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Evaluation of 2024 Meteorological Drought Forecasts for Türkiye: Using ECMWF SEAS5 Data and the SPEI Index

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Abstract: This study aims to evaluate meteorological drought predictions for Türkiye in 2024 using the SEAS5 seasonal forecast system developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The motivation behind this research is to assess the applicability of SEAS5 for drought forecasting and its potential contribution to drought management and early warning systems. Drought analysis was performed using the Standardized Precipitation-Evapotranspiration Index (SPEI) on a 3-month timescale, while the model's predictive performance was evaluated through categorical verification metrics. The forecast data used were the monthly anomaly outputs of the SEAS5 system for 2024, combined with station-based reference normals from the 1991-2020 period to produce station-specific forecast series. Long-term precipitation and temperature data from 190 meteorological observation stations, with records starting from 1969, were employed to identify climate trends using the Mann-Kendall rank correlation method. The study presents spatial and temporal distributions of drought conditions and assesses the SEAS5 model's success in predicting droughts across different months and seasons. The findings suggest that SEAS5 can be effectively used for drought forecasting in Türkiye and can contribute significantly to improving drought management and early warning systems.

Keywords: Drought Forecasting System, SPEI, ECMWF, SEAS5

INTRODUCTION

Climate change is significantly altering weather patterns globally, with an increased frequency, duration, and intensity of meteorological events such as droughts. Recent studies have highlighted the growing environmental, economic, and social impacts of climate change (Vicente-Serrano et al., 2020). Drought, due to its effects on water resources and agricultural production, has become a major barrier to achieving sustainable development goals. In regions with semi-arid climates, such as Türkiye, the management of drought events has become a critical issue both environmentally and economically. The effects of climate change are making drought events more frequent and severe, creating substantial challenges for efficient water resource management, agricultural planning, disaster risk management, and economic sustainability (Sivakumar, 2011; Wilhite et al., 2014).

Drought can be categorized into meteorological, hydrological, and agricultural types, each with distinct impacts. Meteorological drought occurs when precipitation falls below normal levels, leading to water shortages and adverse agricultural effects over time (Cao et al., 2022). Monitoring and forecasting droughts enable the prediction of their onset, duration, and severity, facilitating early warning systems. These systems are crucial for better understanding the effects of climate change and managing future drought events (van Ginkel & Biradar, 2021).

Drought monitoring and forecasting systems, particularly those incorporating long-term climate predictions and atmospheric cycles, have become essential in forecasting droughts (Wood et al., 2015). These systems use meteorological (precipitation, temperature and etc.) and hydrological (soil moisture, streamflow, water levels) data to predict the onset, duration, and intensity of droughts.

Early warning systems play a critical role in ensuring the sustainability of agricultural production and efficient water use. Their applicability and accuracy are closely tied to the use of advanced climate models and high-quality datasets (Vicente-Serrano et al., 2010; Oğuz et al., 2022).

Seasonal forecast data, especially in drought monitoring and prediction, provide valuable insights into the atmospheric conditions of specific periods. These data enable the development of water resource management strategies and agricultural policies. The SEAS5 seasonal forecast system, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides essential resources for long-term predictions of precipitation, temperature, and other meteorological parameters. SEAS5 models long-term climate events, such as droughts, by accounting for the interactions between the atmosphere and land surfaces, enhancing the accuracy of drought predictions at the seasonal scale. This system is a valuable tool for improving drought management strategies in semi-arid and arid regions like Türkiye (Dutra et al., 2014; Carrao et al., 2018).

The SEAS5 system, a fifth-generation seasonal forecast model developed by ECMWF, takes into account the interactions between the atmosphere, ocean, and land surfaces, providing weather forecasts for periods ranging from 1 to 12 months. SEAS5 enhances drought predictability, particularly in regions like Türkiye, which experiences semi-arid and arid climates. With the increased frequency of droughts in Türkiye in recent years, SEAS5's long-term forecasts have become instrumental in water resource planning, agricultural policy development, and disaster management processes (Çamalan, 2022).

The Standardized Precipitation-Evapotranspiration Index (SPEI) is a widely used tool for drought monitoring and analysis. It evaluates both precipitation and evaporation loss, indicating the extent to which a region's water balance is negatively affected. SPEI is effective for monitoring drought conditions across different time scales (e.g., 3-month, 6-month, 12-month) and provides clearer insights into drought severity, duration, and spatial distribution. It is particularly useful in analyzing how droughts evolve in the context of global warming and distinguishing between different types of droughts (Vicente-Serrano et al., 2010; Beguería et al., 2013). In regions like Türkiye, SPEI analyses offer a better understanding of drought events and help in preparing for future drought scenarios (Byakatonda et al., 2018; Homdee et al., 2016). Given the impacts of climate change, particularly increasing temperatures and irregular precipitation patterns, the use of SPEI for drought monitoring and prediction is becoming increasingly important (Çamalan, 2024).

The accuracy of precipitation forecasts from the SEAS5 seasonal forecast system is typically lower due to its inherent sensitivity to atmospheric chaos and the influential regional factors such as complex topography and localized cyclonic/anticyclonic systems. Türkiye's precipitation regime is intricately shaped by the interaction of atmospheric circulation patterns and diverse geographical/topographical conditions, leading to distinct regional variations where orographic and frontal precipitation dominate in coastal areas, while convective and continental precipitation types prevail in central and eastern regions (Türkeş & Tatlı, 2011). Given Türkiye's highly variable terrain, comprising mountains, plateaus, and valleys, SEAS5's horizontal resolution (~36 km) often proves insufficient to adequately represent the localized effects of topography, thereby complicating the accurate modeling of orographic precipitation, particularly the precise capture of precipitation mechanics on mountain slopes and in valleys. Furthermore, the accurate simulation of the formation and distribution of localized convective precipitation, which is prevalent in Anatolia especially during summer months, presents a considerable challenge. SEAS5 occasionally struggles to fully capture the seasonal transitions and local moisture-dynamics characteristic of Anatolia's Mediterranean climate, which experiences rainy winters and dry summers; specifically, the complex relationship between humid air masses originating from the Mediterranean and precipitation in the interior of Anatolia remains difficult to model. Additionally, as a large-scale model, SEAS5 cannot adequately represent the rapid and multi-directional changes in local winds, temperature, and humidity that characterize Anatolian microclimates, which consequently introduces errors in the prediction of small-to-medium scale precipitation events. In essence, while SEAS5 offers a broad perspective in seasonal forecasts, it encounters critical limitations in precipitation physics within regions of complex terrain and climate, such as Anatolia, specifically encompassing its inability to capture small-scale topographical effects, inadequacies in convective precipitation parametrization, incomplete representation of seasonal and regional climatic interactions, difficulties in modeling microclimate and local air mass dynamics, and inherent error margins stemming from input and data uncertainties (Serkendiz & Tatlı, 2023). Consequently, the model's operation at a 36 km resolution and its limited consideration of topographical effects, compounded by Türkiye's general altitudinal increase of approximately 5000 meters from west to east, constitute primary factors constraining its forecast accuracy, rendering it prone to missing drought dynamics within microclimates.

This study aims to evaluate meteorological drought predictions for Türkiye in 2024 using the SEAS5 seasonal forecast system developed by ECMWF. By examining the model's performance in predicting drought conditions, this research contributes to improving drought management and early warning systems, especially in the context of Türkiye's evolving climate challenges. The research focuses on understanding the predictive capabilities of SEAS5 for drought forecasting and its potential applications in managing water resources and agricultural production effectively.

METHOD

This study aims to assess drought prediction and monitoring in Türkiye using seasonal forecasts, focusing on the integration of meteorological data and SEAS5, the fifth-generation seasonal forecasting system developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). The methodology employed is structured to combine historical observation data with advanced seasonal forecasts to predict and analyze drought events across Türkiye. Additionally, the study integrates observational data, seasonal forecast anomaly data from SEAS5, and the SPEI drought index to predict and monitor drought conditions in Türkiye. By combining advanced forecasting models with historical data, this methodology provides a robust framework for understanding drought dynamics and improving drought preparedness in the region. The use of performance metrics for validation ensures the accuracy and reliability of the predictions, while the spatial analysis with Kriging interpolation provides a detailed geographic view of drought occurrences across Türkiye.

Data Sources and Collection

The study utilizes meteorological observation data from 190 stations in Türkiye, covering monthly total precipitation and average temperature for the period from 1969 to the present. These data are essential for determining the baseline climate conditions in Türkiye, helping to identify trends in precipitation and temperature over time. Additionally, we used 7-month seasonal forecast anomaly data provided by ECMWF's SEAS5 system, which offers predictions for various climate variables at a 36 km resolution. These anomalies were incorporated into the analysis by adding the station-specific normals for the period 1991-2020 to the forecast data.

Seasonal Forecast System (SEAS5)

SEAS5 is a state-of-the-art seasonal forecasting system, developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), designed to provide long-range predictions for a range of atmospheric, oceanic, and land surface conditions. As detailed in Johnson et al. (2019), it is capable of providing forecasts for timeframes ranging from 1 to 12 months. SEAS5 is based on the ECMWF Integrated Forecasting System (IFS), which represents complex interactions among the atmosphere, oceans, land, and other components of the Earth system. The system is run on the first day of each month, and forecasts are typically released on the 5th of the month.

