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Projected Drought Intensification in the Büyük Menderes Basin Under CMIP6 Climate Scenarios

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Abstract: The amplitude and interval of drought events are expected to enhance in upcoming years resulting from global warming and climate alterations. Understanding future drought events' potential impacts is important for effective regional adaptation and mitigation approaches. The main goal of this research is to study the impacts of climate change on drought in the Büyük Menderes Basin located in the Aegean region of western Türkiye by using the outcomes of three general circulation models (GCMs) from CMIP6 considering two different emission scenarios (SSP2-4.5 and SSP5-8.5). Following a bias correction using a linear scaling method, daily precipitation and temperature projections are used to compute the Standardized Precipitation Evapotranspiration Index (SPEI). The effectiveness of the GCMs in projecting precipitation and temperature is evaluated using observational data from the reference period (1985–2014). Future drought conditions are then assessed based on drought indices for three periods: 2015–2040 (near future), 2041–2070 (mid-term future), and 2071–2100 (late future). Consequently, the number of dry months is projected and expected to elevate, informed by SSP2-4.5 and SSP5-8.5 scenarios, during the late-century timeframe (2071–2100) in comparison to the baseline period (1985–2014). The findings of this study offer an important understanding for crafting adaptation strategies aimed at reducing future drought impacts in the Büyük Menderes Basin in the face of changing climate conditions.



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Keywords: CMIP6; climate change; drought; Türkiye; SPEI

1. Introduction

For several decades, drought has posed a significant global challenge for humanity and all living creatures. An extensive assessment of drought probability in a region is required for the investigation of historical climatic factors like temperature and precipitation. Therefore, the collected data are utilized to produce a variety of parameters for imagining the drought occurrences over time in a region. Evaluation of historical droughts can provide a reliable perspective on future situations. Analyzing the outputs generated by climate models, generally known as General Circulation Models (GCMs), under several emission scenarios can be useful to obtain reliable drought forecasting [1–5].

One of the most common approaches for drought assessment is the use of various drought indices. According to the World Meteorological Organization (WMO), drought indices can be classified into meteorology, soil moisture, hydrology, and remote sensing classes based on the field of study [6]. Accordingly, those indices have been used

in drought assessment studies based on the purpose of this study, available data, and ease in the application of the index [7,8]. On the other hand, a number of studies have focused on the comparison between drought indices in terms of drought monitoring and assessment [9–13]. For instance, in a study conducted by Silva et al. [14], the authors concluded that the Standardized Precipitation Index (SPI) is highly conscious of extreme drought events and can be used for short times, while the Standardized Precipitation Evapotranspiration Index (SPEI) can be applied for long-term drought assessments. The SPEI was first developed by Vicente-Serrano et al. [15] as a multiscale index to represent the effects of global warming.

Extensive research has been conducted to produce drought indices using the output of GCMs. Cook et al. [16] predicted a drought in the 21st century for the entire world and reported that the conclusions from drought studies are influenced by the specific regions, seasons, and drought metrics analyzed. They emphasized the importance of regional climate change studies and drought analysis. Kamruzzaman et al. [17] conducted drought analysis across different regions of Bangladesh using SPEI and illustrated that the northern and western regions of the study area will gradually experience severe droughts until the end of the current century. Polong et al. [18] determined the significant dry and wet event patterns in the Tana River Basin (TRB), Kenya. They applied SPEI and found out that, between 1960 and 2013, droughts were more severe in the lowlands, while wet events increased more in the highlands, but the rising trend of drought frequency was much more significant. In another study conducted by Gao et al. [19], results indicate that drought severity and frequency are projected to increase from 2001 to 2050 when applying SPEI. Research conducted in Korea projected drought events across the near, mid, and distant future up to 2100, highlighting an increased frequency of a moderately arid climate under SSP1-2.6 and SSP8.5 scenarios [20]. It was found that the drought severity index, recorded as 0.97 during the historical period, is anticipated to rise to 1.37 and 1.66 in the respective future scenarios. Hernandez and Uddameri [21] applied SPEI in semi-arid South Texas and revealed trends of increasing drought frequency that strongly correlated with temperature increase and changes in precipitation. Mtilatila et al. [22] performed a study over the largest lake in the Malawi region of Southeast Africa and found that drought intensity is estimated to amplify within the range of 25–50% and 131–388% in the periods of 2021–2050 and 2071–2100, respectively. Liu et al. [23] conducted a study in Sichuan Province in China using SPEI and showed an increasing trend of drought in the region as the result of temperature increase. Jamro et al. [24] investigated drought assessment in Pakistan using the SPEI and reported that the southern regions of the country experienced a significant dry trend while central regions showed a wetting trend and the northern part showed a drought pattern but not significant. Balting et al. [25] examined drought susceptibility in the Northern Hemisphere through CMIP6 analyses and SSP projections. Zeng et al. [26] investigated the circumstances and modeling of future drought occurrences and highlighted intensified drought events in the Mediterranean region.

As outlined previously, global drought predictions have been developed with CMIP6 frameworks, SSP emissions data, and applying SPEI. Research findings commonly point to an escalation in drought intensity in the foreseeable future [27–36]. According to the Intergovernmental Panel on Climate Change (IPCC), the Aegean region, situated within the Mediterranean, is highly susceptible to the impacts of climate change [37]. The Aegean region of Türkiye is considered one of the key regions of the country for its economic, agricultural, and ecological activities. For this reason, extensive forecasting of drought would benefit society by giving an exact point of view and enabling secure politics, which would lead to a sustainable economy following environmental and ecological concerns.

In the present work, we apply the output of three GCMs across SSP2-4.5 and SSP5-8.5 emission scenarios to produce a broadly adopted drought index, SPEI, in the Büyük Menderes Basin across the Aegean area. This study aims to investigate the projected intensification of drought under changing climate conditions to provide insights for policymakers and stakeholders on adaptation strategies to mitigate future drought risks.

2. Methodology

2.1. Study Area

The region under investigation includes the Büyük Menderes Basin in western Türkiye, which is recognized as part of the Aegean Region (Figure 1). The Büyük Menderes Basin covers approximately 25,987 km², accounting for about 3.2% of the country's total surface area. It is one of the most significant basins in Türkiye, playing a crucial role in agriculture, industry, and water resources management. The Büyük Menderes River, one of the longest rivers in western Türkiye, originates in the eastern highlands of Denizli Province and flows westward into the Aegean Sea, which shapes the hydrology and landscape of the region [38].

