanded globally in recent years, excluding Europe and South America, due to an increase in arid (+3.4%) and semi-arid (+0.9%) areas (Prävãlie et al., 2019). Model projections also indicated that arid and semi-arid lands would likely continue to expand during the 21st century. Drier regions are projected to dry earlier, more severely, and to a greater extent than humid regions due to the decreasing precipitation and increasing evapotranspiration (Koutroulis, 2019; Pradhan et al., 2019; Wang et al., 2021). For example, based on the simulations of the HadGEM3A model under the RCP8.5 concentration scenario, 2% of the global land area is projected to shift towards drier types and 4.24% to wetter at a 4°C warmer world above pre-industrial levels (Koutroulis, 2019). Results of the 103 high-resolution simulations from the coordinated regional climate downscaling experiment, based on a combination of 16 global circulation models and 20 regional circulation models,

showed that under the RCP4.5 and RCP8.5 scenarios, 15% of the world's land is likely to experience more frequent and severe meteorological droughts (standardized precipitation index [SPI]) during 2071–2100 compared to 1981–2010. The increase is greater when the standardized precipitation-evapotranspiration index (SPEI) is employed (47% under RCP4.5 and 49% under RCP8.5). Only western South America, the Mediterranean and the southwest regions of southern Africa that resemble the Mediterranean will endure three or more droughts that have never been recorded in 1981–2010 for SPI under RCP8.5 (Spinoni et al., 2020). According to the results from 21 coupled model intercomparison project phase 5 models under the RCP8.5 scenario, the largest expansion of drylands will occur in semi-arid regions, followed by the expansion of arid regions, with area changes of 4% (7%) and 3% (4%) at 2 and 4°C levels of global warming above the pre-industrial period, respectively (Wang et al., 2021). Recent modelling studies have projected that approximately 6.8 million km<sup>2</sup> (4.5% of global land) could become arid at a warming of 4°C, particularly over South America and southern Europe (Spinoni et al., 2021).

The Mediterranean Basin has been identified as one of the regions that shifted to more arid conditions due to global anthropogenic climate change (Seager et al., 2019; Spinoni et al., 2021). For example, the aridity index showed downward trends over the Sahel in northern Africa, southern Africa and Mediterranean regions from 1948 to 2008 (Huang et al., 2016). In the 1948–2018 period, the aridity index showed a statistically significant downward trend in eastern and western Iran, west and central Türkiye, the north of Iraq and Syria, and the west of Jordan and Israel (Sahour et al., 2020). The frequency, duration and intensity distributions of SPI-based droughts have changed significantly in the Mediterranean region during the 1956–2005 period compared to the 1851–1900 period. The results show that the Mediterranean region has experienced unprecedented drought intensity compared to the pre-industrial revolution

(Chiang et al., 2021). Arid conditions were significantly on the rise over most of Europe–Mediterranean (EURO–MED) region, and there were regional increasing signals for the dry days for the 1979–2016 period. Extreme drought (percentage of monthly Palmer drought severity index below the 10th percentile) also had a significant increasing trend of 3.8% decade over the EURO–MED region during the same period (Kelebek et al., 2021).

While the amplitude of the changes after 2050 depends on the emission scenario, the results of the climate models indicate that more frequent, longer and more intense droughts will occur in the Mediterranean region at the end of the 21st century, even under the lowest warming scenarios (Barredo et al., 2019; Cook et al., 2020; Drobinski et al., 2020; Trambly et al., 2020). Compared with the estimates for the historical period (1971–2000), the drought area will change from 28% on average to 49%, and the number of drought months occurring per year will reach from 2.1 months to 5.6 months under a warming of 3 K for the Mediterranean (Samaniego et al., 2018). Another study that assesses the spatial shifts of the Mediterranean and arid climates indicates that the current Mediterranean climatic zone is expected to decline by 16% by the end of the century under RCP8.5 and that the extension of the dry zone is nearly always the cause of the shrinking of the Mediterranean zone (Barredo et al., 2019). According to their findings, that process will be evident in 2021–2050 and will continue towards the end of the century. The extreme drought risk, defined as years with event magnitudes below the 10th percentile from 1851 to 1880 baseline, increases by over 100% ( $\times 2$ ) over southern Africa, Europe and the Mediterranean, even under the lowest warming scenarios (SSP1-2.6 scenario; Cook et al., 2020).

Over the past decades, studies related to drought conditions and projected future (up to 2100) changes have shown that Türkiye will be most influenced by the adverse impacts of projected climate change, suggesting an increase in drought frequency and severity as Mediterranean Basin (Önol & Ünal, 2014; Türkeş et al., 2020; Türkeş et al., 2016; Yeşilköy & Şaylan, 2022). For instance, using reference (1961–1990) and future (2071–2100) climate simulations produced by ICTP-Reg-CM3, a precipitation amount decrease of 24% has been shown to be significant over the southeastern part of Türkiye for winter (Önol & Ünal, 2014). From 1950–1980 to 1981–2010, the semi-arid and dry sub-humid continental central Anatolia climate characteristics expanded significantly, while the semi-humid and humid temperate coastal climate regions became narrower in Türkiye (Türkeş et al., 2016). When changes in seasonal precipitation climatology and aridity conditions in Türkiye are evaluated from 2021 to 2050 for the reference period of 1971–2000 by using regional climate model simulations

with the MPI-ESM-MR global climate model under both RCP4.5 and RCP8.5 emission scenarios, the obtained results show a substantial decrease in precipitation over almost all parts of Türkiye as well as an increase in the intensity of drought conditions and more arid conditions (Türkeş et al., 2020). The rate of moderate and high drought (drought occurrence) in northwest Türkiye was 17.2%–30.3%, respectively, between 1971 and 2018, according to the SPEI-12 and the self-calibrated Palmer drought severity index (sc-PDSI). The results of SPEI-12 and sc-PDSI showed that the occurrence of drought would increase by 38.3%–35.3% in RCP 4.5 and 47–41% in RCP 8.5 for the years 2051–2099, respectively (Yeşilköy & Şaylan, 2022).

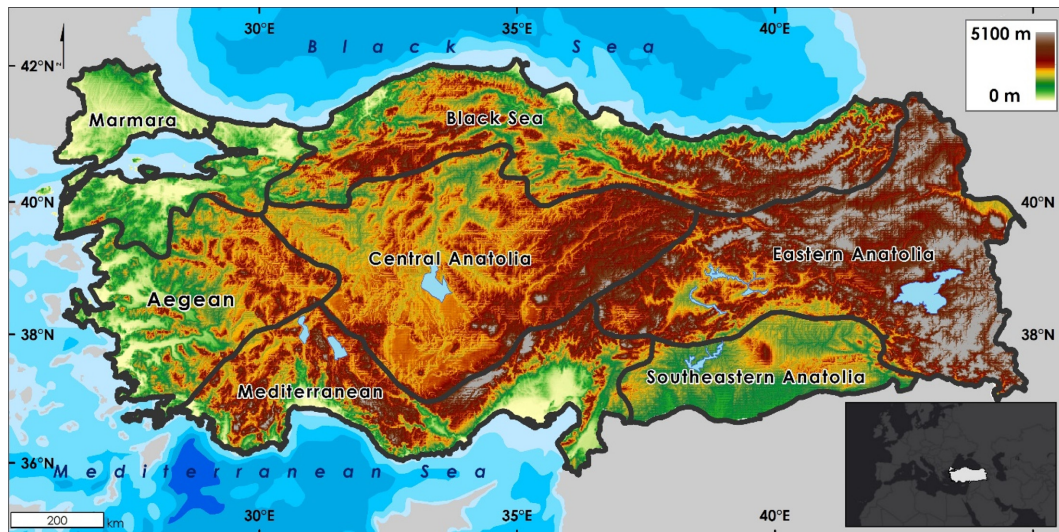
Quantitative assessments of meteorological drought conditions related to future warming are necessary to understand its potential impacts on human society and natural ecosystems. The primary goal of this research is to predict how aridity indices in Türkiye will change in the 21st century.