The forecasts generated by SEAS5 are useful for various sectors, including agriculture, water management, energy, and health, as they provide critical information to anticipate extreme weather events and prepare for potential drought periods. For instance, Busker et al. (2023) demonstrate its utility in triggering early actions for drought preparedness. In this study, SEAS5 anomalies for temperature and precipitation were used to predict drought conditions. However, it's important to acknowledge that while SEAS5 shows strengths in predicting large-scale phenomena like ENSO, its skill for mid-latitude precipitation and certain drought indices can be more limited and spatially variable. Precipitation forecasts from SEAS5 generally exhibit lower skill compared to temperature forecasts, especially in mid-latitudes, and their ability to estimate sectoral drought impacts varies. Furthermore it can be useful for detecting soil moisture anomalies related to drought, its performance can be influenced by terrain complexity.

SPEI Index Calculation

The Standardized Precipitation Evapotranspiration Index (SPEI) is used as the primary tool for analyzing drought conditions. SPEI is based on the climate water balance, calculated using precipitation and potential evapotranspiration (PET). The SPEI values in this study were computed using the Thornthwaite method for Potential Evapotranspiration (PET) estimation (Begueria et al., 2013). This method estimates PET as a function of average monthly temperature and latitude, assuming a fixed relationship between temperature and evapotranspiration (Mertens, 2002). Although simple and requiring limited input data, Thornthwaite can underestimate PET in arid regions. The use of Thornthwaite is consistent with prior applications in Turkish drought studies (Çamalan & Çetin, 2022), and aligns with the scope of available meteorological station data. Nevertheless, incorporating more physically-based methods such as Penman-Monteith in future work could enhance accuracy, particularly in energy-limited or topographically diverse regions.The formula for calculating SPEI is given by:

$$Di = Pi - PETi \quad (1)$$

Where Di is the drought index at time i; Pi is the precipitation at time i; $PETi$ is the potential evapotranspiration at time i.

SPEI values are used to determine the severity and duration of drought events. The SPEI calculation and detailed explanation of the index formulation can be found in the literature (Vicente-Serrano et al., 2010; Çamalan & Çetin, 2022).

PET Calculation (Thornthwaite Method)

The Thornthwaite method is used for estimating PET based solely on temperature. The key formulas are:

1. Monthly Heat Index (i):

$$\mathrm{i} = \left(\frac{\mathrm{t}}{5}\right)^{1.514} \quad (2)$$

Where *i* is monthly temperature index; *t* is mean monthly temperature (°C); and *I* is annual heat index (sum of 12 monthly *i* values).

2. Empirical Coefficient (A):

$$A = 6.75 * 10^{-7} * I^3 - 7.71 * 10^{-5} * I^2 + 1.79 * 10^{-2} * I + 0.492 \quad (3)$$

3. Monthly PET Formula:

$$\mathrm{PET} = 16 * \mathrm{K} * \left[\frac{10 * \mathrm{T(I)}}{\mathrm{I}}\right]^{\mathrm{A}} \quad (4)$$

Correction Factor (K):

$$\mathrm{K} = \left(\frac{\mathrm{N}}{12}\right)\left(\frac{\mathrm{NDM}}{30}\right) \quad (5)$$

$$N = \left(\frac{24}{\pi}\right)\omega_s \quad (6)$$

$$\omega_s = \arccos(-\tan\varphi\tan\delta) \quad (7)$$

$$\delta = 0{,}4083 \sin\left(\frac{2\pi J}{365} - 1{,}405\right) \quad (8)$$

Where ɸ: Latitude in radians; δ: solar declination in radians; J: Mean Julian day of the month; and NDM: Number of days in the month.

SPEI Calculation Process

1. Water surplus or deficit (D_i): Di=Pi−PETi
2. Time Series Aggregation: D_i series is aggregated over different time scales (e.g., 1, 3, 6, 12, 24 months), as in SPI
3. Probability Distribution Fit: The aggregated series is modeled using a three-parameter log-logistic distribution.
4. Parameter Estimation: Parameters α, β, γ are estimated using the L-moment method, derived from probability-weighted moments (Hosking, 1986).
5. Standardization and SPEI Computation:

$$\mathrm{SPEI} = \mathrm{w} - \frac{\mathrm{C_0} + \mathrm{C_1 w} + \mathrm{C_2 w^2}}{1 + \mathrm{d_1 w} + \mathrm{d_2 w^2} + \mathrm{d_3 w^3}} \quad (9)$$

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

If P>0.5, use P=1−P and reverse the sign of the final SPEI value. The classification of SPEI can be seen in Table 1.

Table 1. SPEI Classification Table (Nam et al., 2015)

SPEI Index	Classification
2.00 +	Extremely wet
1.50 –1.99	Very wet
1.00 – 1.49	Moderately wet
(-0.99) – 0.99	Near normal
(-1.00) – (-1.49)	Moderately dry
(-1.50) – (-1.99)	Severely dry
(-2.00) and less	Extremely dry

Validation and Performance Metrics

Validation of the seasonal forecasts is conducted by comparing the forecasted drought events with observed data. The comparison is performed using a binary classification method (Table 2) where drought is identified as SPEI ≤ -1 (drought/no drought). For each prediction-observation pair, the following performance metrics are calculated:

- Probability of Detection (POD): The fraction of observed drought events correctly predicted as drought.
- False Alarm Ratio (FAR): The fraction of non-drought events incorrectly predicted as drought.
- Hit Rate (HIT): The overall fraction of correct predictions (both drought and non-drought).
- Threat Score (TS): The fraction of correct drought predictions among all predicted drought events.
- Bias (BIAS): The ratio of predicted drought events to observed drought events.

Table 2. Validation and Performance Metrics (Gaurihar et al., 2023)

↓Forecast \ →Observed	Yes	No	Total
Yes	a = Hits	b = False Alarms	a + b = Forecast Yes
No	c = Misses	d = Correct Negatives	c + d = Forecast No
Total	a + c = Observed Yes	b + d = Observed No	a + b + c + d = Total

These metrics are computed using the following equations (Stanski et al., 1989; Nurmi, 2023):

$$POD=\frac{A}{A+C}, FAR=\frac{B}{A+B}, HIT=\frac{A+D}{A+B+C+D}, TS=\frac{A}{A+B+C}, BIAS=\frac{A+B}{A+C} \quad (10)$$

Where:

- A is the number of correct positive predictions (Hit),
- B is the number of false positive predictions (False Alarm),
- C is the number of missed events (Missed Event),
- D is the number of correct negative predictions (Correct Rejections).

A perfect prediction would result in POD = 1, FAR = 0, HIT = 1, TS = 1, and BIAS = 1. The performance metrics provide insights into the accuracy and reliability of the seasonal drought predictions.

Data Analysis

Maps illustrating drought conditions are created using Kriging interpolation, implemented through the Surfer program (Figure 1). These maps are based on the observed and predicted drought conditions across Türkiye, providing a spatial representation of drought events. The SPEI values are calculated for different time scales (e.g., 3-month, 6-month, 12-month) to evaluate the temporal evolution of drought conditions.

In addition to the seasonal forecast analysis, the study investigates the long-term trends in temperature and precipitation data from 1971 to 2024. A Mann-Kendall test is applied to assess the statistical significance of changes in precipitation and temperature over the study period. This analysis helps in understanding the broader climatic trends in Türkiye and their potential implications for drought occurrences.

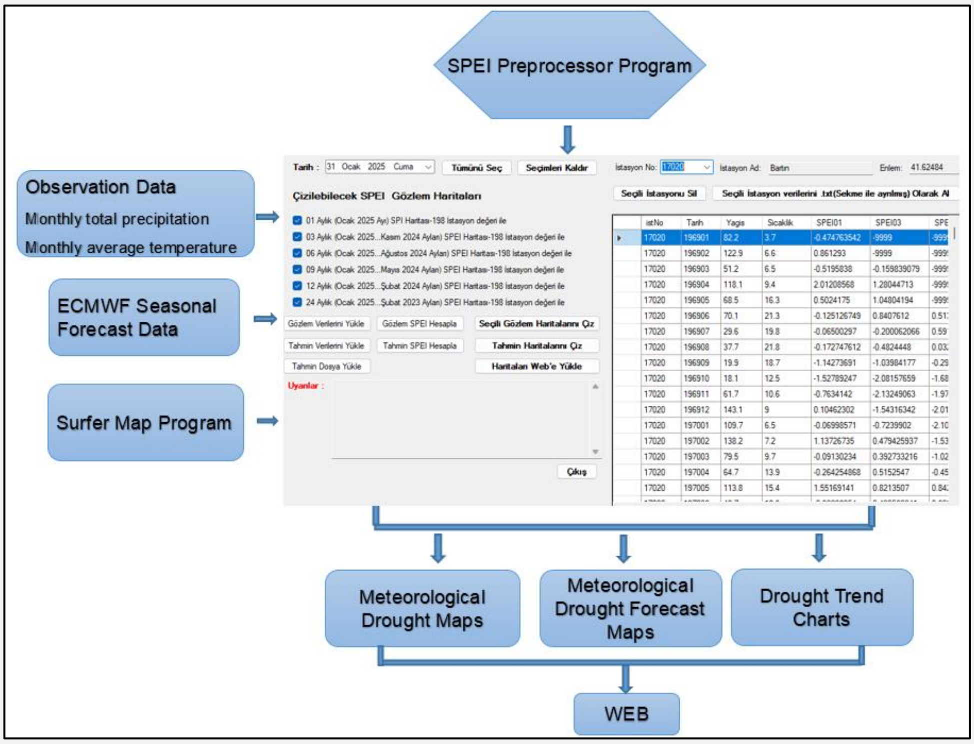


Figure 1. Flow chart of SPEI Index Calculation.