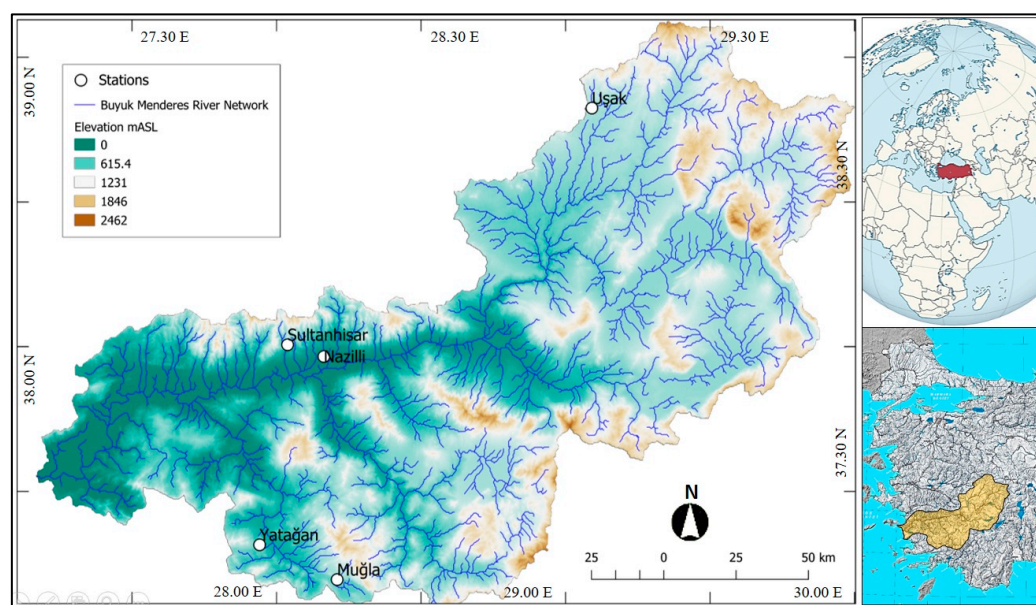


Figure 1. Geographical location of the Büyük Menderes Basin in the Aegean region of Türkiye.

The Büyük Menderes Basin experiences a Mediterranean climate characterized by hot, dry summers and mild, wet winters. The annual mean temperature ranges from 14 °C to 18 °C, with summer temperatures frequently exceeding 35 °C, especially in the lowland areas. Winter temperatures are mild, with average lows of between 2 °C and 10 °C, though frost can occasionally occur in elevated areas. The annual precipitation varies between 500 mm and 1200 mm with most rainfall occurring in the winter months (December and January) and the driest period in July and August. The precipitation pattern is primarily influenced by frontal systems while orographic effects enhance rainfall in the southern and highland areas. According to the Köppen-Geiger climate classification, the Büyük Menderes Basin falls under the 'Csa' category, indicating a hot-summer Mediterranean climate [38,39]. Snowfall is rare in the lower elevations but can be observed in the Denizli and Uşak provinces at higher altitudes [38,40]. The topography of the basin is diverse ranging from rugged highlands in the east to fertile plains in the west. Major physiographic characteristics include [41] the following: Mountain ranges: The basin's eastern section is dominated by high mountain ranges including the Babadağ and Honaz Mountains

with elevations exceeding 2000 m. Lowland plains: The western region consists of broad alluvial plains which provide fertile soil for agriculture. Hydrological system: The Büyük Menderes River and its tributaries serve as the primary hydrological network significantly impacting water availability and agricultural practices. Soils and vegetation: Alluvial and clay-rich soils dominate the lowlands, supporting cotton, olive, and fig cultivation and higher elevations feature forests of pine, oak, and Mediterranean scrub vegetation.

2.2. Data Collection

In this study, two types of data are utilized for assessment. The first dataset comprises temperature and precipitation measurements from 1985 to 2014 for the stations listed in Table 1. The statistical properties of the data are presented in Table 2. These data were obtained from meteorological stations operated by the Turkish State Meteorological Service (MGM). The stations are part of a standardized observation network consisting of automated climatological and synoptic stations that are regularly maintained and calibrated. Figure 1 illustrates the locations of these stations.

Table 1. Geographical features of selected meteorological stations in the Büyük Menderes Basin.

Station	Station No.	Lon/Lat	Altitude	Station Type	Time Resolution	Time Period
Sultanhisar	17493	37.8843° N/ 28.1503° E	73	Automatic Meteorological	Monthly	1985–2014
Uşak	17188	38.6712° N/ 29.4040° E	917	Automatic Meteorological	Monthly	1985–2014
Yatağan	17886	37.3395° N/ 28.1368° E	365	Automatic Meteorological	Monthly	1985–2014
Muğla	17292	37.2095° N/ 28.3668° E	646	Automatic Meteorological	Monthly	1985–2014
Nazilli	17860	37.9135° N/ 28.3436° E	84	Automatic Meteorological	Monthly	1985–2014

Table 2. Statistical features of selected meteorological stations in the Büyük Menderes Basin.

Station	Parameter	Statistics	January	February	March	April	May	June	July	August	September	October	November	December
Sultanhisar	temperature	mean std	7.69 1.55	8.94 1.52	11.63 1.53	15.21 1.36	20.16 1.21	24.80 1.09	27.39 1.14	26.75 1.35	22.80 1.09	17.99 1.36	12.47 1.44	8.86 1.31
	precipitation	mean std	100.57 67.2	83.00 55.5	68.02 38.6	52.35 29.6	30.89 26.4	10.55 13.0	4.82 7.5	4.17 9.2	10.42 20.0	37.95 37.2	83.05 58.7	115.50 66.1
Uşak	temperature	mean std	2.3 1.7	3.5 1.6	6.6 1.6	10.6 1.4	15.3 1.2	19.6 1.2	23.1 1.2	23.1 1.4	18.9 1.1	13.6 1.4	7.9 1.6	4.0 1.4
	precipitation	mean std	67.0 42.5	58.4 37.4	52.6 28.0	58.3 30.8	45.1 30.1	24.6 24.4	16.3 18.8	9.6 10.2	16.8 24.3	44.8 29.2	62.6 39.1	76.0 39.2
Yatağan	temperature	mean std	6.5 1.9	7.7 2.1	10.3 1.8	13.8 1.7	18.6 1.3	23.4 1.0	26.9 1.4	26.5 1.6	22.2 1.4	16.9 1.5	11.4 1.8	7.7 1.5
	precipitation	mean std	112.7 73.1	89.5 55.0	72.0 44.8	49.8 26.7	36.0 28.0	18.3 18.6	9.6 17.5	4.4 8.2	14.5 26.6	42.0 30.9	89.1 53.2	126.8 69.4
Muğla	temperature	mean std	5.2 1.4	6.1 1.6	8.8 1.7	12.4 1.4	17.4 1.4	22.5 1.2	26.0 1.2	25.8 1.4	21.5 1.2	16.0 1.4	10.1 1.4	6.5 1.3
	precipitation	mean std	221.3 141.4	169.8 98.9	116.7 71.0	72.7 41.9	51.1 47.2	23.9 27.5	8.2 13.7	7.4 13.7	16.1 25.4	65.0 51.2	148.6 80.3	240.3 123.4
Nazilli	temperature	mean std	7.2 1.5	8.7 1.5	11.7 1.5	15.4 1.3	20.5 1.2	25.2 1.0	28.0 1.1	27.3 1.4	23.1 1.1	18.0 1.4	12.1 1.4	8.4 1.4
	precipitation	mean std	94.6 66.1	71.4 47.4	64.0 35.6	53.5 29.6	27.9 27.5	15.5 17.8	5.7 11.0	4.4 9.3	9.3 15.6	36.8 30.3	78.2 49.7	110.5 61.1

MGM ensures data reliability through its accredited Calibration Center, which has been operational since 20 April 2010. Sensors for key meteorological parameters, including temperature, relative humidity, atmospheric pressure, wind speed, rainfall amount and

intensity, and global radiation, are routinely calibrated. The Temperature Calibration Laboratory calibrates electronic sensors, liquid-in-glass thermometers, and thermometers with displays within a measurement range of from $-40\text{ }^{\circ}\text{C}$ to $+50\text{ }^{\circ}\text{C}$ using a comparison method.