This paper examined three aridity indices according to the reference and future simulations in seven climate zones over Türkiye (Figure 1). The primary aim of this study is to provide a comprehensive assessment of the potential changes in aridity across Türkiye using multiple aridity indices and climate models under different future scenarios. This is essential in light of the increasing water stress, agricultural challenges and population growth in the country. By incorporating a range of indices and scenarios, this study offers a more robust understanding of the potential future aridity patterns and their implications for water resource management, agricultural planning and adaptation strategies. The novelties of this study include the use of multiple aridity indices, the application of the latest climate model projections under a range of SSPs, and a detailed analysis of the spatial and temporal changes in aridity patterns for different regions of Türkiye. This comprehensive approach contributes to the existing body of knowledge on aridity and climate change in Türkiye and can help inform more effective and targeted strategies for addressing the challenges associated with increasing aridity in the future.

## 2 | DATA AND METHODS

### 2.1 | Study area

Türkiye belongs to the Mediterranean macroclimate type, which has wet and dry seasons. It has various sub-climate types that vary within short distances due to orography, land-sea distribution, continentality and altitude (Turunçoğlu et al., 2018). As a result, Türkiye has been divided into



**FIGURE 1** The study area and the seven major geographical regions of Türkiye, namely the Black Sea (BLS), Aegean (AEG), Marmara (MAR), Mediterranean (MED), and the Central (CEA), Eastern (ESA) and Southeastern Anatolia (SEA) regions. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

seven geographical regions based on differences in climatic and physical geography (Figure 1).

In summer, the atmospheric circulation over Türkiye is characterized by localized intense subsidence which enhances aridity by reducing precipitation events. On the other hand, Türkiye is mostly dominated by the westward movement of mid-latitude storm systems originating over the Mediterranean Sea and the Atlantic from October to April. The North Atlantic and Mediterranean Sea, provide most of the moisture needed for precipitation during the wet season of the year (Batibeniz et al., 2020). Türkiye is also influenced by droughts on varying spatial and temporal scales during the wet season from October to April (Türkeş et al., 2020). The previous studies showed that the winter precipitation anomalies and drought conditions over Türkiye depend on atmospheric oscillations such as the North Atlantic Oscillation (NAO) and the North Sea Caspian Pattern (NCP; Kutiel et al., 2002; Türkeş & Erlat, 2005). During the negative phase of the NAO, most of the Mediterranean lands experience a noticeable increase in winter precipitation due to the storm tracks moving southward (Batibeniz et al., 2020). In contrast, in winter, the positive phase of the NAO index relates to below-normal precipitation over Türkiye under the influence of easterly and north-easterly circulation (Türkeş & Erlat, 2006). For example, the NAO index was in a predominantly positive phase, causing precipitation decreases in many parts of the Mediterranean area as well as Türkiye between the 1970s and early 1990s (Pinto & Raible, 2012; Türkeş & Erlat, 2005). The North Sea-Caspian pattern index (NCP), which refers to an atmospheric teleconnection between the North Sea and North

Caspian at the 500 hPa geopotential height level, is also affected by winter droughts. Except for the Black Sea region, Türkiye receives more rainfall in the wet season during the NCP negative phase. Contrary, there is more rainfall during the NCP positive phase from October to April (Kutiel et al., 2002).

Studies have documented that due to global climate change in Türkiye, changes in the warming more prominently in the summer season and precipitation patterns have occurred since the middle of the 20th century (Hadi & Tombul, 2018; Tayanç et al., 2009; Türkeş et al., 2016). The trends determined based on ERA5 and ERA5-Land temperature data showed that the increase in average temperatures in Türkiye for 2001–2020 and 1951–2020 was 0.91 and 0.21°C per decade, respectively (Yılmaz, 2023). Indeed, since the 1980s, there have been indications that warming in the Mediterranean Basin has been greater than on a global scale. The Mediterranean Basin is warming at a rate comparable to the global mean in winter and spring, but much higher in summer and autumn (Lionello & Scarascia, 2018). In Türkiye, where precipitation variability is high, annual precipitation showed a decrease in Southeastern Anatolia and Mediterranean regions and an increase in Marmara and Black Sea regions in the period 1951–2020, while there was no specific pattern in other regions (Hadi & Tombul, 2018).

## 2.2 | Data

Grid data are frequently used in ecological and environmental models that use climate data. Worldclim (Fick &

TABLE 1 Selected CMIP6 models (Karger et al., 2017; Lange &amp; Büchner, 2021).

Model	Institution	Native resolution	Ensemble member
GFDL-ESM4	National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA	288 × 180	r1i1p1f1
MRI-ESM2-0	Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan	320 × 160	r1i1p1f1
IPSL-CM6A-LR	Institut Pierre Simon Laplace, Paris 75252, France	144 × 143	r1i1p1f1

Hijmans, 2017), CRU TS (Harris et al., 2020) and CHELSA (Karger et al., 2017) are some of the most widely used. Among these, CHELSA is a high-resolution climate data set (30 arc seconds or 1 km) that offers climate data for land surface regions all over the world and is a reliable data set that provides for both baseline and future scenarios. The temperature algorithm is mainly based on atmospheric temperature statistical downscaling. With a bias correction, the precipitation method combines orographic predictors such as wind fields, valley exposition and boundary layer height. Monthly temperature and precipitation data, as well as several derived factors, are included in the output (Karger et al., 2017). In this study, we have used the variables of the CHELSA V2.1 dataset. We have used four periods of data: 1981–2010 as the reference period, and future scenarios for the 2011–2040, 2041–2070 and 2071–2100 periods.

The IPCC's sixth assessment report features Version 6 of Coupled Model Intercomparison Project models (CMIP6) that consist of the 'runs' from around 100 distinct climate models being produced across 49 different modelling groups. As distinct from the previous version, in CMIP6, future greenhouse gas emission scenarios are called 'Shared Socioeconomic Pathways'. These are SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0 and SSP5-8.5, each of which results in similar 2100 radiative forcing levels as their predecessor in AR5 (Hausfather, 2019).

In this study, we have used three of the CMIP6 models, namely GFDL-ESM4, MRI-ESM2-0 and IPSL-CM6A-LR, to determine the future of aridity indices (Table 1). These models have equilibrium climate sensitivity (ECS) of 2.7, 3.1 and 4.6°C, respectively (Hausfather, 2019). ECS refers to the response of global mean surface temperature (GMST) to the radiative forcing caused by a doubling of the atmospheric CO<sub>2</sub> concentration (Zhu et al., 2021). By selecting three CMIP6 models, we have aimed to assess the role of ECS in the prediction of aridity by using low, medium and high ECSs. Various studies have evaluated CMIP6's performance in modelling precipitation and temperature on continental or regional scales (Ajibola et al., 2020; Fan et al., 2020; Ajibola

et al., 2022; Dong & Dong, 2021), and it has been shown that multi-model ensembles perform better overall than individual models (Vogel et al., 2020; Zhao et al., 2021). Therefore, we have calculated the multi-model means of the GFDL-ESM4, MRI-ESM2-0 and IPSL-CM6A-LR models and assessed the results based on the multi-model mean results. The individual model results can be found in the supplementary data (see Data S1).

We also have examined three scenarios to represent the best, medium and worst cases: while SSP1-2.6 (+2.6 W m<sup>-2</sup> imbalance; low forcing sustainability pathway) corresponds to a more gradually shifting world, emphasizing more inclusive development, SSP3-7.0 (+7.0 W m<sup>-2</sup>; medium- to high-end forcing pathway) refers to countries focusing on achieving energy and food security goals within their regions at the expense of broader-based development, and SSP5-8.5 (+8.5 W m<sup>-2</sup>; high-end forcing pathway) refers to the fossil-fuelled development of countries that leads to an increase in radiative forcing of 8.5 W/m<sup>2</sup> by the end of the century (Bonnet et al., 2021).

## 2.3 | Methods

The computation of three aridity indices, namely the Pinna combinative index (PCI), Erinç's aridity index (EAI) and the United Nations environment programme aridity index (UNEP AI), was selected in this study (Table 2). There are several reasons for focusing on the PCI, EAI and UNEP AI. First, these three indices were selected because they are specifically designed to assess aridity conditions rather than solely focusing on drought, which is the primary concern of indices such as the Palmer drought severity index (PDSI), the SPI and the SPEI. Aridity indices provide a more comprehensive understanding of the long-term climate conditions in a region, taking into account factors such as precipitation, potential evapotranspiration and temperature, which are critical for assessing the overall aridity trends in Türkiye. Moreover, the PCI, EAI and UNEP AI indices

**TABLE 2** The climate classification of the selected aridity indexes (Erinç, 1965; Middleton & Thomas, 1992; Zambakas, 1992).