Drought Event Classification

Based on the SPEI index, drought events are classified as "normal," "dry," or "severe" according to predefined thresholds. The categorization helps in assessing the intensity and extent of droughts, which is crucial for planning mitigation strategies in agriculture, water resources, and disaster management.

RESULTS

Temperature and Precipitation Analysis

Between 1971 and 2024, the annual average temperature in Türkiye was 13.7°C, while the normal temperature (1991-2020) was 13.9°C. In 2024, the annual average temperature reached 15.6°C, exceeding the normal by 1.7°C. The year 2024 became the hottest year in the last 54 years. Monthly average temperatures were above normal for most months, except for May and November. In particular, record high temperatures were recorded in January, April, June, and July. Between 1971 and 2024, Türkiye's annual total arithmetic precipitation average was 625.5 mm, with the normal (1991-2020) being 625.3 mm. In 2024, the arithmetic precipitation was recorded as 593.8 mm, falling below the normal. Additionally, precipitation levels for February, April, June, October, November, and December were below normal.

According to the Mann-Kendall test results, variability in precipitation was observed both inter-annually and within the year for the period 1971-2024; however, no statistically significant trend was detected. In contrast, a significant increasing trend was found in temperature, which became particularly evident starting from 2005 (Figure 2).

The year 2024 was marked by a rapid increase in global warming, an increase in extreme weather events, and significant impacts on human health, ecosystems, and infrastructure. Throughout the year, several extreme events occurred, including heatwaves, floods, droughts, wildfires, and tropical storms. The majority of these events, along with the extreme rise in temperatures, were a result of accelerating climate change, human-induced greenhouse gas emissions, the El Niño effect, oceanic and stratospheric anomalies, decreasing sulfur dioxide emissions, increased solar activity, and water vapor feedback mechanisms. The interaction of all these factors made 2024 a year in which global temperatures reached record levels and the impacts of climate change became increasingly pronounced.

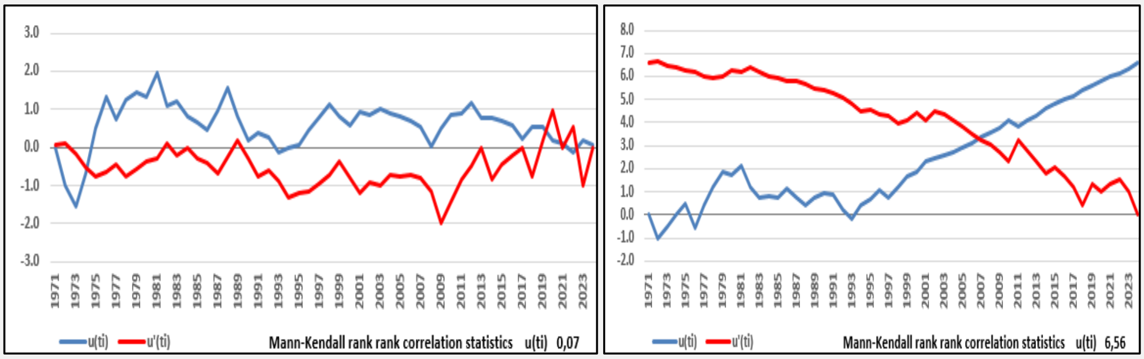
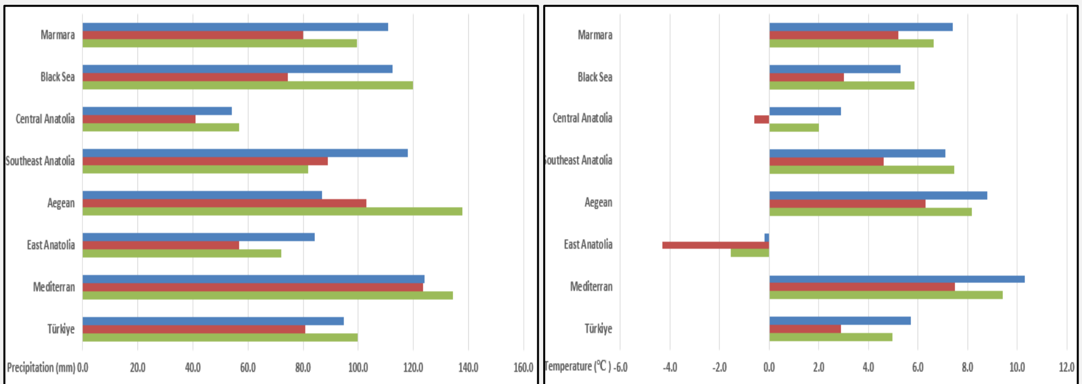


Figure 2. Mann-Kendall Analysis of Annual Total Precipitation and Average Temperature for Türkiye.

Analysis of SPEI-3 Drought and Forecast Maps for the Year 2024 (Monthly)

Analysis and Validation of January SPEI-3 Drought Forecast and Observation Maps

According to the ECMWF SEAS5 seasonal forecasts for January, temperatures across the country and in all regions were expected to be above seasonal normals, while precipitation was predicted to be above normal in all regions except for the Southeastern Anatolia Region (Figure 3). In line with these forecasts, droughts of varying intensities were expected in the southeastern parts of Central Anatolia, as well as in areas such as Korkuteli, Elmalı, Samandağ, Bolvadin, Erçiş, Bafra, and Zile (Figure 4). However, based on actual meteorological data, temperatures in January were above seasonal normals across the country, and precipitation was recorded above normal in all regions except for the Aegean Region. Furthermore, Eastern Anatolia, Southeastern Anatolia, and the Marmara Region received precipitation amounts exceeding the forecasts. As a result, droughts of varying intensities were observed in limited areas in the southern and eastern parts of Central Anatolia, in the interior of the Aegean Region (specifically in Denizli, Emirdağ, and Bolvadin), and in the Central Black Sea Region (particularly in the areas around Samsun, Ordu, Çorum, Bafra, and Tokat).



	Türkiye	Mediterran	East Anatolia	Aegean	Southeast Anatolia	Central Anatolia	Black Sea	Marmara
2024 January	94.8	124	84.2	86.9	118	54	112.5	110.9
1991-2020	80.6	123.5	56.8	103.0	88.9	40.8	74.5	80.1
ECMWF SEAS5	99.6	134.3	72.0	137.7	81.9	56.7	119.8	99.5

	Türkiye	Mediterran	East Anatolia	Aegean	Southeast Anatolia	Central Anatolia	Black Sea	Marmara
2024 January	5.7	10.3	-0.2	8.8	7.1	2.9	5.3	7.4
1991-2020	2.9	7.5	-4.3	6.3	4.6	-0.6	3	5.2
ECMWF SEAS5	5.0	9.4	-1.6	8.2	7.5	2.0	5.9	6.6

Figure 3. Monthly Total Precipitation and Average Temperature Distributions for January.

Analysis and Validation of February SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 seasonal forecasts for February, it was anticipated that temperatures across the country and in all regions would be above seasonal norms, while precipitation was expected to be above normal, except in the Southeastern Anatolia, Mediterranean, and Aegean

Regions. Based on these forecasts, moderate meteorological drought conditions were projected for the coastal and inland areas of the Western Mediterranean, the Inner Aegean regions including Muğla, Denizli, and Afyon, the Konya section of the Central Anatolia Region, certain limited areas in the interior, as well as the vicinities of Bafra, Zile, and Birecik (Figure 5).

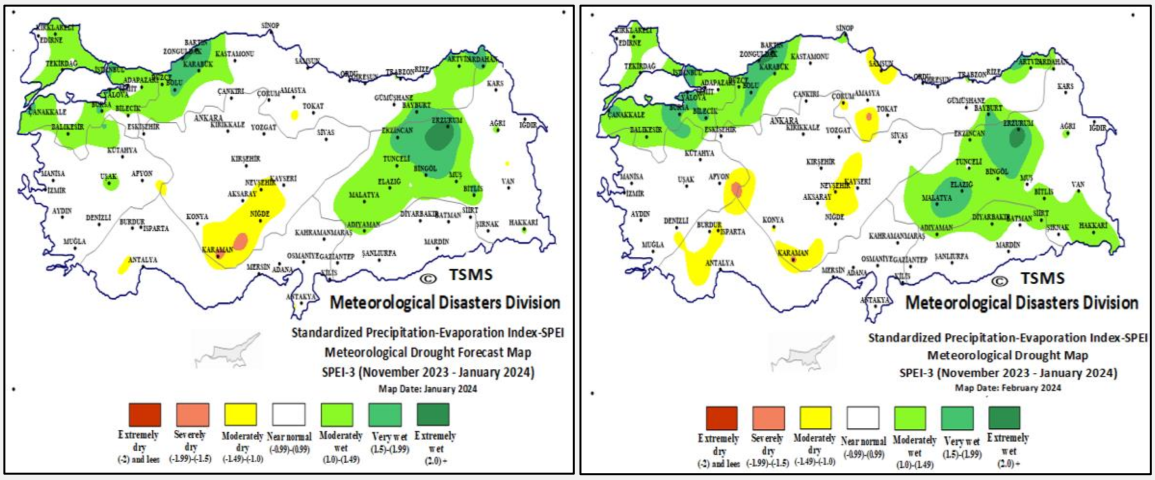
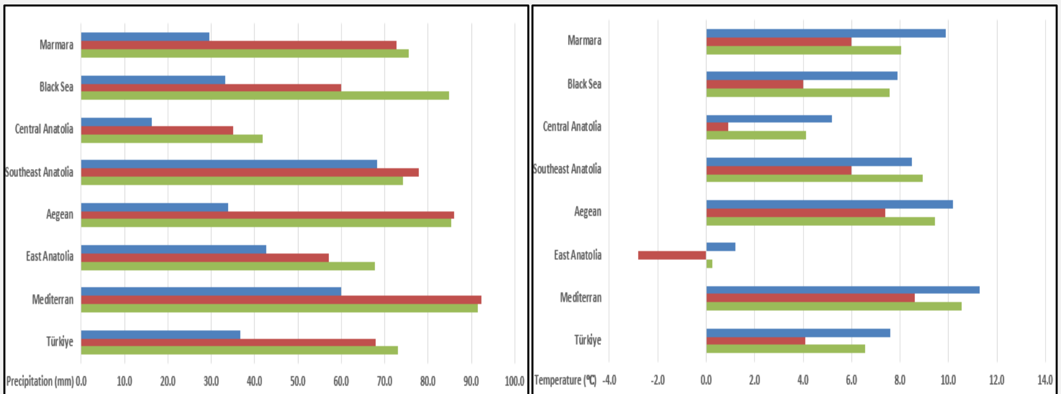