The meteorological stations used in this study typically operate automated and manual sensors that adhere to MGM calibration standards. Although specific sensor models, resolutions, and data collection intervals were not explicitly provided for the stations in this study, MGM stations generally record the following:

- Temperature measurements with a resolution of approximately $0.1\text{ }^{\circ}\text{C}$.
- Precipitation measurements with an estimated resolution of 0.2 mm .
- Data collection intervals at hourly and daily time steps.

The second dataset consists of General Circulation Model (GCM) outputs for the reference timeframe (1985–2014) and the projected period (2015–2100). The models used in this research are listed in Table 3.

Table 3. List of General Circulation Models (GCMs) used in this study.

Model	AWI-CM-1-1-MR (Germany)	NorESM2-MM (Norway)	EC-Earth3-CC (Europe)
Organization	Alfred Wegener Institute Helmholtz Center for Polar and Marine Research	NorESM Climate Modeling Consortium	Euro-Mediterranean Climate Change Center
Resolution (lon $\times$ lat)	0.937×0.935	1.25×0.942	0.703×0.701
Simulations used	Historical, SSP2-4.5, SSP5-8.5	Historical, SSP2-4.5, SSP5-8.5	Historical, SSP2-4.5, SSP5-8.5
References	(Semmler et al. [42])	(Seland et al. [43])	(Döscher et al. [44])

2.3. GCMs Outputs

This study employs outputs from three GCMs, namely, AWI-CM-1-1-MR (Germany), NorESM2-MM (Norway), and EC-Earth3-CC (Europe) to analyze historical and future drought conditions in the Büyük Menderes Basin under two climate scenarios (SSP2-4.5 and SSP5-8.5). The models were selected based on their performance in simulating climate variables over the study region. The historical period (1985–2014) was used as a reference for calibration, while projections were analyzed for 2015–2100.

The initial step involved extracting precipitation and temperature data from the GCMs for both historical and projected periods. Since the raw GCM outputs are gridded and differ in spatial resolution, they were downscaled using the Inverse Distance Weighted (IDW) method to match the locations of meteorological stations, ensuring improved spatial coherence [45]. To correct inherent biases in GCM simulations, a linear scaling method was applied [46]. This statistical bias correction technique adjusts model-simulated precipitation and temperature by computing a correction factor derived from the ratio of observed and modeled monthly mean values over the reference period (1985–2014). It ensures that the corrected model projections align more closely with observed historical records.

Following bias correction, the effectiveness of the GCMs in representing historical climate conditions was evaluated. This assessment involved statistical and graphical comparisons between observed data and bias-corrected GCM outputs for the reference period. The goal was to determine the extent to which each model captures temperature and precipitation trends to allow for a better understanding of their reliability in future climate projections. After bias correction and validation, the SPEI was computed using the adjusted precipitation and temperature data. By implementing interpolation, bias correction, and validation using statistical indicators, a robust methodological framework for projecting future drought trends in the Büyük Menderes Basin has been conducted.

2.4. Standardized Precipitation and Evapotranspiration Index (SPEI)

The Standardized Precipitation and Evapotranspiration Index (SPEI) assesses drought severity. The water balance is calculated by fitting a continuous probability distribution to time series data, ensuring the resulting index aligns with a standard normal distribution. Selecting an appropriate distribution is crucial, as an unsuitable choice can result in inaccurate values and negatively impact the interpretation of SPEI results [47]. SPEI is applied to evaluate the outcomes of drought events on water accessibility and can be assessed across various timeframes, ranging from 1 to 24 months [20]. Uncertainty in SPEI calculations arises from factors such as the choice of distribution and observation, which can significantly affect the results [48]. This SPEI can be determined as follows:

$$\text{SPEI} = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} \quad (1)$$

$$W = \sqrt{-2\ln(P)} \text{ for } P \leq 0.5 \quad (2)$$

in which P represents the probability of exceeding a specified measure of D . If $P > 0.5$, thereafter, P is superseded by $1 - P$, and the resulting SPEI sign is flipped. In this calculation, the constants are $C_0 = 2.515517$, $C_1 = 0.802853$, $C_2 = 0.010328$, $d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$ [15].

Generally, there are limitations across drought indices, such as regional variability, data availability, and uncertainty in climate change projections. However, among all indices, SPEI has significant advantages, making it an excellent choice for long-term drought analysis in the context of climate change, which is shifting precipitation patterns. These advantages have led to its widespread use in drought analysis [15]. The SPEI integrates potential evapotranspiration (PET) that makes it more responsive to warming trends and climate change effects. By including temperature-driven PET, SPEI captures the increasing role of temperature-induced drought stress, which is crucial for regions experiencing rising heat extremes. Furthermore, SPEI is effective in arid, semi-arid, and humid climates that offer a more globally applicable drought index. SPEI can be calculated at various timescales (e.g., from months to years) for effective assessment of meteorological, agricultural, and hydrological droughts in a single framework.

2.5. Appropriate Timeframe for the Drought Analysis

To compute the SPEI, both precipitation and temperature data are required [15]. The index can be calculated for various timeframes, including 1, 3, 6, 9, 12, 24, and 36 months, depending on the focus of the analysis. The selection of an appropriate timescale is crucial, as it determines how drought conditions are represented for different sectors, such as meteorology, agriculture, and hydrology. For this study, a 6-month timescale was chosen based on the precipitation patterns and water availability concerns in the Büyük Menderes Basin. The region experiences distinct dry and wet seasons, with peak precipitation occurring in winter and spring, while the summer months are notably dry. Given that drought impacts on agriculture and water resources typically manifest over several months, a 6-month SPEI provides a balanced representation of drought variability, capturing both short-term fluctuations and longer-term trends. Additionally, the region's agricultural economy relies on crops such as seedless raisins, figs, olives, citrus fruits, cotton, and tobacco, which have different sensitivity levels to drought [49]. The 6-month timescale aligns well with seasonal agricultural cycles, which allows for a more practical assessment of drought impacts on crop production and water resource management. In conclusion, selecting a 6-month timeframe ensures that this study effectively captures both seasonal water availability and agricultural vulnerability.