Index	Climate type	Abbr.	Index values
Pinna combinative index	Dry	D	PCI < 10
	Semi dry	SD	10 ≤ PCI ≤ 20
	Humid	H	PCI > 20
Erinç aridity index	Severe arid	SevA	EAI ≤ 8
	Arid	A	8 < EAI ≤ 15
	Semi-arid	SA	15 < EAI ≤ 23
	Semi humid	SH	23 < EAI ≤ 40
	Humid	H	40 < EAI ≤ 55
	Per humid	PH	EAI > 55
UNEP aridity index	Hyper arid	HA	UNEP AI < 0.05
	Arid	A	0.05 ≤ UNEP AI ≤ 0.2
	Semi-arid	SA	0.2 ≤ UNEP AI ≤ 0.5
	Dry sub-humid	DSH	0.5 ≤ UNEP AI ≤ 0.65
	Sub-humid	SH	0.65 ≤ UNEP AI ≤ 1
	Humid	H	UNEP AI > 1

represent different approaches to quantifying aridity, which allows for a more robust and comprehensive evaluation of future aridity conditions under various climate change scenarios. By utilizing these three indices, the study can capture different aspects of aridity, such as the balance between precipitation and potential evapotranspiration (PCI and EAI) and the impact of temperature on aridity (UNEP AI). Using aridity indices specifically tailored to capture the broader climatic context allows for a more accurate and relevant analysis of the potential future impacts of climate change on aridity patterns in the region.

Among selected indices, PCI is regarded as helpful in characterizing the climatic conditions of an area during the dry season. It precisely distinguishes the locations and seasons when agricultural activities predominate with regular irrigation, as it employs the multiyear mean precipitation and air temperature of the driest month to calculate aridity (Deniz et al., 2011). The EAI is useful for describing arid and humid locations as well as the duration of the dry season separately (Ullah et al., 2022). Additionally, in selecting the aridity indices for our study, we considered various factors, including the suitability of the index for capturing aridity conditions in Türkiye. EAI was chosen as one of the indices due to its relevance and applicability to the local climate characteristics of Türkiye. The EAI takes into account parameters such as temperature, precipitation, and potential evapotranspiration, which are key factors influencing aridity conditions in Türkiye.

Furthermore, the EAI has been widely used in previous studies on aridity assessment in the region, providing a consistent and comparable basis for our analysis. By utilizing the EAI, we aimed to capture the specific aridity patterns and changes that are relevant to Türkiye's climate context. The UNEP AI is among the most often used indices for describing water-stressed circumstances in a specific climate (Middleton & Thomas, 1992). It is commonly used to examine aridity-related spatial patterns at the national or regional level (Huang et al., 2016). UNEP AI is considered as one of the best metrics to identify water scarcity for several reasons (Vicente-Serrano et al., 2020). First, it takes into account both precipitation and potential evapotranspiration, which allows for a more accurate assessment of the water balance in a given area. This is particularly important for understanding water scarcity, as it provides a comprehensive overview of the available water resources and the demand for water due to evapotranspiration. Second, the UNEP AI is based on a well-established methodology that has been widely used in numerous studies and assessments of water scarcity and aridity at regional and global scales. This widespread use lends credibility and comparability to the index, making it an ideal choice for assessing water scarcity in Türkiye. Last, the UNEP AI is relatively straightforward to calculate and interpret, making it an accessible and practical tool for policymakers and water resource managers to assess water scarcity and plan for future water needs. The simplicity of the index also facilitates communication of the results to a broader audience, which is crucial for raising awareness of water scarcity issues and driving action to address them.

The PCI (Zambakas, 1992) takes the total annual precipitation, the annual mean air temperature, total precipitation and the mean air temperature of the driest month into consideration. It is calculated using the following Equation (1):

$$PCI = 1/2 ((P/T + 10) * (12P_d/T_d + 10)) \quad (1)$$

where  $P$  is the total annual precipitation in mm,  $T$  is the annual mean air temperature in °C,  $P_d$  is the total precipitation of the driest month and  $T_d$  is the mean air temperature of the driest month.

The EAI suggested by Erinç (1965) and is acquired using the Equation (2):

$$EAI = P/T_{max} \quad (2)$$

where  $P$  is the total annual precipitation in mm and  $T_{max}$  is the annual mean of the daily maximum air temperature.

The widely used UNEP AI is based on the ratio of the total annual precipitation ( $P$ ) and total annual potential evapotranspiration (PET; Middleton & Thomas, 1992), where the PET is calculated using the Thornthwaite formula. According to the following Equations (3–5), UNEP AI is calculated:

$$PET = 16 * AdjF * \left( \frac{10 * T_d}{I} \right)^a \quad (3)$$

where,

$$I = \sum_{i=1}^{12} \left( \frac{T_m}{5} \right)^{1.514} \quad (4)$$

and

$$a = (6.75 * 10^{-7}) I^3 - (7.71 * 10^{-5}) I^2 - (1.792 * 10^{-2}) I + 0.49239 \quad (5)$$

In the formula, the AdjF is the adjustment factor related to hours of daylight,  $T_d$  is the average daily temperature of the month in °C (0 is used for negative values), and  $I$  is the annual heat index depending on 12 monthly mean temperatures  $T_m$ . The climate types based on the three indices are shown in Table 2. All the calculations are undertaken for each grid cell. For the projected changes in aridity conditions, we compare the difference between the reference period (1981–2010) and the future periods under three SSPs.

### 3 | RESULTS

#### 3.1 | Projected changes in the PCI

Figure 2 shows the spatial distribution of aridity during the reference period, based on Pinna aridity indices. The values of PCI in Türkiye ranged from 5 (in the Southeastern Anatolia Region) to 362 (in the East of the Black Sea Region), implying dry to humid climate conditions. According to the reference period (1981–2010), almost 50% of Türkiye has semi-dry conditions. Semi-dry conditions are widespread in the west of the Marmara region, most of the Aegean region, and Central and Southeastern Anatolia. 42% of the areas in Türkiye are classified as humid. According to PCI, humid conditions prevail along the entire northern coast, including parts of the Marmara region, nearly the whole Black Sea region, and parts of Eastern Anatolia and the Mediterranean. Only 8% of the country's land is classified as 'dry', including the majority of Central and Southeastern Anatolia.

When the outputs of all CMIP6 models, namely GFDL-ESM4, MRI-ESM2-0 and IPSL-CM6A-LR for the PCI, are examined, it is seen that the projections for the change of arid, semi-arid and humid areas in Türkiye in the period until the end of the 21st century are in agreement with each other (Table 3). Only the most important difference between the outputs of the models is seen in the results of the GFDL-ESM4 model for the period 2071–2100 according to the SSP5-8.5 scenario. According to the outputs of the other two models, the ratio of dry and humid areas in the GFDL model does not show a significant

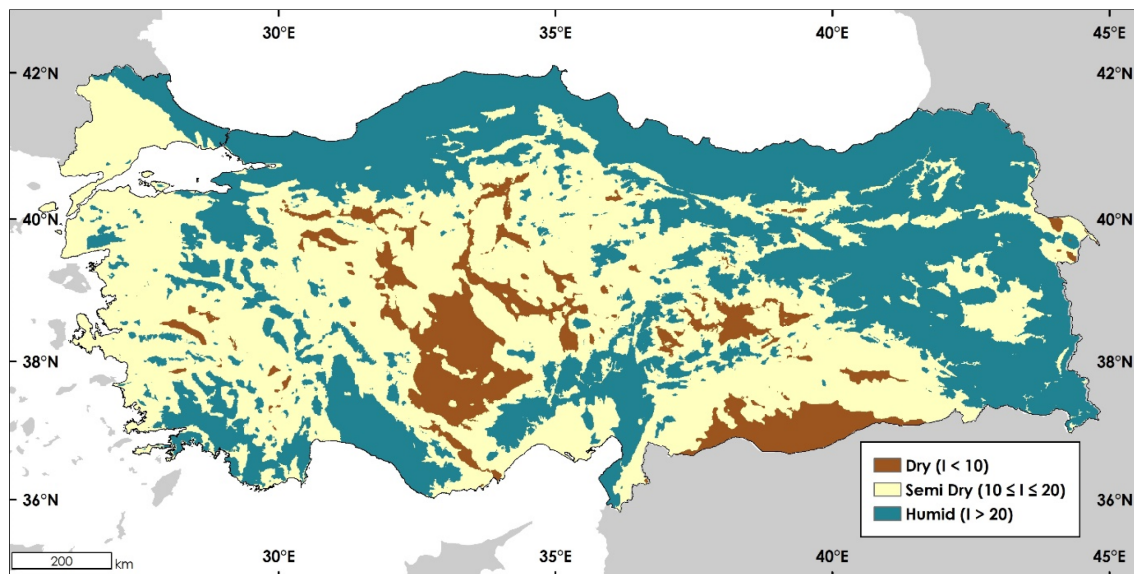


FIGURE 2 Spatial distribution of Pinna combinative index in the Türkiye for the reference period (1981–2010). [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

**TABLE 3** Percentage of the territory for the Pinna combinative index (PCI) for projected futures for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5.