Figure 4. January SPEI-3 Forecast and Observation Meteorological Drought Map.

However, meteorological data indicated that during this month, while temperatures remained above normal across the country, precipitation fell below expected levels. This discrepancy led to more severe and widespread drought conditions than initially projected. Specifically, various intensities of meteorological drought were observed in the coastal and inland areas of the Western Mediterranean, the interior parts of the Eastern Mediterranean, regions around Iğdır, Tatvan, and Horasan in the Eastern Anatolia Region, the southern and interior parts of the Aegean Region, the northwestern and eastern parts of the Central Anatolia Region (excluding areas around Kırşehir), the Central Black Sea Region, Western Thrace, as well as the vicinities of Istanbul and Adapazarı.

The SPEI-3 data for February also provides insights into the winter season. The winter of 2024 was characterized by moderate drought conditions across Türkiye, with the Aegean and Central Anatolia Regions notably experiencing similar conditions (Figure 6).



Precipitation (mm)	Türkiye	Mediterran	East Anatolia	Aegean	Southeast Anatolia	Central Anatolia	Black Sea	Marmara
2024 February	36.7	59.9	42.7	33.8	68.3	16.3	33.2	29.6
1991-2020	68.0	92.3	57.2	86.0	77.9	35.1	60.0	72.8
ECMWF SEAS5	73.1	91.5	67.7	85.3	74.3	41.9	84.8	75.5

Temperature (°C)	Türkiye	Mediterran	East Anatolia	Aegean	Southeast Anatolia	Central Anatolia	Black Sea	Marmara
2024 February	7.6	11.3	1.2	10.2	8.5	5.2	7.9	9.9
1991-2020	4.1	8.6	-2.8	7.4	6	0.9	4	6
ECMWF SEAS5	6.6	10.5	0.3	9.4	8.9	4.1	7.6	8.0

Figure 5. Monthly Total Precipitation and Average Temperature Distributions for February.

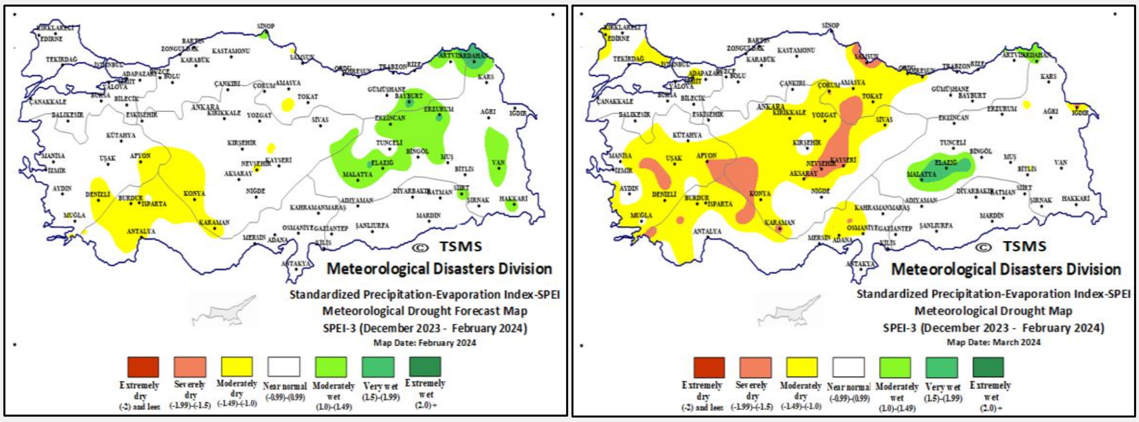


Figure 6. February SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of March SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 seasonal forecasts for March, temperatures across Türkiye were anticipated to be above the seasonal norms, with precipitation expected to be near or below average, except for the Black Sea region (Figure 7). Based on these projections, moderate drought conditions were forecasted for several areas, including, the southern and interior parts of the Aegean region, Western Thrace, Istanbul, the interior sections of the Mediterranean region, and the vicinity of Iğdır (excluding Kırşehir, eastern Kayseri, Central Anatolia's northwest and Sivas).

However, meteorological data for March indicated that, while temperatures remained above normal nationwide, precipitation levels were below average in all regions except Eastern Anatolia, Southeastern Anatolia, the Black Sea, and Central Anatolia. This discrepancy led to more severe and widespread drought conditions than initially projected. Notably affected areas included the Central Black Sea region, the Konya section of Central Anatolia, the surroundings of Ankara and Kırıkkale, the southern and interior parts of the Aegean region, Western Thrace, the vicinity of Istanbul, and both the interior and coastal areas of the Western and Central Mediterranean regions, all experiencing varying degrees of meteorological drought (Figure 8).

Regional assessments highlighted that the Aegean region experienced moderate drought conditions during this period.

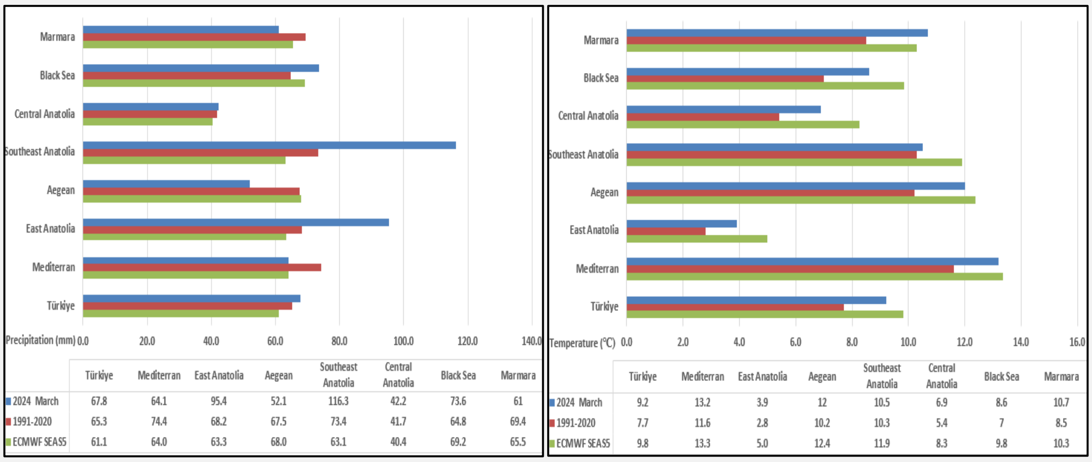


Figure 7. Monthly Total Precipitation and Average Temperature Distributions for March.

Analysis and Validation of April SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 seasonal forecasts for April (Figure 9), temperatures across all regions of the country were expected to be above seasonal norms, while precipitation was anticipated to be below normal, except for the Southeastern Anatolia Region. Based on these forecasts, varying intensities of drought were projected for areas including the Marmara, Aegean, and Central Anatolia regions (excluding coastal areas of the Western and Eastern Mediterranean), as well as limited zones in the Western and Central Black Sea and Eastern Anatolia regions.

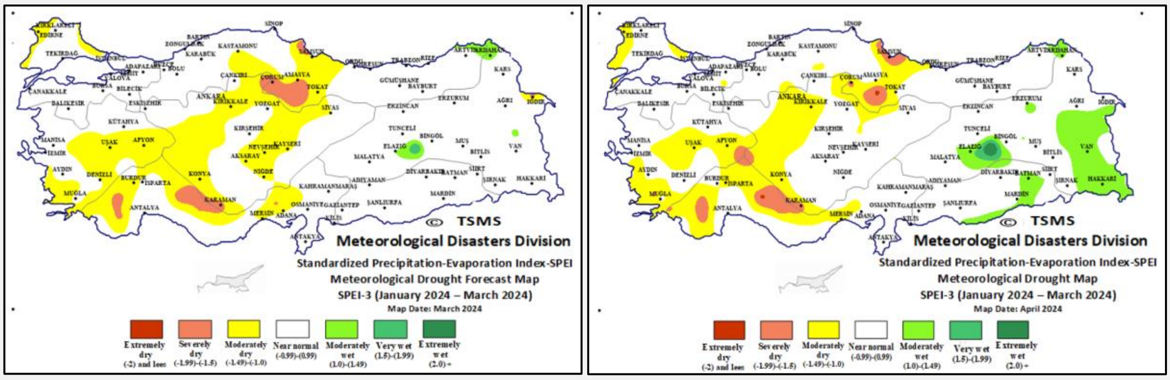


Figure 8. March SPEI-3 Forecast and Observation Meteorological Drought Map.