3. Results and Discussions

3.1. GCMs' Performance Assessment

Figure 2 shows the boxplot of the monthly precipitation of observed and simulated values during the reference period (1985–2014). The ensemble means of the GCMs were used as simulated values. The comparison between the observed and simulated graphs shows an underestimation in precipitation simulations. Considering the high level of uncertainty in the simulation of precipitation, the performance of the models can be categorized as relatively fair. On the other hand, there is a high confidence in temperature simulations, as shown in Figure 2. In general, the effectiveness of the GCMs in capturing precipitation and temperature simulations is at an acceptable level and future projections are applicable to climate change impact assessments considering the likelihood level. Also, studies, such as that of Cook et al. [16], reported that CMIP6 models exhibit systematic underestimation of precipitation but higher accuracy in temperature projections.

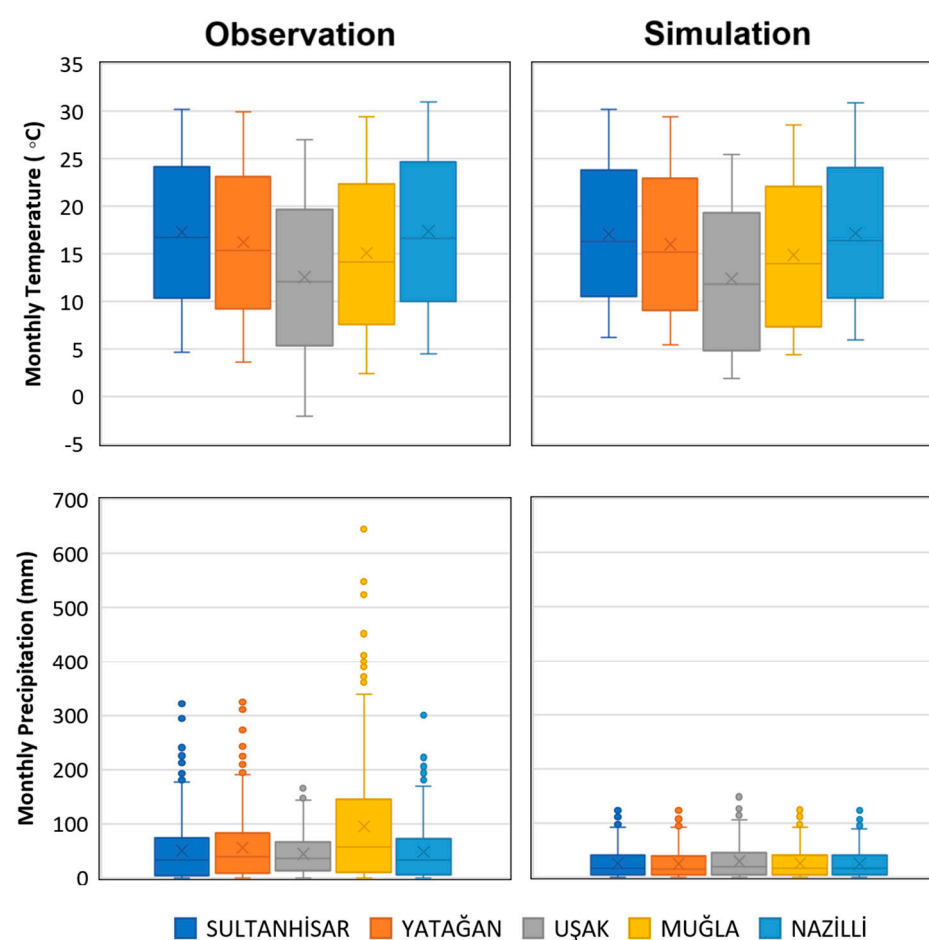


Figure 2. Boxplot for comparison of observed and simulated monthly temperature and precipitation (1985–2014) for the Büyük Menderes Basin Using CMIP6 GCMs.

The monthly mean temperature and precipitation for the reference period, determined using observed and simulated data, together with the projected values for the near future (2015–2040), mid-term future (2041–2070), and late future (2071–2100), are presented in Figures 3 and 4, respectively. The climate condition of the basin, which can be categorized as a Mediterranean climate [50], is reflected in the graphs, where hot and dry summers and wet and cold winters are perfectly represented. For the reference period, there are some biases between observed and simulated temperature, especially for Yatağan Station. Additionally, for the future period, no high-temperature difference is projected, except for

a slight increase in monthly temperature during the late future under the SSP5-8.5 scenario. In the case of precipitation, in contrast with temperature, the biases between observed and simulated values during the reference period are more significant. An underestimation of precipitation can be interpreted from the graphs. This underestimation is bolder for higher precipitation amounts (Nazilli station in this case). This status can be speculated as the complexity of the climate and topography of the region, which can affect the quality of the simulation [51]. Considering the biases between observations and simulations, high confidence and low confidence can be regarded for temperature and precipitation projections, respectively, according to the IPCC's guidelines [51]. However, considering the higher level of uncertainties in precipitation simulations, by taking the likelihood of occurrence into account, there will be no noticeable change in the future precipitation for all periods and under both scenarios.