Pinna index	Reference period	SSP1-2.6			SSP3-7.0			SSP5-8.5		
		GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR
2011–2040										
Dry	8.4	11.3	12.2	9.4	12.0	10.2	10.6	11.1	11.4	10.0
Semi dry	49.7	50.4	50.8	49.9	50.4	50.7	50.6	50.1	51.1	50.1
Humid	41.9	38.3	37.0	40.7	37.6	39.1	39.3	38.8	37.5	40.0
2041–2070										
Dry	8.4	11.5	9.9	12.9	19.7	14.7	16.3	18.0	16.8	19.4
Semi dry	49.7	50.7	51.1	50.9	50.5	51.8	50.9	50.6	50.9	50.4
Humid	41.9	37.8	39.0	36.2	29.8	33.5	32.8	31.4	32.3	30.2
2071–2100										
Dry	8.4	11.3	11.4	14.1	23.3	25.4	24.0	12.2	25.9	32.2
Semi dry	49.7	50.4	50.7	51.1	50.4	48.8	49.2	47.5	49.1	45.7
Humid	41.9	38.3	37.9	34.8	26.3	25.8	26.8	40.3	25.0	22.1

change compared to the reference period. The magnitude of the changes is higher for the dry and humid aridity indexes. The results of the three models were also provided as Supplementary Materials (Figures S1–S6).

The outputs of the multi-model mean show no significant change in the near future for the PCI, including all three scenarios according to the reference period. According to the three scenarios, the maximum change in the near future is seen in the humid climate index, with an almost 3% decrease as a result of all three models relative to the reference period (Figure 3). However, an increase in dry conditions is projected for mid-century, rising to 3.0%, 8.4% and 9.6% under SSP1-2.6, SSP3-7.0 and SSP5-8.5 according to the reference period, and is more pronounced in almost all Central and Southeastern Anatolia Regions, the southeastern regions and the western coast of Türkiye. The semi-dry areas remain roughly the same during the period. On the other hand, humid conditions are projected to decrease by –4.2%, –9.8% and –10.6% under SSP1-2.6, SSP3-7.0 and SSP5-8.5 according to the reference period, especially in the Marmara and Eastern Anatolia regions for mid-century (Figure 4).

The greatest spatial change in the Pinna index category represents the humid and dry conditions at the end of the century. The SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios show an increase in dry areas to 3.8%, 15.8% and 15.0%, according to the reference period in Türkiye. The areas with humid climate types decrease during this period, leaving only the northern coast and some of Eastern Anatolia's highlands. Concerning future projections, the CMIP6 models used to predict that the extent of aridity has increased from the first period to the last period, according to the PCI.

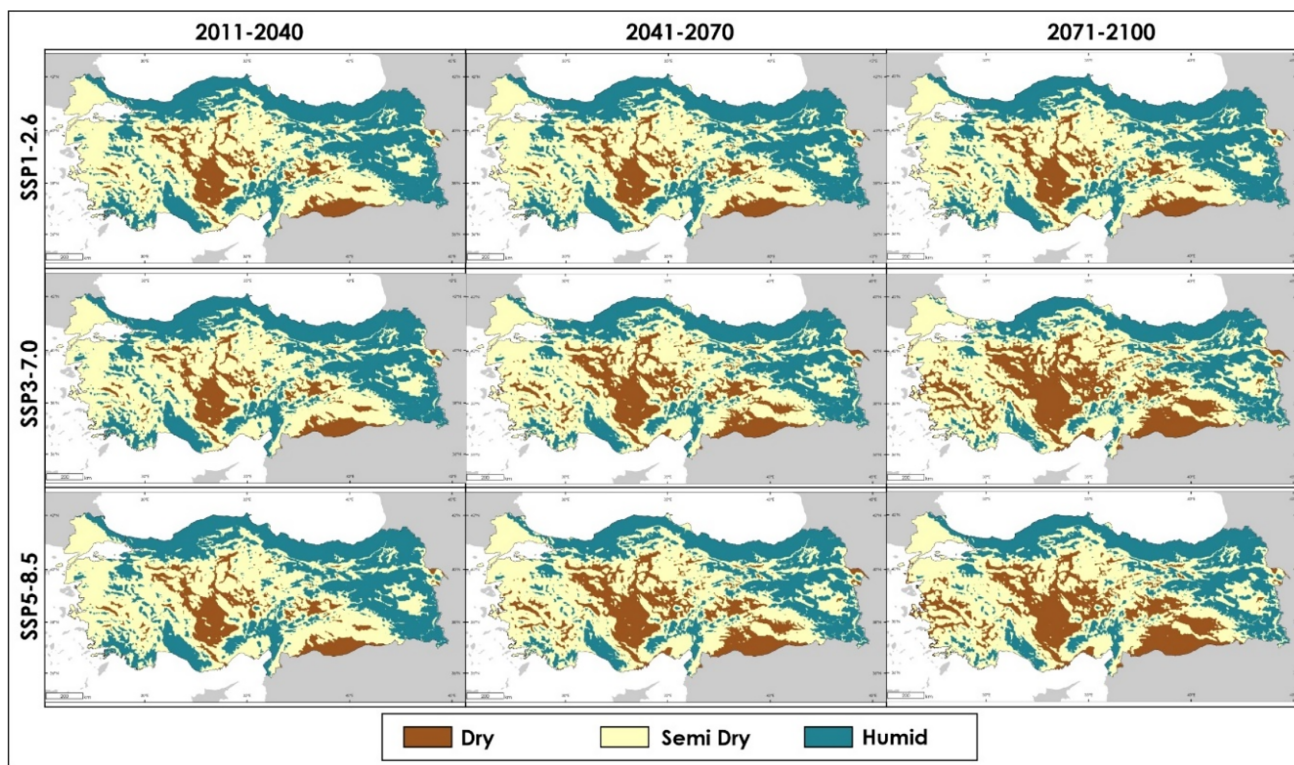
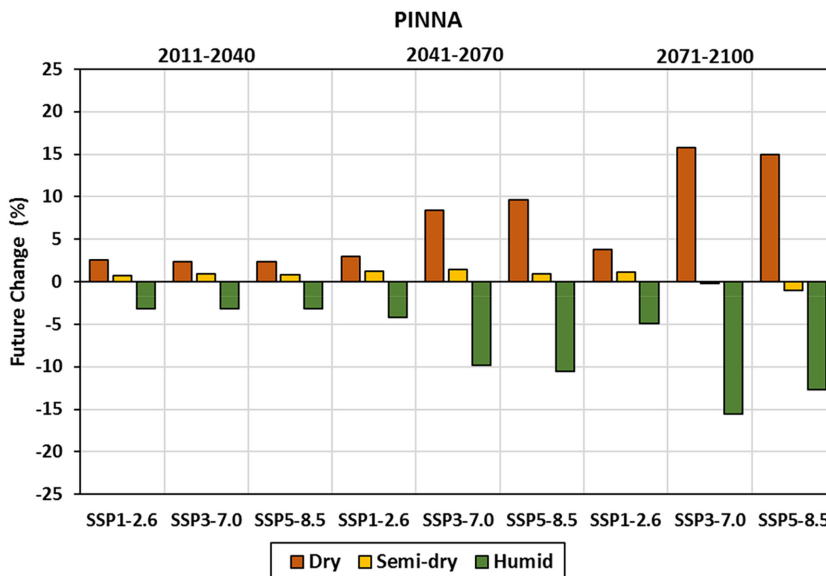
### 3.2 | Projected changes in Erinç aridity index

The spatial patterns for EAI in 1981–2010 show a prevalence of semi-humid conditions (in more than 36% of the territory) in most of the Aegean, Central Anatolia and Southeast Anatolia regions. On the other hand, humid and per-humid climatic conditions cover a large area (21% and 34%, respectively), especially in the Eastern Black Sea Region, the eastern part of Anatolia, and the Eastern Taurus Mountains of the Mediterranean. Semi-arid areas, with a covering percentage of 8%, are mostly dominant in the Central Anatolia region, the Southeast Anatolia region, and the easternmost part of the East Anatolia region. The arid climate type also covers a minimal area (0.3%) and can be observed at the Syrian border of the Southeastern Anatolia region. The severely arid areas cover a negligible part of the country less than 0.04%. These areas are located at the highest peaks of the mountainous regions (Figure 5).