However, meteorological data indicated that in April, temperatures remained above normal nationwide, and precipitation fell below average. This resulted in more severe and widespread drought conditions than initially predicted, extending into the Eastern Black Sea, Eastern Mediterranean, and the northern and western parts of Eastern Anatolia. Notably, April 2024 was recorded as the third driest month of the year in Türkiye, experiencing severe drought conditions. The Aegean and Black Sea regions faced extreme drought, while the Marmara, Mediterranean, and Central Anatolia regions experienced severe drought, and the Eastern Anatolia Region encountered moderate drought conditions (Figure 10).

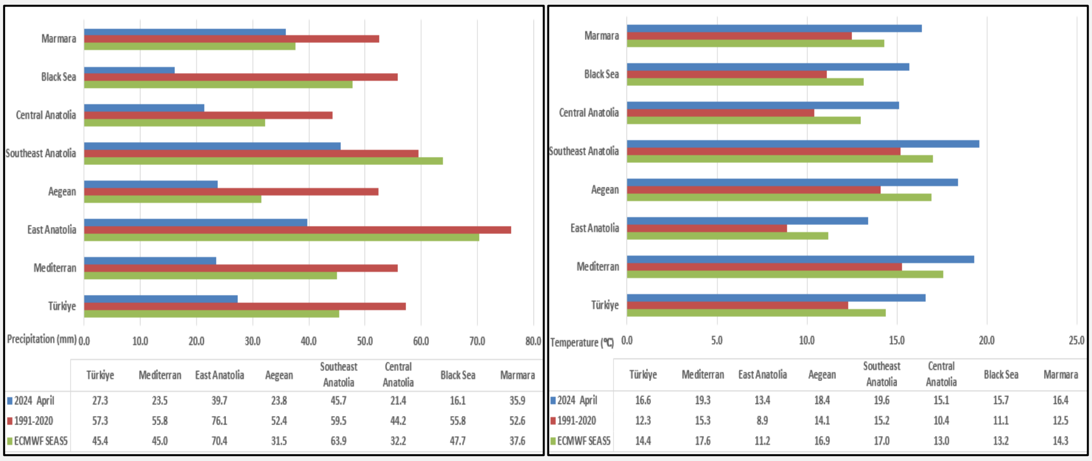


Figure 9. Monthly Total Precipitation and Average Temperature Distributions for April.

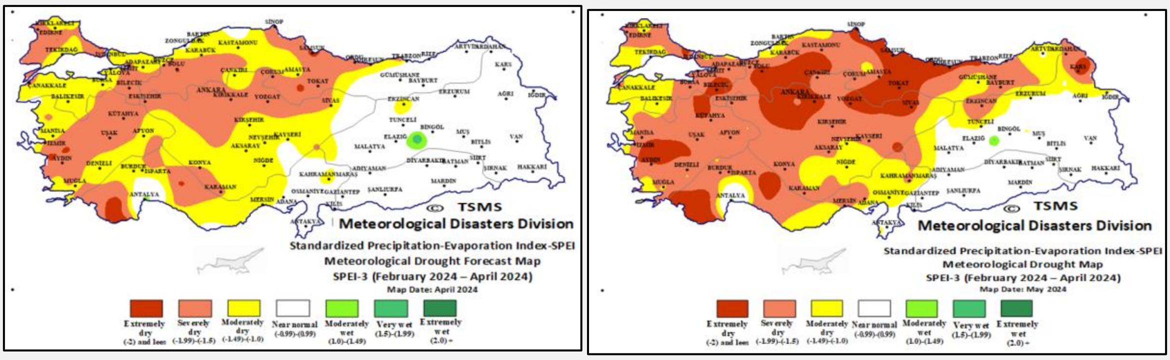


Figure 10. April SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of May SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 seasonal forecasts for May (Figure 11), temperatures were expected to be above seasonal norms in all regions except the Marmara Region, while precipitation was anticipated to be above normal in all regions except the Aegean Region. Based on these forecasts, moderate drought conditions were projected in various areas, including the northern and eastern parts of the Marmara Region, Çanakkale vicinity, the interior parts of the Western Black Sea, coastal areas of the Central and Eastern Black Sea, the central and eastern parts of Central Anatolia (excluding Kırşehir, Kayseri, and eastern Sivas), and most areas of the Western and Central Mediterranean, except around Antalya and Anamur.

However, meteorological data indicated that in May, temperatures were below normal in regions other than the Mediterranean and Aegean, while precipitation exceeded normal levels in all regions except the Aegean and Marmara. This resulted in more severe drought conditions than initially forecasted in the Southern Aegean and Western Mediterranean regions. Additionally, varying intensities of drought were observed in the Central Mediterranean, the northern and eastern parts of the Marmara Region, Çanakkale vicinity, the interior parts of the Western Black Sea, coastal areas of the Central and Eastern Black Sea, the eastern interior parts of the Central Black Sea, most areas of Central Anatolia (excluding the central regions and the Konya section), and a limited area in the western part of Eastern Anatolia (Figure 12).

The SPEI-3 data for May provides insights into the spring season. In 2024, the spring season was moderately dry across Türkiye, with the Marmara and Mediterranean regions exhibiting similar conditions. Notably, the Aegean Region experienced severe drought conditions.

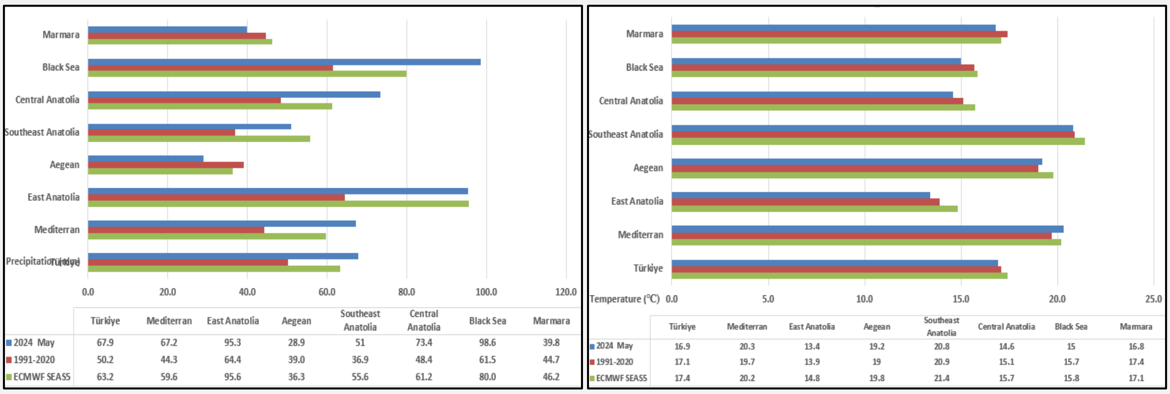


Figure 11. Monthly Total Precipitation and Average Temperature Distributions for May.

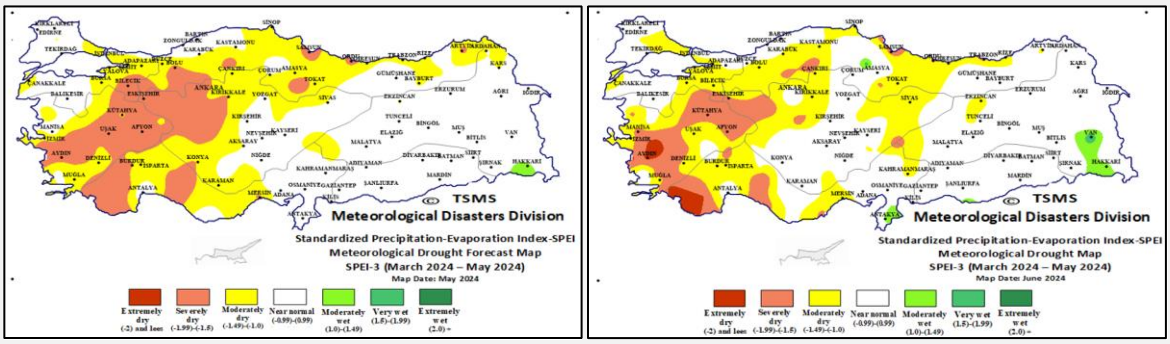


Figure 12. May SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis of June SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 temperature forecasts for June (Figure 13), temperatures across Türkiye were anticipated to be above seasonal norms, while precipitation was expected to be below average. Based on these forecasts, varying intensities of drought were projected for most regions, excluding eastern parts of the Eastern Anatolia Region (including areas around Elazığ), areas surrounding Osmaniye, Hatay, and Kilis, the western interior parts of the Central Black Sea Region, and limited areas within the Konya section and interior parts of the Central Anatolia Region.

However, meteorological data for June indicated that temperatures remained above normal across all regions, and precipitation levels were below both the seasonal norms and the forecasted amounts. This resulted in more severe and widespread drought conditions than initially anticipated. Specifically, except for the eastern parts of the Eastern Anatolia Region, areas around Ardahan and Elazığ, limited areas in the interior parts of the Central Black Sea Region, and regions surrounding Nevşehir, Karaman, Ankara, Hatay, and Osmaniye, the majority of Türkiye experienced droughts of greater severity and extent than forecasted (Figure 14).