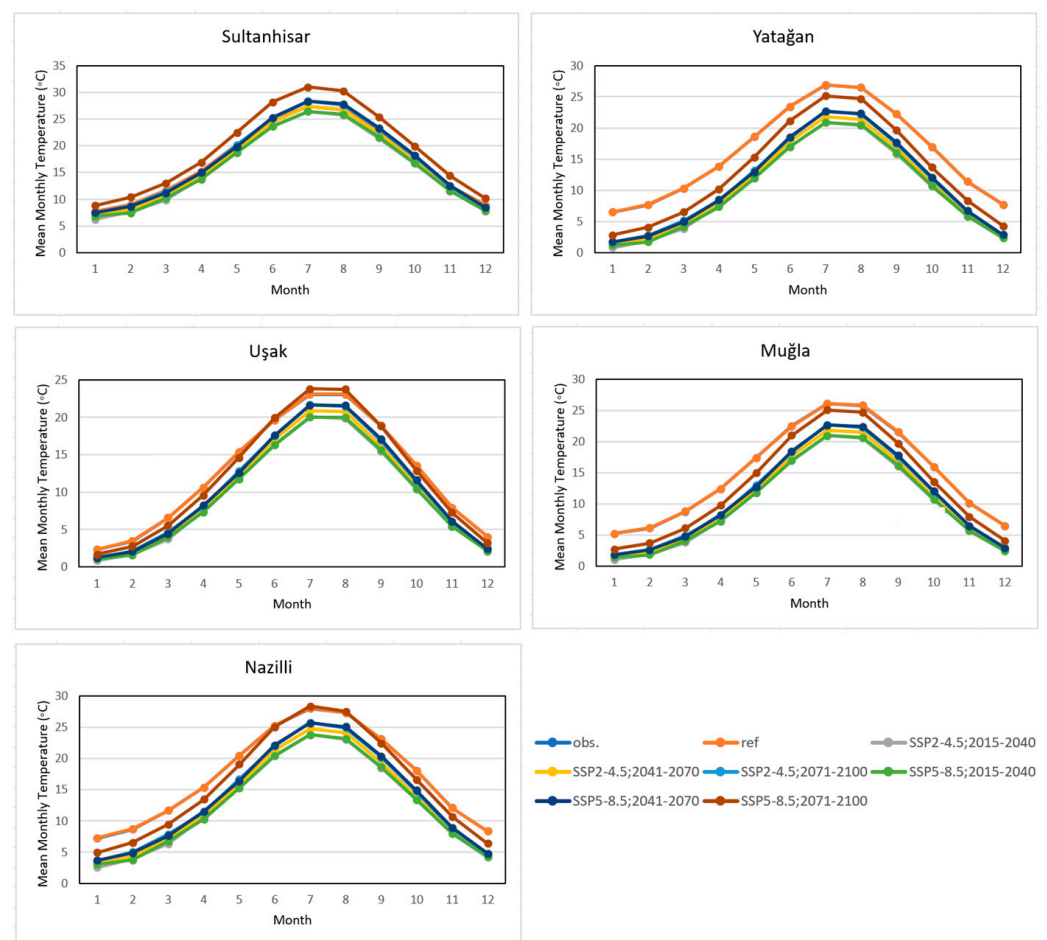


Figure 3. Monthly average temperature for observed and simulated data (1985–2014), and projected values under SSP2-4.5 and SSP5-8.5 during the near future, mid-term future, and late future.

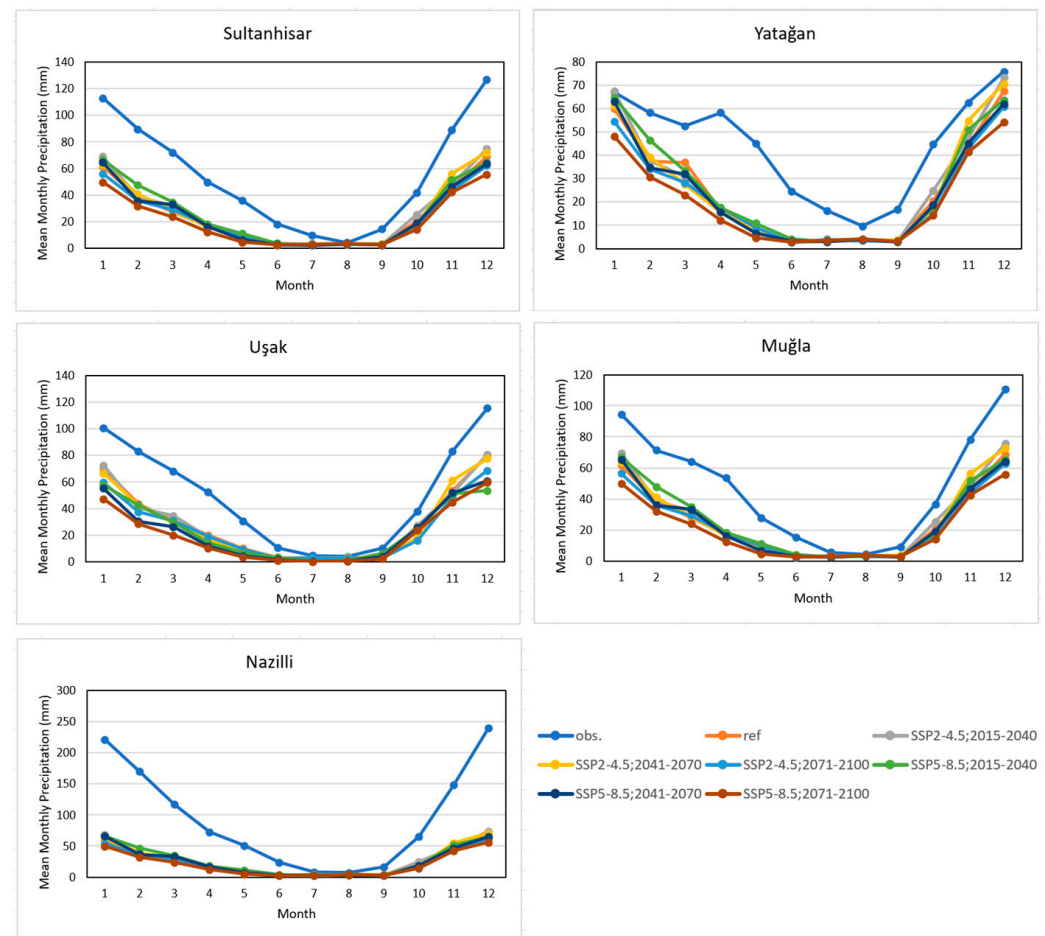


Figure 4. Monthly average precipitation for observed and simulated data (1985–2014), and projected values under SSP2-4.5 and SSP5-8.5 during the near future, mid-term future, and late future.

3.2. Future Drought Assessments

SPEI values were employed to project drought over the Büyük Menderes basin. The assessment of the drought was based on the categorization of each month depending on the value of SPEI, where values between -1 and -1.5 are considered moderately dry, between -1.5 and -2 as severely dry, and less than -2 as extremely dry. Table 4 reveals the number of dry months for each station within the reference period and three subsequent future periods. As can be seen from Table 4, in all stations in both scenarios and all three climate models, an increasing trend is seen in the number of dry months so that the number of dry months between the years (2015–2040) is low and even less than the reference years. However, by entering the time period (2041–2070), the number of dry months increases and in the time period (2071–2100) this number reaches its peak in all five stations. What is clear from Table 4 is that, the Sultanhisar station will experience a higher average number of dry months than other stations, and the Uşak station will experience the lowest number of dry months considering the SSP5-8.5 scenario. In general, the SSP5-8.5 scenario predicts a higher number of dry months than the SSP2-4.5. Similar patterns have been observed in Mediterranean regions, where drought severity is projected to intensify under high-emission scenarios [16]. The reductions in the number of dry months in the middle years of the current century can be explained by considering the mitigative actions via the emission scenarios especially for SSP2-4.5.

Table 4. Comparison of projected dry months at meteorological stations based on SPEI values for reference and future periods under SSP2-4.5 and SSP5-8.5 scenarios.