According to the EAI, the outputs of all three models for the next three periods show a great deal of similarity (Table 4; Figures S7–S12). Considering the EAI, the land of Türkiye is projected to face an increase in semi-arid areas and a decrease in per-humid areas over time with a multi-model agreement according to the reference period.

The CMIP6 models comply with EAI results, and there is no significant change in the 2011–2040 period for EAI classification. For the 2071–2040 period, negative values are projected for per-humid areas, with values ranging from 6.8% under SSP1-2.6, 11.4% under SSP3-7.0 and 12.7% under SSP5-8.5. However, relative to the reference

**FIGURE 3** Changes in Pinna combinative index (PCI) according to reference period of multi-model mean CMIP6 models projected future for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]



**FIGURE 4** Projected spatial changes in Pinna combinative index 2011–2040, 2041–2071, 2071–2100 versus 1981–2010 in the SSP1-2.6, SSP3-7.0, SSP5-8.5 according to the multi-model mean of CMIP6 models. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

period, projections point out a progressive decrease in the areas characterized by humid and per-humid conditions as well as a shift in the climate class from semi-humid towards semi-arid by the end of the century. For example, projections for the end of the century indicate that semi-arid areas will increase by 4.8%, 15.0% and 18.2% for the best, medium and worst-case scenarios, respectively, according to the reference period (Figure 6).

The most remarkable area-wide change will be observed in the arid and semi-humid index values for the end of the century, according to the EIA Index. Semi-humid areas will likely decrease compared with the reference period. For example, some parts of the Black Sea region are not even classified as humid or per-humid in this period. The only humid and per-humid areas are on the Northern Coast and in the Eastern Anatolia highlands (Figure 7).

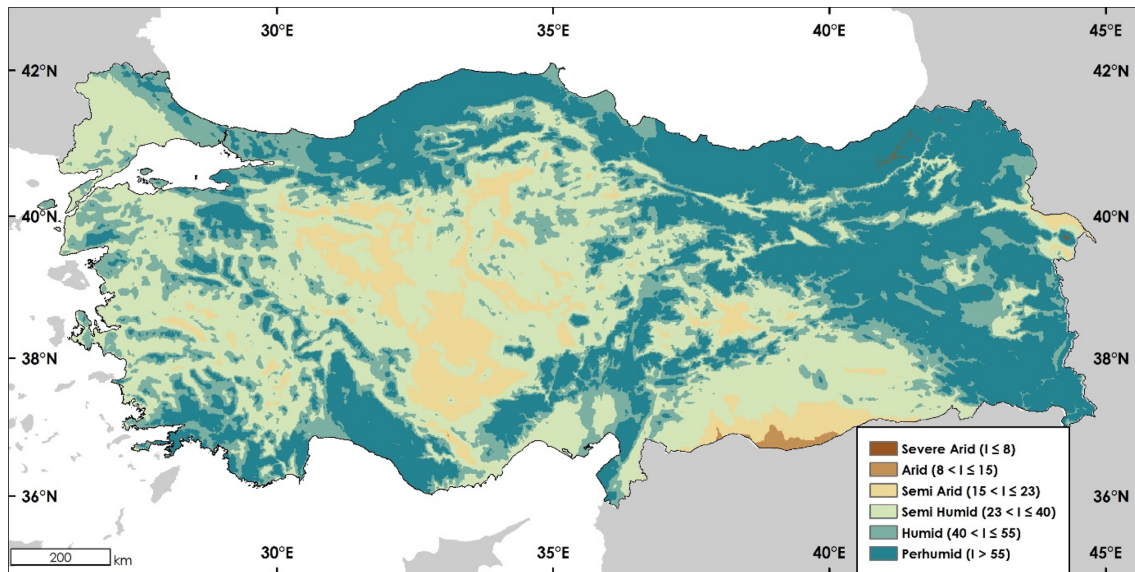
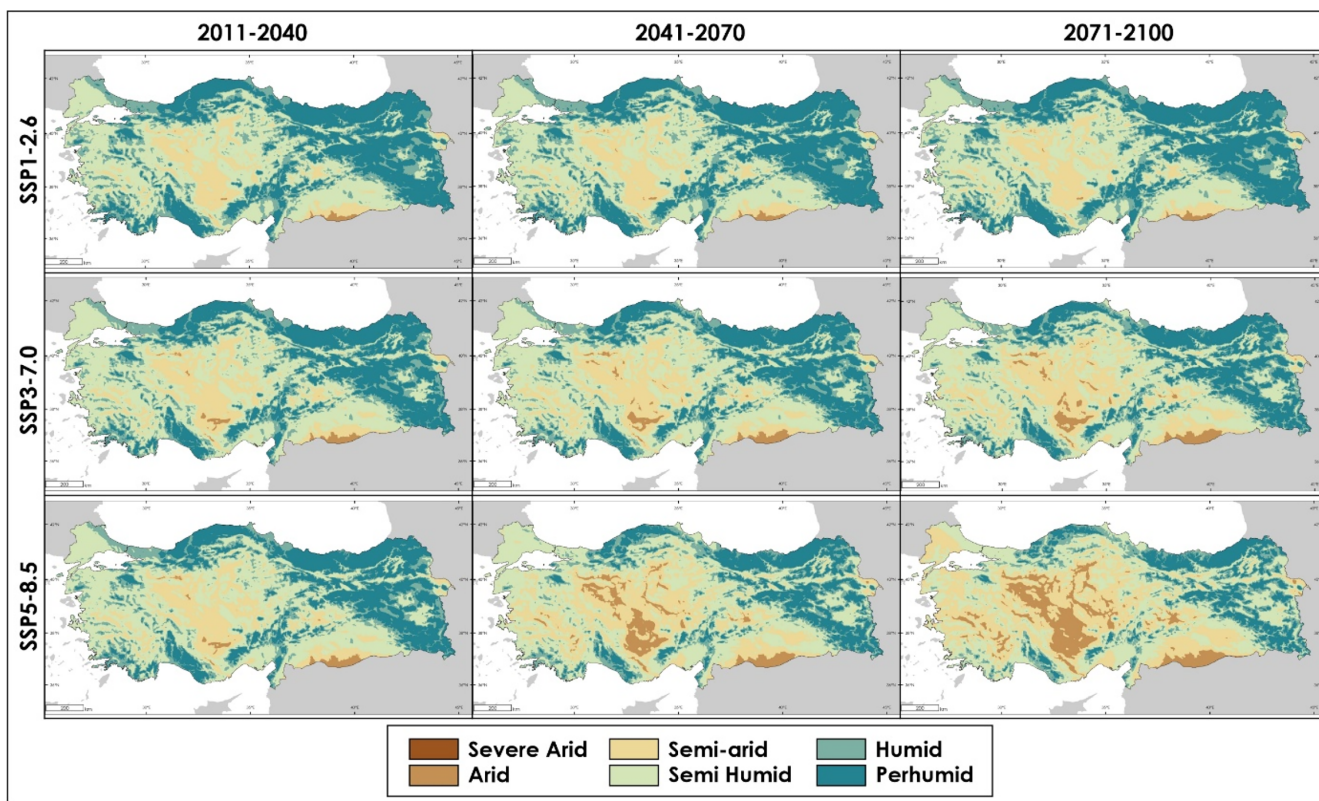
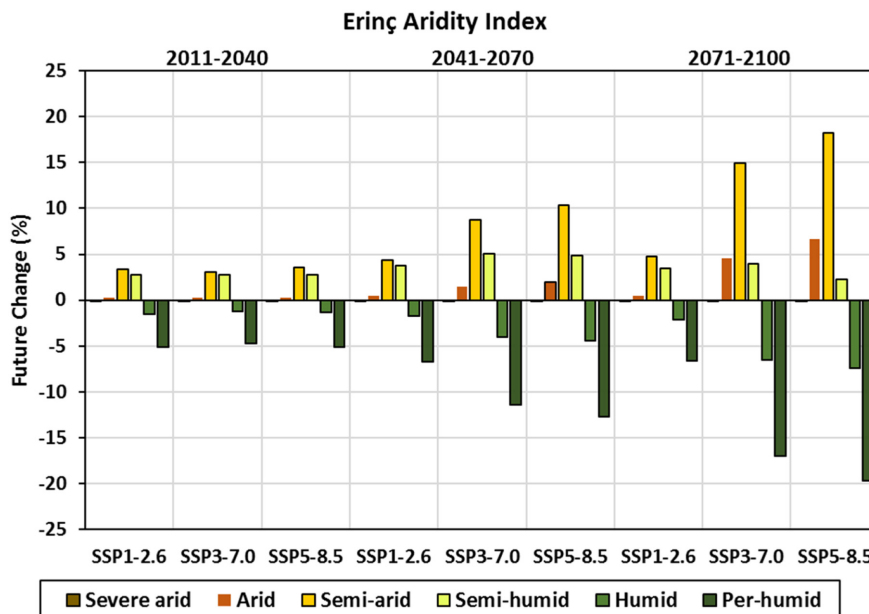