June was recorded as the driest month in Türkiye for the year 2024, with extreme drought conditions prevailing. The Aegean, Marmara, and Mediterranean Regions experienced exceptional drought, the Central Anatolia and Black Sea Regions faced severe drought, while the Eastern and Southeastern Anatolia Regions encountered moderate drought conditions.

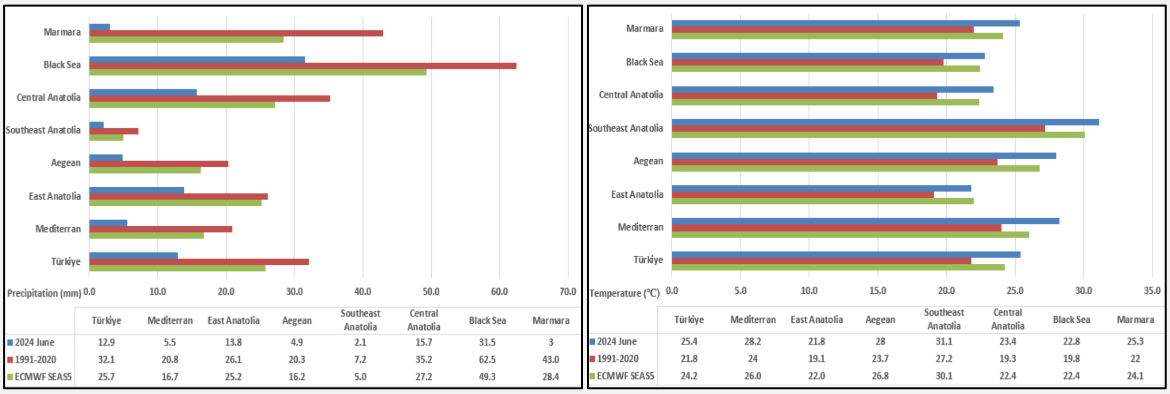


Figure 13. Monthly Total Precipitation and Average Temperature Distributions for June.

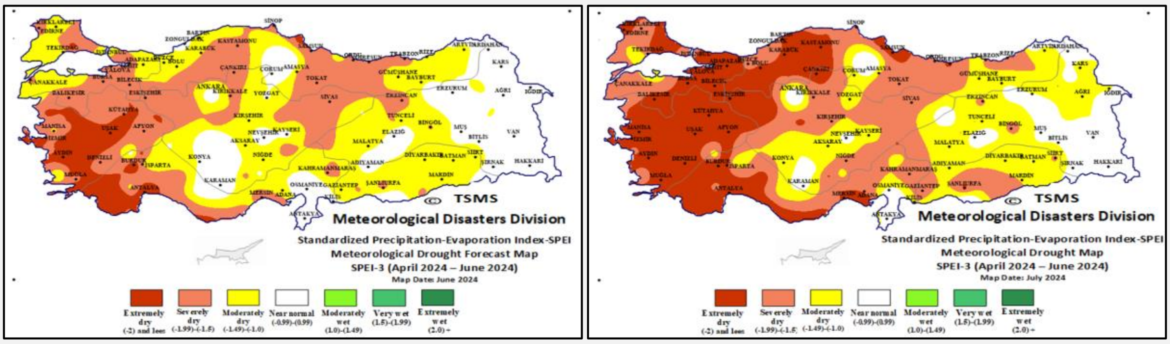


Figure 14. June SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of July SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 temperature forecasts for July (Figure 15), both temperatures and precipitation were expected to exceed seasonal normals nationwide and across all regions. Based on these projections, varying degrees of drought were anticipated in several areas, including the Marmara, Aegean, and Mediterranean regions (with the exception of the vicinities of Kahramanmaraş, Osmaniye, and Hatay), as well as in Southeastern Anatolia, the Western Black Sea region, the vicinities of Samsun and Tokat, and in the southwestern part of Eastern Anatolia along with the northwestern part of Central Anatolia—specifically in the areas around Kırıkkale, Kırşehir, Aksaray, Niğde, and Sivas.

However, the meteorological observations for July indicated that, while temperatures remained above normal throughout the country and in all regions, precipitation levels were above normal in all regions except for the Marmara Region. This discrepancy suggests that, aside from the areas around Afyon and the Lakes Region, as well as the vicinities of Aksaray, Niğde, and Sivas, the drought conditions predicted in the forecasts generally persisted with varying intensities (Figure 16).

Overall, moderate drought conditions were observed across Türkiye during July 2024. Notably, the Aegean and Marmara regions experienced extreme drought, the Mediterranean region encountered severe drought, and the Southeastern Anatolia region exhibited moderate drought conditions.

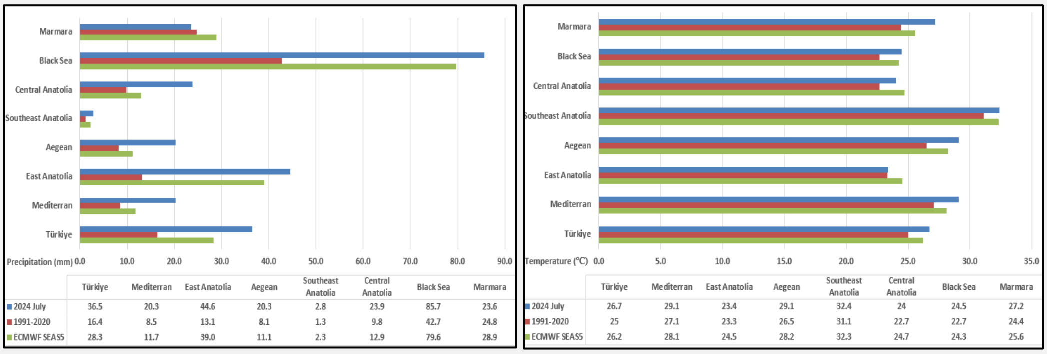


Figure 15. Monthly Total Precipitation and Average Temperature Distributions for July.

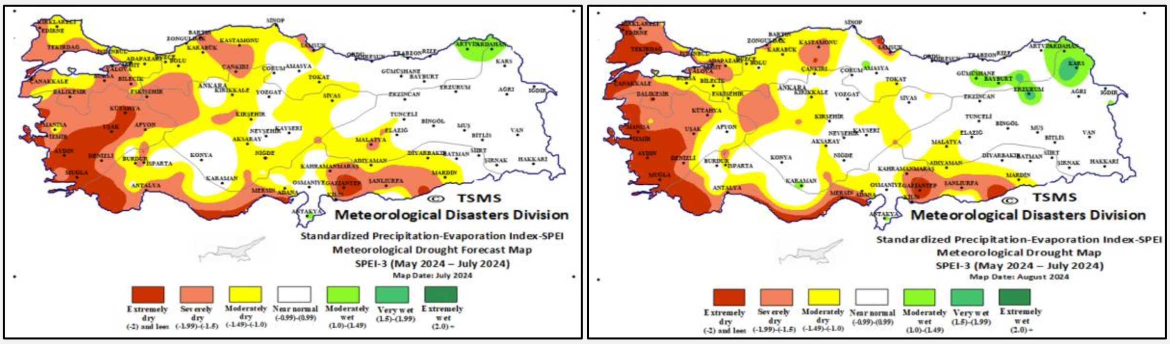


Figure 16. July SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of August SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 temperature forecasts for August (Figure 17), temperatures were projected to exceed seasonal normals across Türkiye and in all regions, while precipitation was expected to remain below average. Based on these predictions, drought conditions of varying intensities were anticipated in most areas of the country with the exception of the Eastern Black Sea region, the northern and eastern parts of the Eastern Anatolia region, and the vicinities of Afyon, Karaman, and Yozgat.

However, meteorological observations for August indicated that temperatures persisted above normal nationwide and across all regions, whereas precipitation levels were recorded as above normal in all regions except for the Southeastern Anatolia, Black Sea, and Marmara regions. This discrepancy suggests that although the forecasted drought conditions generally persisted, the severity of the drought was mitigated in the Inner Aegean, Lakes Region, and the interior parts of Central Anatolia (Figure 18).

August 2024 was evaluated as the second driest month in Türkiye, experiencing extreme drought conditions. The SPEI-3 data for August provide critical insights into the summer climatology; regionally, the Aegean, Marmara, Mediterranean, and Southeastern Anatolia regions experienced extreme drought, the Central Anatolia region encountered severe drought, and the Black Sea region exhibited moderate drought conditions.

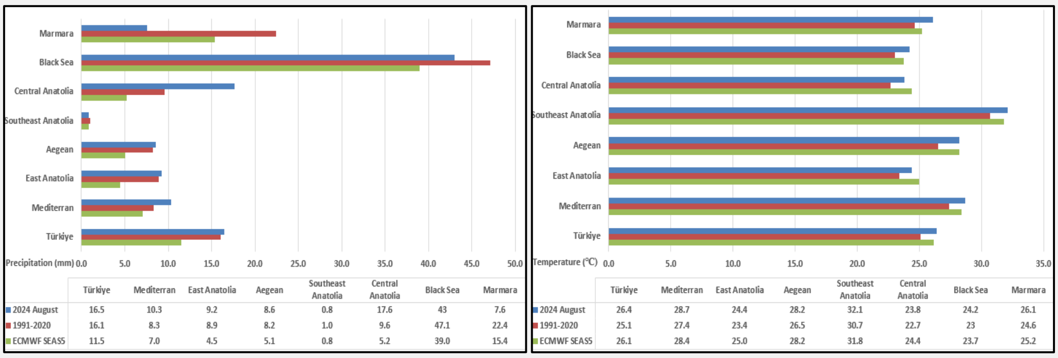


Figure 17. Monthly Total Precipitation and Average Temperature Distributions for August.