GCM	Datasets	Period	Number of Dry Months Based on SPEI index														
			Sultanhisar			Uşak			Yatağan			Muğla			Nazilli		
			Mid.	Sev.	Ext.	Mid.	Sev.	Ext.	Mid.	Sev.	Ext.	Mid.	Sev.	Ext.	Mid.	Sev.	Ext.
	Obs.	1985–2014	47	21	11	46	23	7	48	25	4	53	18	5	51	29	3
AWI-CM1-1-MR	Ref.	1985–2014	55	22	2	41	14	4	54	22	2	48	21	2	55	21	2
		2015–2039	8	0	0	21	0	0	10	0	0	12	0	0	17	0	0
	SSP2-4.5	2040–2069	40	27	6	41	30	6	39	27	4	38	28	5	43	26	8
		2070–2099	72	24	6	58	23	4	53	35	7	56	34	5	62	26	4
		2015–2039	0	0	0	6	0	0	6	0	0	0	0	0	0	0	0
	SSP5-8.5	2040–2069	21	7	0	32	7	1	22	6	2	16	0	0	26	7	2
		2070–2099	106	44	12	90	40	9	83	49	10	97	62	10	95	45	10
	Ref.	1985–2014	36	31	6	56	24	5	39	27	6	41	26	6	37	31	6
		2015–2039	12	8	1	19	9	1	14	8	1	16	8	1	11	8	1
NorESM2-MM	SSP2-4.5	2040–2069	22	9	2	25	12	3	24	11	2	24	11	2	21	9	1
		2070–2099	79	38	7	62	34	7	76	38	5	76	35	5	76	41	7
		2015–2039	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SSP5-8.5	2040–2069	10	0	0	19	1	0	13	0	0	16	0	0	9	0	0
		2070–2099	102	71	9	99	63	8	99	64	10	97	62	10	104	69	9
	Ref.	1985–2014	57	20	5	53	23	3	56	20	5	58	19	5	54	19	6
		2015–2039	13	3	0	19	9	1	12	2	0	12	2	0	13	3	0
	SSP2-4.5	2040–2069	16	4	0	25	12	3	15	5	0	13	6	0	14	4	0
		2070–2099	98	42	15	62	34	7	92	42	14	88	46	15	98	44	15
		2015–2039	0	0	0	0	0	0	2	0	0	4	0	0	0	0	0
EC-Earth3-CC	SSP5-8.5	2040–2069	10	0	0	19	1	0	3	0	0	6	0	0	2	0	0
		2070–2099	102	71	9	99	63	8	128	78	2	121	79	2	131	79	2

3.3. Temporal Analysis of Drought for Historical and Future Periods

The fluctuations in the projected SPEI for Sultanhisar, Uşak, Yatağan, Muğla, and Nazilli stations based on outputs of the GCMs are presented in Figures 5 and 6 in the given order for the SSP2-4.5 and SSP5-8.5 scenarios. The amplitude of the fluctuations varies slightly for stations and scenarios. The skewness of the graphs to the negative values (i.e., drought) is more significant for SSP5-8.5. However, in general, the SPEI values start from positive values and end with negative values by the end of the century. On the other hand, the decreasing trend in the value of SPEI started in the middle of the reference period. Those values increase for the future projections which, as stated before, is an effect of the emission scenarios' structures.

The SPEI time series shown in Figures 5 and 6 for Sultanhisar, Uşak, Yatağan, Muğla, and Nazilli provide significant insights into the evolution of drought conditions in the Büyük Menderes basin under historical and future climate scenarios (SSP2-4.5 and SSP5-8.5). The analysis reveals distinct patterns of increasing drought frequency and severity under the high-emission SSP5-8.5 scenario. The historical data for all stations indicate a mixed pattern of wet with positive SPEI values and dry with negative SPEI values periods experiencing drought events being sporadic and less severe. The variability is relatively balanced reflecting the typical climatic fluctuations in the region during the historical time-frame. This aligns with the findings of Balting et al. [25], who reported a similar long-term decrease in SPEI values across the Northern Hemisphere highlighting a trend toward more frequent and intense droughts in the future.

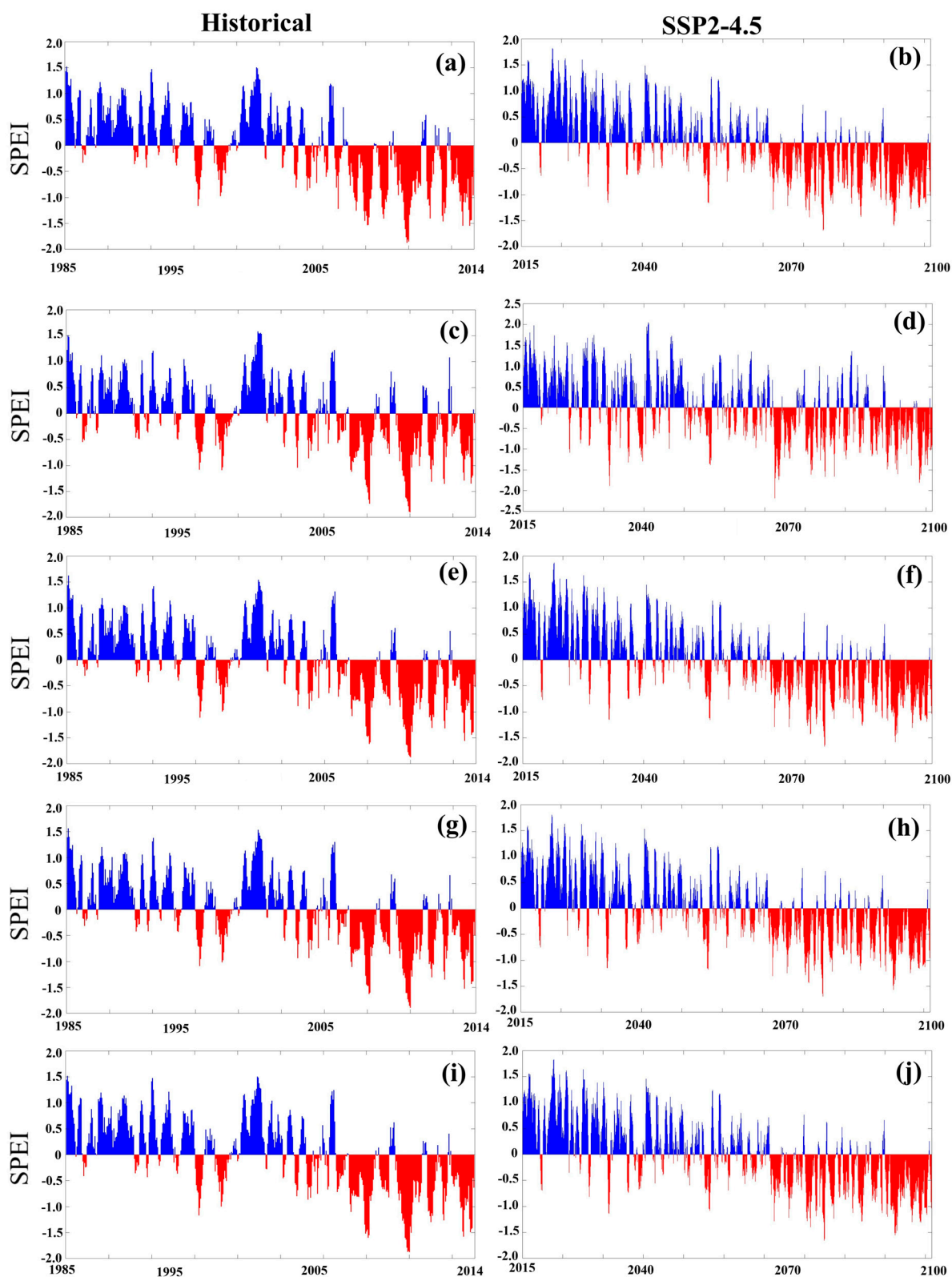


Figure 5. Projected SPEI time series for Sultanhisar (a,b), Uşak (c,d), Yatağan (e,f), Muğla (g,h), and Nazilli (i,j) stations under SSP2-4.5 scenario (2015–2100).