FIGURE 5 Spatial distribution of Erinç aridity index in the Türkiye for the reference period (1981–2010). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

TABLE 4 Percentage of the territory for the Erinç aridity index (EAI) for projected futures for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5.

Erinç index	Reference period	SSP1-2.6			SSP3-7.0			SSP5-8.5		
		GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR
2011–2040										
Severe arid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arid	0.3	0.6	0.7	0.4	0.8	0.4	0.5	0.6	0.5	0.5
Semi-arid	8.2	11.9	13.3	10.3	12.1	10.6	11.1	11.9	12.3	11.0
Semi humid	36.4	39.2	40.2	38.2	39.4	39.0	39.0	38.6	40.1	38.7
Humid	21.1	19.7	19.0	19.9	19.8	20.6	19.3	20.1	19.2	19.7
Per-humid	34.0	28.6	26.8	31.2	27.9	29.4	30.1	28.8	27.9	30.1
2041–2070										
Severe arid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arid	0.3	0.7	0.5	1.0	2.2	1.2	1.8	2.0	2.1	2.7
Semi-arid	8.2	13.1	10.9	13.6	18.8	15.8	16.8	18.3	17.8	19.6
Semi humid	36.4	39.6	40.3	40.7	41.2	42.0	41.2	41.0	41.5	41.3
Humid	21.1	19.7	19.9	18.2	16.6	17.8	16.9	16.9	17.2	15.8
Per-humid	34.0	26.9	28.4	26.5	21.2	23.2	23.3	21.8	21.4	20.6
2071–2100										
Severe arid	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arid	0.3	0.7	0.7	1.1	3.8	5.5	5.3	5.5	5.9	9.7
Semi-arid	8.2	12.6	11.6	14.7	22.0	24.7	22.8	24.6	25.4	29.2
Semi humid	36.4	39.2	39.5	40.8	41.0	39.7	40.3	40.4	39.7	35.9
Humid	21.1	19.6	19.3	18.0	15.3	14.0	14.4	14.2	14.0	12.7
Per-humid	34.0	27.9	28.9	25.4	17.9	16.1	17.2	15.3	15.0	12.5

**FIGURE 6** Changes in Erinċ aridity index according to reference period of multi-model mean CMIP6 models for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 7** Projected spatial changes in Erinċ aridity index 2011–2040, 2041–2071, 2071–2100 versus 1981–2010 in the SSP1-2.6, SSP3-7.0, SSP5-8.5 according to the multi-model mean of three models. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

### 3.3 | Projected changes in UNEP AI

According to the UNEP aridity index results, sub-humid and humid climate types are calculated at 34% and 47%, respectively, according to the reference period. Dry, sub-humid areas cover 13% of the total area, usually surrounding the semi-arid areas and

extending throughout most of the Continental Central Anatolia and Southeastern Anatolia regions, some parts of the eastern Mediterranean, and the eastern and western parts of the Continental Eastern Anatolia region. Semi-arid areas cover 6% of the country and are found only in the Konya Plain in Central Anatolia and the Iğdir district of the Eastern Anatolia region.

According to the UNEP aridity index, there are no arid or hyper-arid areas in Türkiye (Figure 8).

The future outputs of the three CMIP6 global climate models predict that the areas in the UNEP AI will change at very similar rates. According to the SSP5-8.5 scenario, semi-arid areas appear 10% more frequently in IPSL-CM6A-LR model outputs in the last quarter of the

century than in the other two model outputs (Table 5; Figures S13–S18). Results suggest significant shifts towards more semi-arid areas in Türkiye for three warming scenarios.

Examining the models for the 2011–2040 period, there is a slight increase in semi-arid and dry sub-humid areas, whereas sub-humid areas almost remain the same

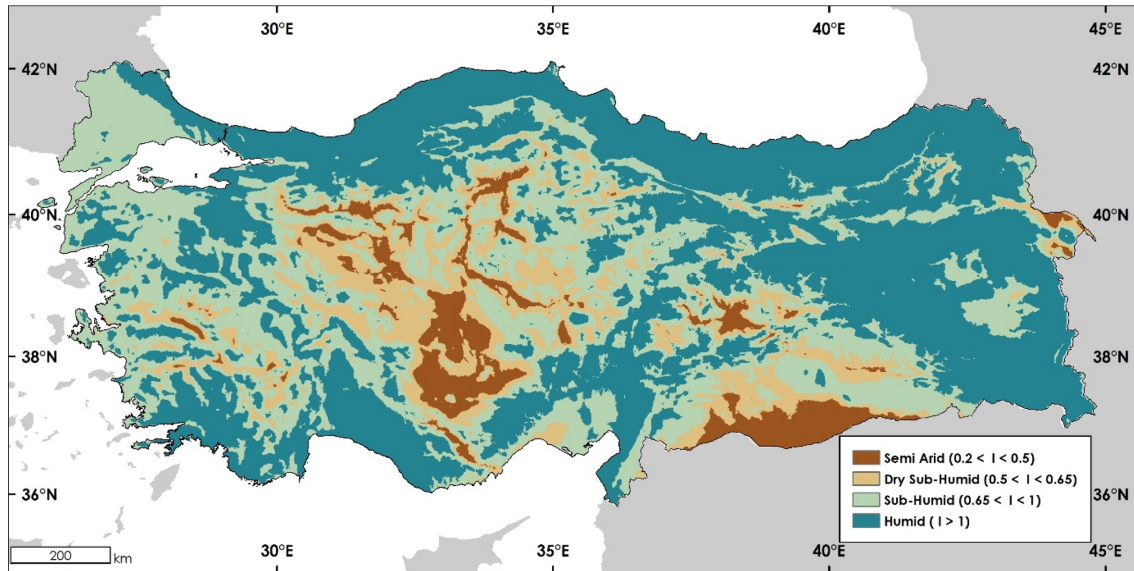


FIGURE 8 Spatial distribution of UNEP aridity index in the Türkiye for the reference period (1981–2010). [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

TABLE 5 Percentage of the territory for the UNEP Aridity Index for projected futures for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5.