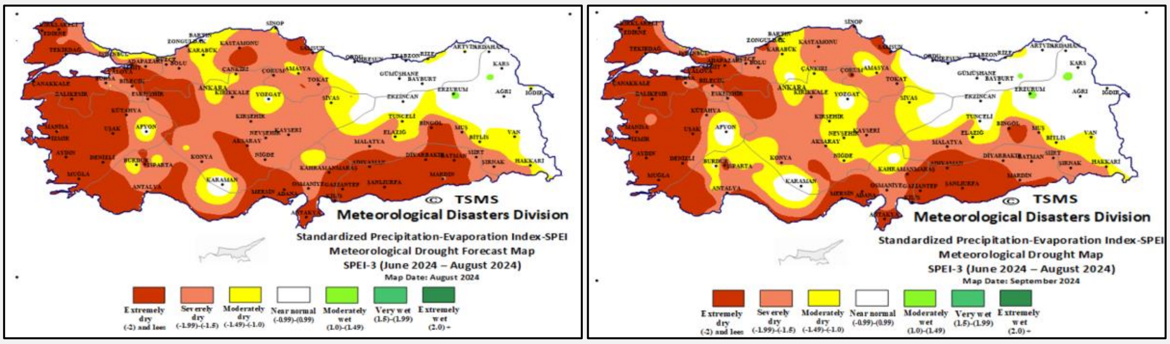


Figure 18. August SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of September SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 forecasts for September, both temperature and precipitation were expected to exceed seasonal normals nationwide and in all regions (Figure 19). Based on these projections, drought conditions of varying intensities were anticipated in the southwestern Marmara Region, Thrace and the areas surrounding İzmit, the western Aegean Region, limited areas in the northwestern and interior parts of the Central Anatolia Region, the coastal zone of the Mediterranean, and the Southeastern Anatolia Region (excluding the vicinity of Diyarbakır) as well as around Şırnak and Hakkâri.

However, in September, both temperature and precipitation levels were observed to be above seasonal normals across the country. Notably, the Eastern and Southeastern Anatolia Regions recorded precipitation levels that exceeded forecasted values. This divergence resulted in an intensification of the forecasted drought conditions in the southwestern Marmara Region, Thrace and the İzmit area, the western Aegean Region, the Mediterranean coastal zone, and the northwestern part of the Central Anatolia Region, while the severity of drought in the Southeastern Anatolia Region diminished and became confined to more limited areas. Regional assessments indicate that the Aegean, Marmara, and Southeastern Anatolia Regions experienced moderate drought conditions in September (Figure 20).

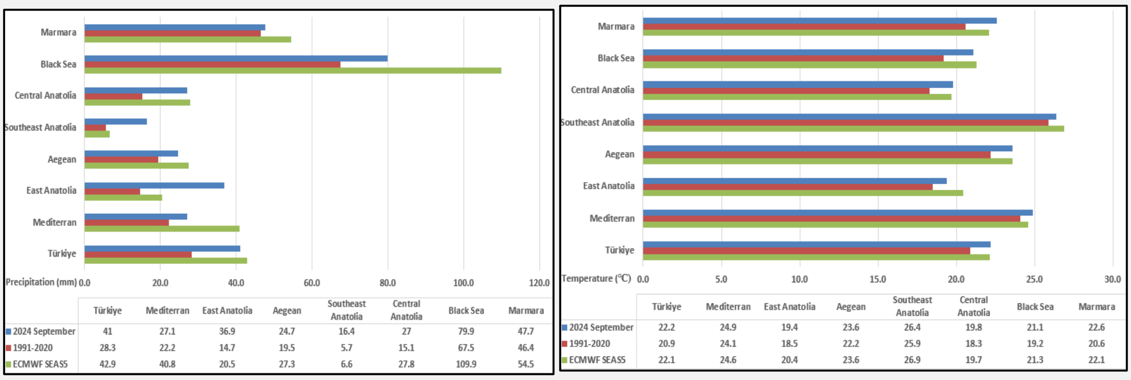


Figure 19. September SPEI-3 Forecast and Observation Meteorological Drought Map.

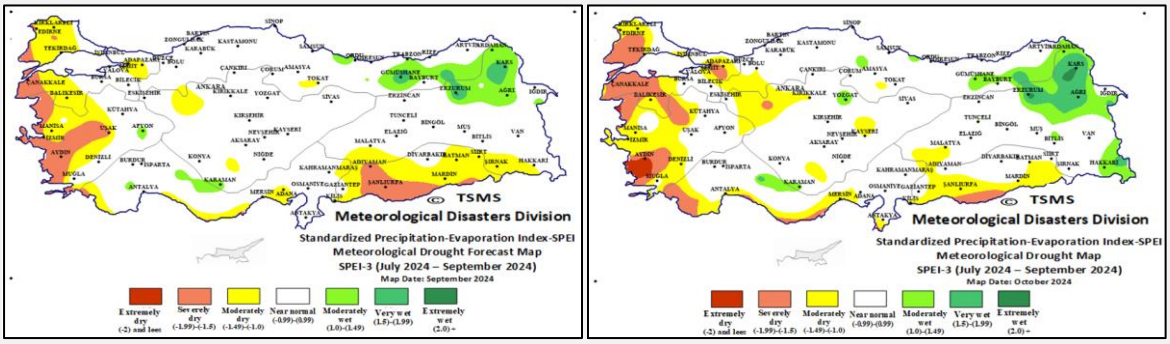


Figure 20. September SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of October SPEI-3 Forecast and Observed Drought Maps

In October, according to ECMWF SEAS5 temperature and precipitation forecasts, temperatures were anticipated to exceed seasonal normals nationwide, while precipitation was expected to fall below seasonal normals across Türkiye except in the Black Sea, Marmara, and Aegean regions (Figure 21). Based on these forecasts, drought conditions of varying intensities were predicted in the eastern Marmara Region, the northwestern parts of the Central Anatolia Region, and in the vicinities of Kayseri, Karaman, Aydın, Denizli, Mersin, Tokat, Amasya, Iğdır, Van, Şırnak, as well as in the southern and eastern parts of the Southeastern Anatolia Region.

However, observed meteorological data for October indicate that, while temperatures in the Mediterranean, Aegean, and Marmara regions remained above normal, precipitation in all regions—except the Black Sea region—was below both seasonal normals and forecasted values. Consequently, drought conditions more severe and extensive than originally projected were recorded across the country. In particular, significant drought was observed in varying intensities in the Marmara, Aegean, Western and Central Mediterranean regions; meanwhile, moderate drought prevailed in the Southeastern Anatolia Region (excluding the vicinities of Diyarbakır and Siirt), as well as in the southwestern parts of Eastern Anatolia and areas around Van, Niğde, Kayseri, and Gümüşhane (Figure 22).

Regional assessments indicate that the Aegean, Mediterranean, and Marmara regions experienced severe drought conditions, whereas the Southeastern Anatolia Region exhibited moderate drought conditions.

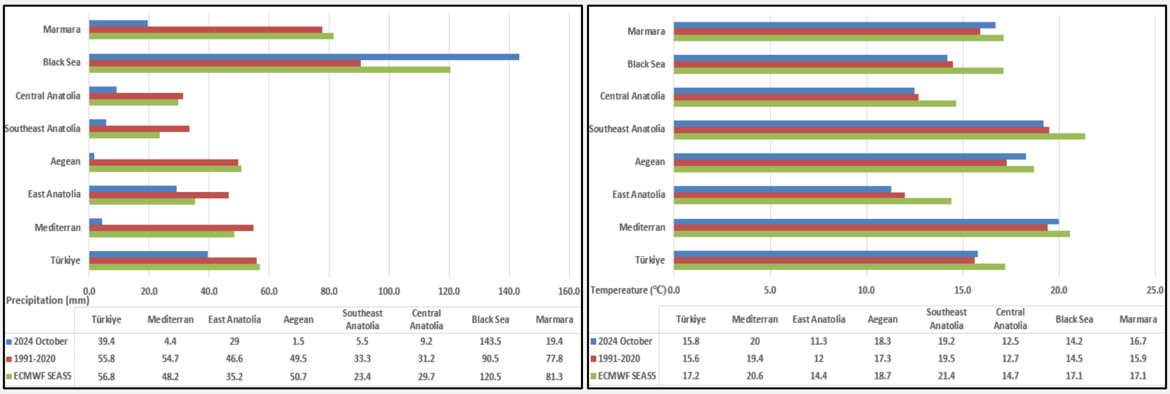


Figure 21. October SPEI-3 Forecast and Observation Meteorological Drought Map.