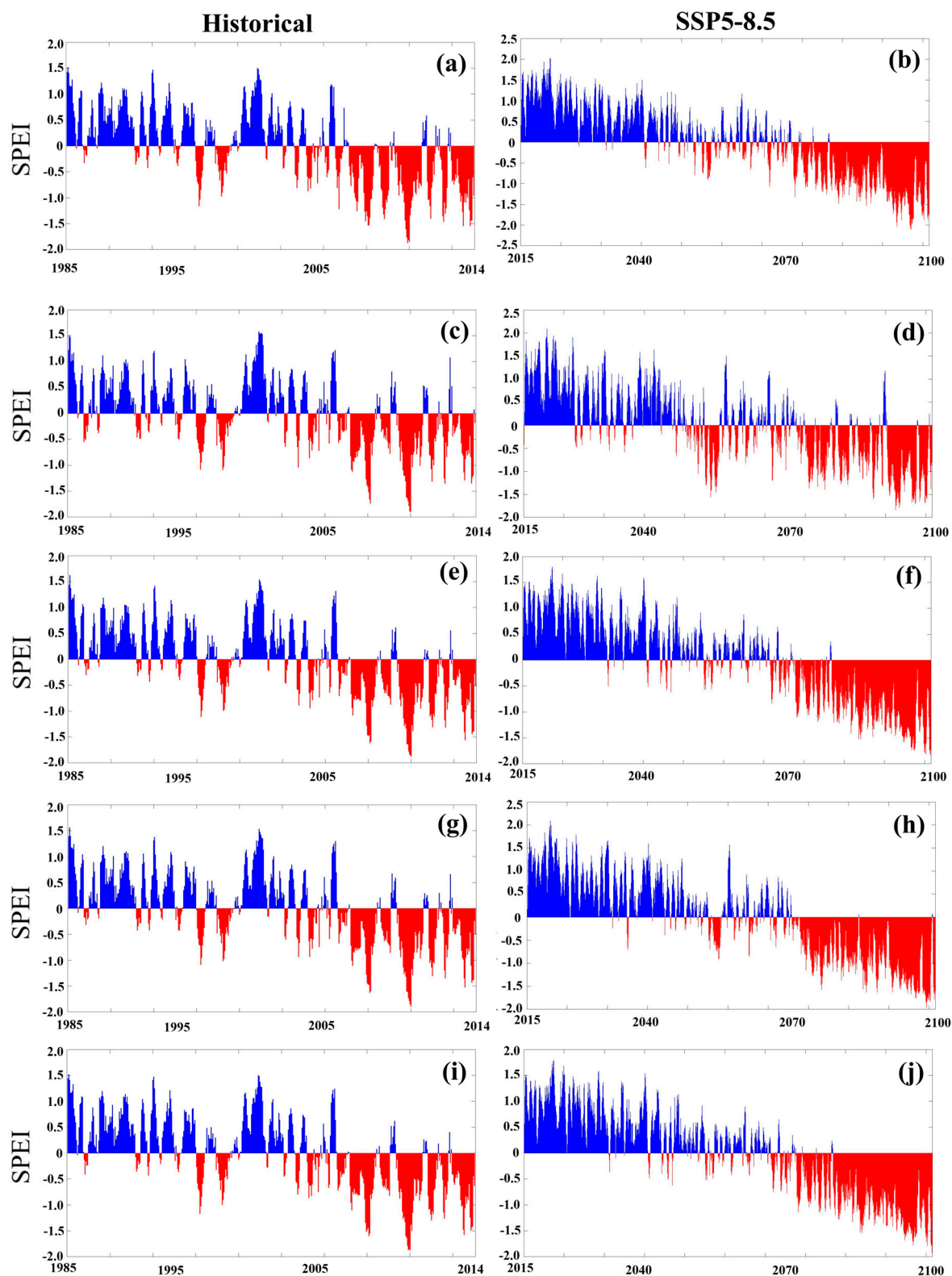


Figure 6. Projected SPEI time series for Sultanhisar (a,b), Uşak (c,d), Yatağan (e,f), Muğla (g,h), and Nazilli (i,j) stations under SSP5-8.5 scenario (2015–2100).

For the case of the near future, i.e., 2015–2040, under both SSP2-4.5 and SSP5-8.5, the near future demonstrates a slight increase in drought events with negative SPEI values. While the SSP2-4.5 scenario projects moderate changes, SSP5-8.5 already exhibits a noticeable shift towards drier conditions particularly in Uşak and Muğla. These changes highlight the early impacts of climate change on short-term drought dynamics. For the

mid-term future, i.e., 2041–2070, the divergence between the two scenarios becomes apparent. SSP2-4.5 maintains a balanced pattern with moderate drought events, whereas SSP5-8.5 shows a significant increase in drought frequency and intensity. Stations such as Sultanhisar and Nazilli display prolonged periods of drought reflecting the region's vulnerability to worsening climatic conditions.

The late future, i.e., 2071–2100, under SSP5-8.5, projects an alarming escalation in drought severity across all stations. Prolonged and extreme droughts dominate the time series with very few wet periods. This trend is particularly severe in Muğla and Nazilli emphasizing the critical impacts of high emissions. Conversely, SSP2-4.5, while still showing an increase in dry months, exhibits less severe conditions, suggesting that mitigation efforts could reduce the impacts. The results show that the Sultanhisar and Nazilli stations have the strongest correlation between increasing drought severity and time, particularly under SSP5-8.5. For the Uşak and Yatağan stations, moderate drought trends are observed under SSP2-4.5, with significant intensification under SSP5-8.5. Among the studied stations, the Muğla station displays the most severe drought conditions, especially in the late future, highlighting its high vulnerability.

3.4. Spatial Analysis of Drought for Historical and Future Periods

The areal distribution of the drought over the basin is illustrated on the maps given in Figure 7. To generate the maps, the number of months with SPEI value of less than -1 for stations during the reference period (1985–2014), mid-term future (2041–2070), and late future (2071–2100) were interpolated over the area. As expected, the number of dry months is projected to be higher under the SSP5-8.5 scenario by the end of the current century. On the other hand, the severity of the drought increases when we approach the western part of the basin. In this case, the difference between the number of dry months on the coastline and highlands (eastern part) will increase by the end of the century under both scenarios, which means the shoreline is expected to suffer more from the effects of climate change. This spatial disparity is consistent with previous assessments in Mediterranean climate zones [31,52], where coastal regions exhibit stronger drought intensification due to changing precipitation regimes.