UNEP aridity index	Reference period	SSP1-2.6			SSP3-7.0			SSP5-8.5		
		GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR	GFDL-ESM4	MRI-ESM2-0	IPSL-CM6A-LR
2011–2040										
Semi-arid	5.9	9.8	10.9	8.2	9.1	8.4	9.1	9.5	10.0	9.0
Dry sub-humid	12.7	14.7	15.5	14.0	15.0	14.2	15.0	14.4	15.6	14.6
Sub-humid	34.4	34.0	34.1	34.1	34.2	34.5	34.2	33.8	34.2	34.1
Humid	47.0	41.5	39.5	43.7	41.7	42.9	41.7	42.3	40.2	42.3
2041–2070										
Semi-arid	5.9	10.6	8.8	12.1	19.5	14.3	16.7	18.7	17.5	20.8
Dry sub-humid	12.7	15.0	14.8	16.8	19.3	18.1	19.0	18.7	18.1	20.0
Sub-humid	34.4	34.0	34.2	33.2	30.7	32.6	31.0	30.7	31.2	28.9
Humid	47.0	40.4	42.2	37.9	30.5	35.0	33.3	31.9	33.2	30.3
2071–2100										
Semi-arid	5.9	10.3	9.9	13.1	25.8	28.3	29.6	30.8	31.4	43.1
Dry sub-humid	12.7	14.7	15.3	17.0	20.2	19.8	19.5	19.6	19.0	16.1
Sub-humid	34.4	33.7	33.9	33.2	27.6	26.1	25.2	25.6	25.0	20.7
Humid	47.0	41.3	40.9	36.7	26.4	25.8	25.7	24.0	24.6	20.1

in all scenarios. The change in the 2011–2040 period also continues incrementally in the 2041–2071 period. Sub-humid and humid areas decrease, whereas semi-arid and dry sub-humid areas expand. For example, an increase in semi-arid types is projected for 2041–2070, rising to 4.6%, 10.9% and 13.1% under SSP1-2.6, SSP3-7.0 and SSP5-8.5.

By the end of the century, the extent of the current humid climate zone is projected to shrink by 24% under SSP5-8.5 (Figure 9).

The most dramatic changes are expected in semi-arid areas in the SSP3-7.0 and SSP5-8.5 scenarios in the 2071–2100 period, which cover almost all of the Aegean,

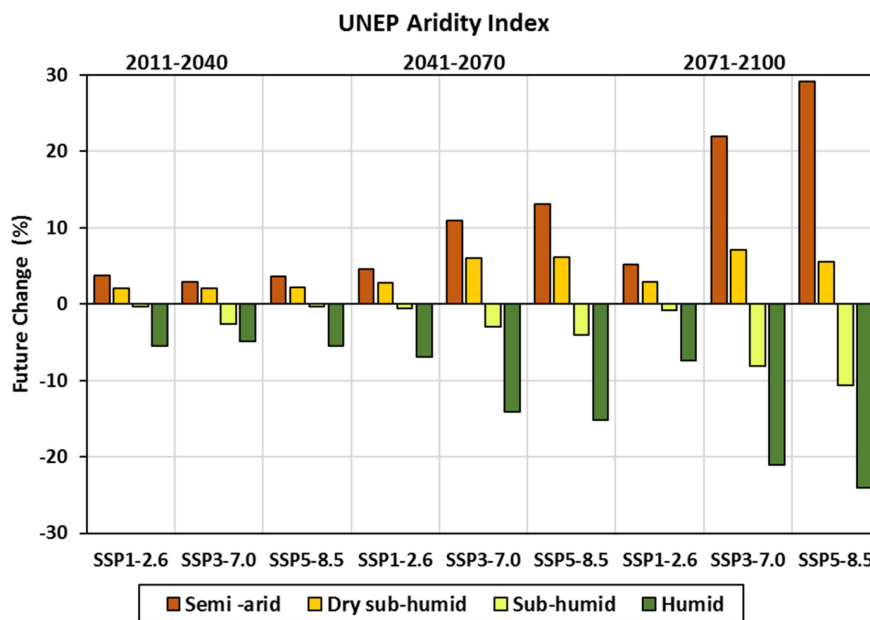


FIGURE 9 Changes in UNEP AI according to the reference period of multi-model mean CMIP6 models for 2011–2040, 2041–2070 and 2071–2100 under SSP1-2.6, SSP3-7.0 and SSP5-8.5. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

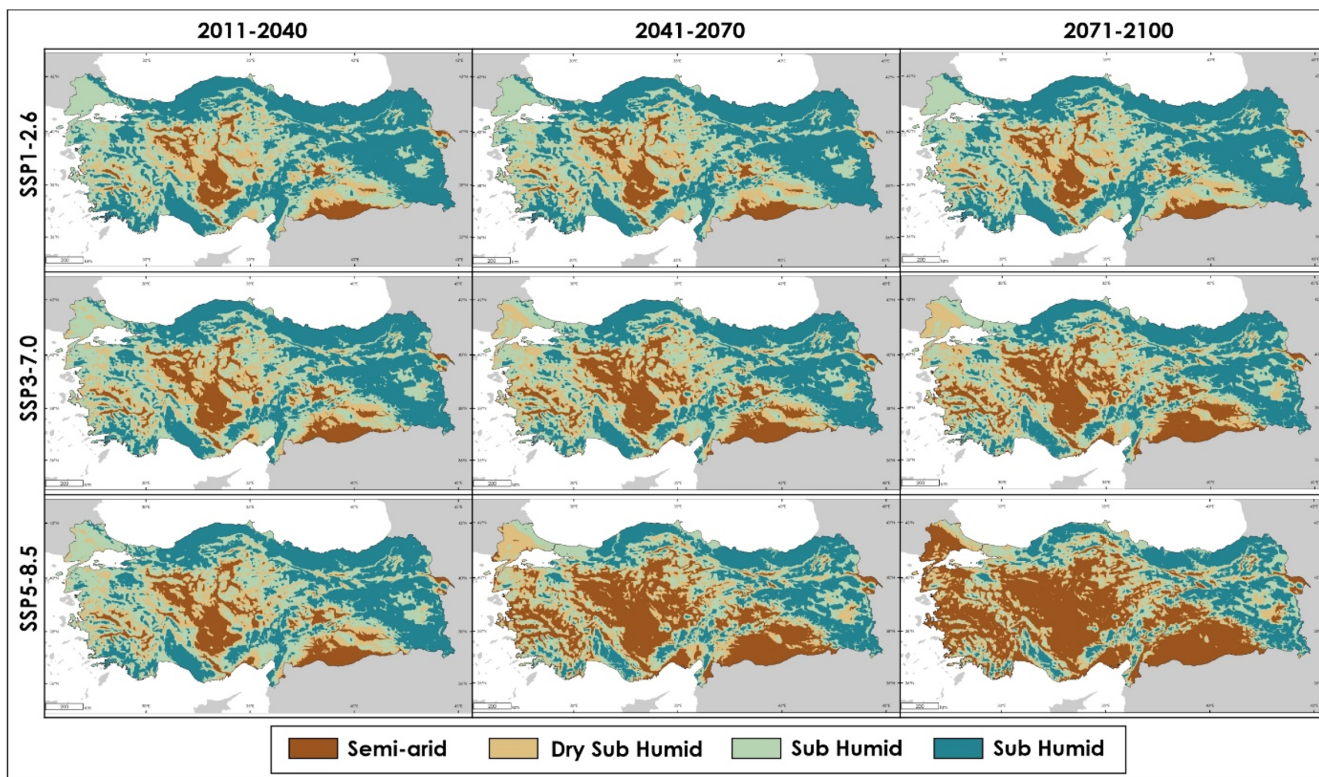


FIGURE 10 Projected spatial changes in UNEP aridity index 2011–2040, 2041–2071, 2071–2100 versus 1981–2010 in the SSP1-2.6, SSP3-7.0, SSP5-8.5 according to the multi-model mean of three models. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Central Anatolia and Southeast Anatolia regions, as well as some parts of the Marmara and Eastern Mediterranean regions (Figure 10).

## 4 | CONCLUSIONS

In this study, we looked at the future of three aridity indices (PCI, EAI and UNEP AI) for three different periods: 2011–2040, 2041–2070 and 2071–2100, in comparison to the baseline period 1981–2010. The models were performed under SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios.

Three aridity indices present a similar trend, suggesting that the area of sub-humid and humid climate conditions will regularly decrease, and the area of arid and semi-arid conditions will increase during the three future sub-periods in Türkiye due to the anthropogenic climate change. Areas with humid conditions in Türkiye during the reference period constitute approximately 45%–55% of the surface area according to the three aridity classifications. The area of the per-humid zone according to the EAI (humid for UNEP AI) by the last quarter of this century (2071–2100) will be approximately 11% (14%) less than that which was observed for the 1981–2010 period under the SSP3-7.0. On the other hand, areas with semi-arid conditions in Türkiye during the reference period constitute approximately 6%–8% of the country's surface area according to the three drought classifications. However, compared to the reference period, the area of the semi-arid zone, according to the EAI (UNEP AI), will increase by just 15% (22%) from 2071 to 2100 under the SSP3-7.0.