As shown in Figure 7a, the number of dry months ranges from 75 to 78, indicating moderate drought conditions throughout the basin. The central and southern regions of the basin experience slightly higher numbers of dry months compared to the northern areas, which reflects spatial variability in historical drought patterns. The uniformity in the values indicates that while drought events occurred, they were relatively consistent across the basin during the historical period. Considering SSP2-4.5 for the mid-term future, i.e., 2041–2070, shown in Figure 7b, the number of dry months decreases significantly, ranging from 39 to 52. The central regions exhibit fewer dry months compared to the outer areas, indicating some mitigation of drought severity under moderate emissions. While, for SSP5-8.5, shown in Figure 7c, a stark contrast emerges with the number of dry months dropping to 13–27. This scenario shows an almost uniform reduction in dry months across the basin, but it may be linked to shifts in precipitation patterns rather than an actual mitigation of drought risks. For the case of the late future, i.e., 2071–2100, considering SSP2-4.5, as shown in Figure 7d, the number of dry months increases dramatically, ranging from 97 to 127. This increase is most pronounced in the central and southern regions, indicating that, even with moderate emissions, prolonged dry periods are likely. Figure 7e for SSP5-8.5 shows the most alarming results for the late-century projections with dry months ranging from 161 to 181. The entire basin experiences extreme drought conditions with the highest severity concentrated in the southern and central regions. This highlights the catastrophic impact of high emissions on drought frequency and intensity.

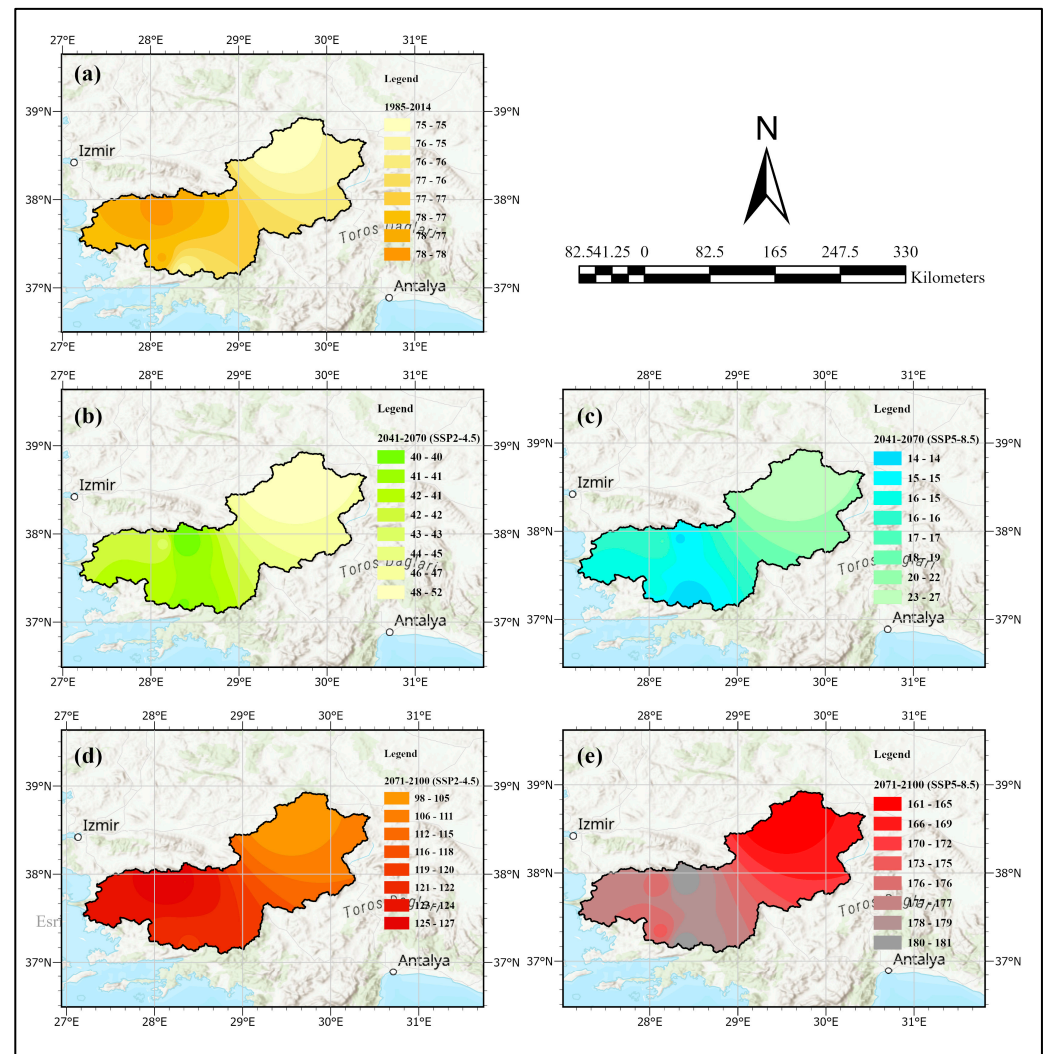


Figure 7. Spatial distribution of dry months in the Büyük Menderes Basin for (a) historical (1985–2014) and (b–e) future periods (2041–2070 and 2071–2100) under the SSP2-4.5 and SSP5-8.5 scenarios.

Considering the spatial analysis given in Figure 7, the maps clearly demonstrate a north-to-south gradient with southern areas consistently showing higher numbers of dry months across all scenarios. The comparison between SSP2-4.5 and SSP5-8.5 highlights the critical importance of emission reductions to mitigate future drought risks. The mid-term SSP2-4.5 map indicates that emission reductions could delay or moderate the onset of severe droughts. However, the late-term map, i.e., 2071–2100, underlines the fact that even moderate mitigation efforts may not fully prevent drought intensification in the long term. The SSP5-8.5 results show that, without significant action, the Büyük Menderes basin will face extreme drought conditions threatening agriculture, water resources, and overall ecosystem stability.

4. Conclusions

This study assessed the projected intensification of drought in the Büyük Menderes Basin under changing climate conditions. Using outputs from three CMIP6 General Circulation Models (GCMs), drought conditions were analyzed for historical (1985–2014) and future (2015–2100) periods under two climate scenarios (SSP2-4.5 and SSP5-8.5). Bias correction and interpolation techniques were applied to enhance the accuracy of temperature and precipitation projections to ensure reliable climate assessments. The SPEI was then used to quantify drought severity across three future timeframes: near future (2015–2040),

mid-term future (2041–2070), and late future (2071–2100). The results indicate a notable increase in drought frequency and severity especially in the late 21st century. Under the high-emission SSP5-8.5 scenario, the number of dry months is projected to rise significantly, with the southern and central parts of the basin experiencing the most extreme drought conditions. While some mitigation effects are observed under SSP2-4.5, the region remains highly vulnerable to prolonged dry periods. These findings highlight the urgent need for adaptive water resource management strategies to mitigate long-term drought risks. To address these challenges, policymakers and stakeholders must implement integrated drought adaptation strategies. This includes the following:

- Enhancing water conservation and storage infrastructure to counteract increased dry periods.
- Developing climate-resilient agricultural practices, such as using drought-tolerant crops and improved irrigation methods.
- Strengthening early warning systems to provide real-time drought monitoring and response planning.
- Promoting sustainable land use and ecosystem conservation to reduce soil degradation and water loss.

In conclusion, this study provides critical insights into the projected intensification of drought in the Büyük Menderes Basin. By integrating these findings into regional climate adaptation policies, decision-makers can minimize the negative impacts of climate change on water resources, agriculture, and ecosystem stability.

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