By examining the aridity indices where the most critical change will be observed in the future according to the three drought indices, it can be noticed that the dry areas will change in the PCI and UNEP AI, and the humid areas will change in the EAI. In the PCI, the most significant change between index classes in the future will be observed in arid areas in the 2071–2100 period, according to SSP3-7.0 and SSP5-8.5. According to the reference period, dry areas will increase by approximately 8% under the SSP3-7.0 scenario and by 16% under the SSP5-8.5 scenario by the end of this century. In EAI, the most significant change between index classes in the future will be observed in per-humid areas between 2071 and 2100 under SSP3-7.0 and SSP5-8.5 with respect to the reference period of 1981–2010. Per-humid areas will decrease by 17% under SSP3-7.0 and by 20% under SSP5-8.5 in the 2071–2100 period compared with the reference period. According to the UNEP AI, the most significant change among the index classes in the future will be observed in semi-arid areas in the 2071–2100 period under the SSP3-7.0 and SSP5-8.5 scenarios. Compared to the

reference period, semi-arid areas will expand by 22% under SSP3-7.0 and by 29% under SSP5-8.5.

Despite some differences between the three aridity indices, the most notable increases in aridity or dry conditions will be observed towards the middle of the century (2041–2070) in Central Anatolia, Southeastern Anatolia and some parts of the Eastern Mediterranean, as well as the eastern parts of Eastern Anatolia and the inner part of the Aegean region that are dominated by dry sub-humid or semi-humid climatic conditions today. By the end of the century (2071–2100), according to the three aridity indexes, semi-arid and arid areas will be widespread, covering more than 30% of the country under the SSP3-7.0 scenario. These results for Türkiye are coherent with the predictions regarding the future changes in drought indices in the Mediterranean Basin.

In the future, the Mediterranean region, in which Türkiye is located, is projected to be more exposed to the risk of aridity than any other land region on Earth. The warming trends above the world average, reduced precipitation and increased potential evapotranspiration can be cited as the climatic drivers of increased aridity (Barredo et al., 2019; Barcikowska et al., 2020; Tuel & Eltahir, 2020; Bağçacı et al., 2021). Due to local feedback mechanisms that accelerate temperature changes, the Mediterranean region's temperature is rising faster than the global average. Annual mean air temperatures over land and sea in the Mediterranean Basin have risen by 1.54°C from 1860–1890 to the present, nearly 20% above the global average, according to observational analyses (Lionello & Scarascia, 2018). In Türkiye, the annual mean temperature shows a significant increase trend (0.88°C/century) in all regions, especially since 1993. The warming trends reached 0.91°C/decade over entire Türkiye for the years 2001–2020 (Hadi & Tombul, 2018; Yilmaz, 2023). On the other hand, drought frequency and intensity have increased since the 1970s over the Mediterranean Basin (Caloiero et al., 2018), and climate simulations project a decrease in precipitation of about 20%–40% by the end of the 21st century relative to the reference period of 1986–2005. On the other hand, PET increases ~15% and ~30% for the 2081–2100 period under the RCP4.5 and RCP8.5 scenarios, respectively over nearly the whole Mediterranean (Carvalho et al., 2022). In Türkiye, the most notable countrywide precipitation decrease is expected in summer (autumn) with SSP2-4.5 (SSP5-8.5) in the long term. For spring and winter precipitation in the long term, similar anomaly patterns are expected in both scenarios. On the other hand, winter precipitation increase in the Black Sea Region would become significant according to CMIP5 and CMIP6 models (Bağçacı et al., 2021). Widespread drying across the Mediterranean region is explained by a

poleward shift of the subtropics and Hadley circulation over the last 30–40 years. This causes a gradual northward shift of the winter jet over the North Atlantic and midlatitude storm tracks, leading to a northward transport of air moisture away from the Mediterranean (Birner et al., 2014; Lucas et al., 2014; Staten et al., 2018; Watt-Meyer et al., 2019). Another driver of the increasing aridity is the dwindling snow cover due to the reduction in the snowfall ratio and earlier spring snowmelt in Türkiye. Concerning basins influenced by snow, several studies report a general decrease in snow amounts and increasing snowmelt for Türkiye, implying a contribution that could influence changes in drought indices in the future (Özgür & Koçak, 2019; Sönmez et al., 2014; Yılmaz et al., 2019). For instance, results from multiple remote sensing products showed a strong relationship between significant water loss and snow cover decline between 2002 and 2018 in the Euphrates-Dicle, Kura-Aras, Çoruh and Van basins. The magnitude of significant negative SWE trends for areas above 2000 m ranged from 2.41 to 4.51 mm per year, while snow cover duration was shortened by up to 1 month per decade in all four basins, particularly at higher altitudes (Yılmaz et al., 2019). The model results showed that the snow water equivalent for the Euphrates-Tigris Basins will decrease by 30%–39% until 2099 and the days covered with snow will be shortened by 37–43 days (Peker & Sorman, 2021).

Even in the current climatic conditions, Türkiye is a drought-prone country and considerably vulnerable to desertification processes, especially in semi-arid regions (Türkeş et al., 2020; Yeşilköy & Şaylan, 2022). According to future projections, the arid and semi-arid regions will be severely impacted by serious land degradation and desertification, a decrease in groundwater, damage to vegetation and wetland ecosystems, a loss of biodiversity and food insecurity (Cramer et al., 2018; Gouveia et al., 2017; Keenan et al., 2011). As in other developing nations, Türkiye's water and land resources, particularly in agricultural areas, have already been impacted by fast population growth and industrialization, as well as changes in demand, technology and socio-economic and legal situations (Türkeş, 2003).

In order to address the increasing aridity risk in Türkiye, several recommendations can be made. First, water resource management and planning should incorporate the projected changes in aridity. This can be achieved by updating water resource plans with the consideration of climate model projections to ensure the sustainability of water resources in the face of climate change. Second, implementing water-saving measures and promoting water use efficiency can help alleviate the impact of increasing aridity. This can be done through the development and implementation of policies that encourage

water-saving technologies, water reuse and recycling, as well as the promotion of water-efficient agriculture practices.

Furthermore, investing in research and development of drought-resistant crops and agricultural practices is essential to minimize the adverse effects of aridity on agricultural productivity. This can be achieved by supporting research institutions and programmes focused on developing drought-resistant crops and innovative agricultural practices that can adapt to changing climatic conditions. Finally, strengthening early warning systems and monitoring networks for drought and aridity will help in a timely and effective response to aridity-related challenges. This can be done by enhancing the capacity of meteorological and hydrological services to monitor and forecast drought and aridity, as well as investing in the development of reliable and high-resolution climate models specific to Türkiye and the Mediterranean region.

Despite the comprehensive approach and valuable findings, there are a few limitations to the study. For example, the study only considers aridity indices up to 2100, and the long-term implications of the observed trends are not discussed. Future research could extend the analysis to consider projections beyond 2100. The study relies on existing climate models and projections, which are subject to uncertainty. Further advancements in climate modelling and the incorporation of new data may result in refined or altered projections of future aridity trends in Türkiye. The potential impacts of future socioeconomic changes, such as population growth, urbanization, land-use change and technological advancements, are not explicitly incorporated into the analysis. These factors may interact with climate change to influence aridity trends in Türkiye and should be considered in future studies. The study does not evaluate the effectiveness of various adaptation and mitigation measures to address the projected aridity trends in Türkiye. Future research should focus on evaluating and proposing appropriate strategies to manage the impacts of increasing aridity on water resources, ecosystems, agriculture and human well-being.

In conclusion, this study sheds light on the future aridity trends in Türkiye, emphasizing the need for proactive measures to address increasing aridity risks. The novel contributions of this research lie in the simultaneous examination of multiple aridity indices, evaluation under multiple scenarios and time periods, the regional focus on Türkiye and the comprehensive analysis of future aridity patterns. By better understanding and managing aridity changes, Türkiye can enhance its resilience to climate change, protect water resources, ecosystems and agriculture, and ensure the well-being of its population in the face of growing aridity challenges.

## AUTHOR CONTRIBUTIONS

**Doğukan Doğu Yavaşlı:** Methodology; conceptualization; visualization; writing – review and editing; data curation; formal analysis. **Ecmel Erlat:** Project administration; writing – original draft; supervision.

## CONFLICT OF INTEREST STATEMENT

The authors have no relevant financial or non-financial interests to disclose.

## DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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