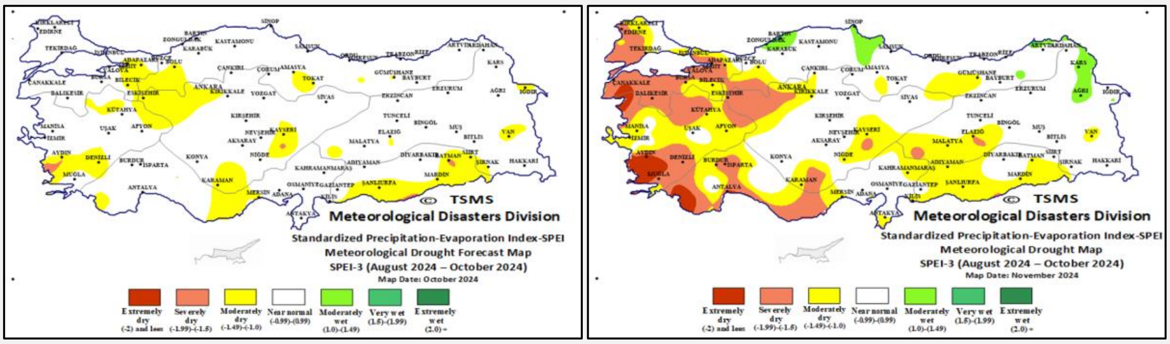


Figure 22. October SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis of November SPEI-3 Forecast and Observed Drought Maps

According to ECMWF SEAS5 temperature forecasts for November, temperatures were predicted to exceed seasonal normals nationwide with the exception of the Central Anatolia, Black Sea, and Marmara regions while precipitation was expected to fall below seasonal normals in all regions except the Black Sea region (Figure 23). Based on these forecasts, drought conditions of varying intensities were anticipated in the Marmara, Aegean, and Western and Central Mediterranean regions, as well as in the vicinities of Hatay and Kahramanmaraş, the northwestern and eastern parts of Central Anatolia, and the southwestern parts of Eastern Anatolia.

However, actual observations for November revealed that temperatures were above normal in the Mediterranean and Aegean regions and below normal in the remaining regions. Meanwhile, precipitation was recorded as below normal in all regions except the Black Sea, yet it exceeded the forecasted values across the board. This discrepancy led to a reduction in drought severity and a contraction of the affected areas in the Aegean, Marmara, and Mediterranean regions (Figure 24).

Specifically, drought conditions of varying intensities were observed in the western Marmara region, the interior and southern parts of the Aegean region, the Western Mediterranean, the northwestern and eastern parts of Central Anatolia, the southern parts of Southeastern Anatolia, as well as in the vicinities of Hatay and Elazığ. The SPEI-3 data for November provide valuable insights into the autumn season; during autumn 2024, the Aegean region experienced severe drought conditions, whereas the Marmara and Mediterranean regions exhibited moderate drought conditions.

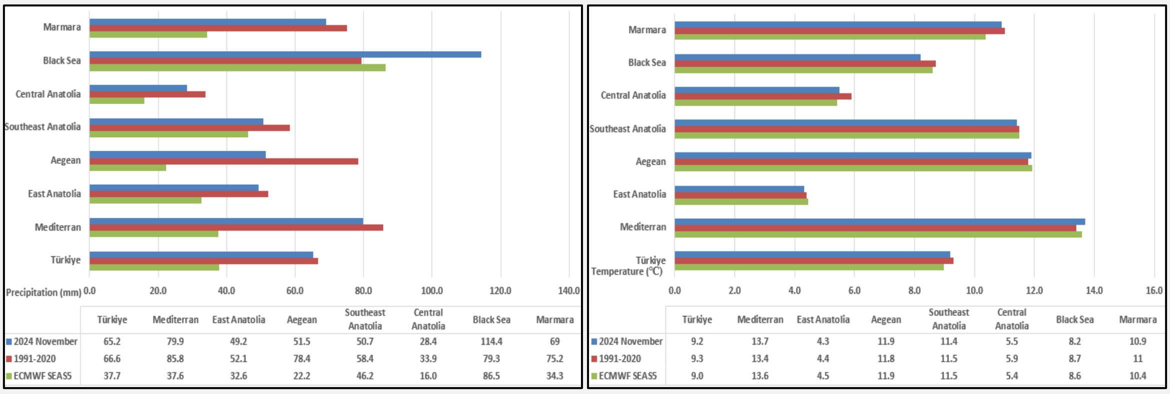


Figure 23. November SPEI-3 Forecast and Observation Meteorological Drought Map.

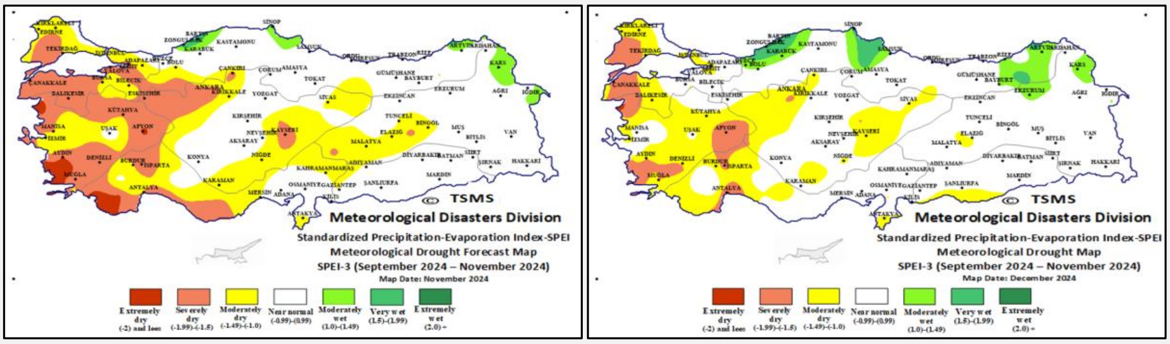


Figure 24. November SPEI-3 Forecast and Observation Meteorological Drought Map.

Analysis and Validation of December SPEI-3 Forecast and Observed Drought Maps

According to the ECMWF SEAS5 temperature forecasts for December, temperatures across Türkiye and in all regions were expected to exceed seasonal normals, whereas precipitation was anticipated to fall below seasonal normals in all regions except the Aegean and Marmara Regions (Figure 25). Based on these forecasts, drought conditions of varying intensities were predicted for several areas: the western part of the Marmara Region and its surroundings (including the Istanbul area), the eastern part of the Aegean Region, the vicinity of Manisa, the Lakes Region, and the Central Anatolia Region (excluding its interior and the Eskişehir area), the southern parts of the Southeastern Anatolia Region, limited areas in the southern portion of the Eastern Anatolia Region, as well as the vicinities of Gümüşhane, Osmaniye, Kilis, and Hatay.

Observed data revealed that temperatures exceeded normal values in all regions. Precipitation, on the other hand, was recorded above both the seasonal normals and the forecasted values in the Mediterranean, Aegean, and Marmara Regions, while in the Eastern Anatolia, Central Anatolia, Black Sea, and Southeastern Anatolia Regions, precipitation remained below normal. This resulted in drought conditions that were confined to limited areas in the Aegean, Marmara, and Mediterranean regions, while in the Southeastern Anatolia, Central Anatolia, and the southern and eastern parts of Eastern

Anatolia—as well as in the interior sections of the Central and Eastern Black Sea Regions—drought conditions were more severe and widespread than anticipated.

Specifically, varying intensities of drought were observed in the Eastern Mediterranean, the southern and eastern parts of the Eastern Anatolia Region, and across extensive areas of the Aegean Region (with the exception of Uşak, Kütahya, Emirdağ, Bergama, and Bolvadin); in large parts of the Southeastern Anatolia Region (excluding Siirt, Diyarbakır, and Batman); in the interior and eastern sections of the Central Anatolia Region (excluding Kayseri); and in the interior sections of the Central Black Sea Region, as well as in the Thracian and southwestern parts of the Marmara Region. Regional assessments indicate that the Southeastern Anatolia Region exhibited moderate drought conditions, whereas the Central Anatolia Region approached the threshold of moderate drought (Figure 26).

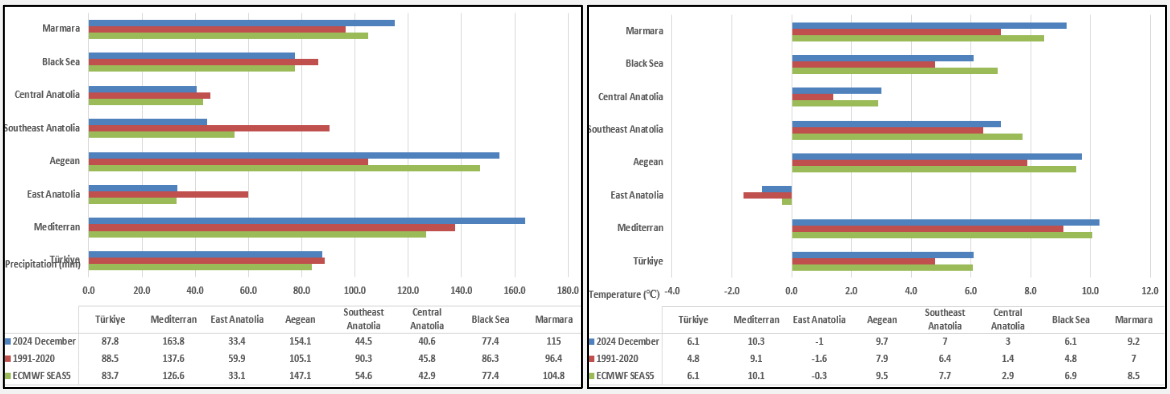


Figure 25. December SPEI-3 Forecast and Observation Meteorological Drought Map.

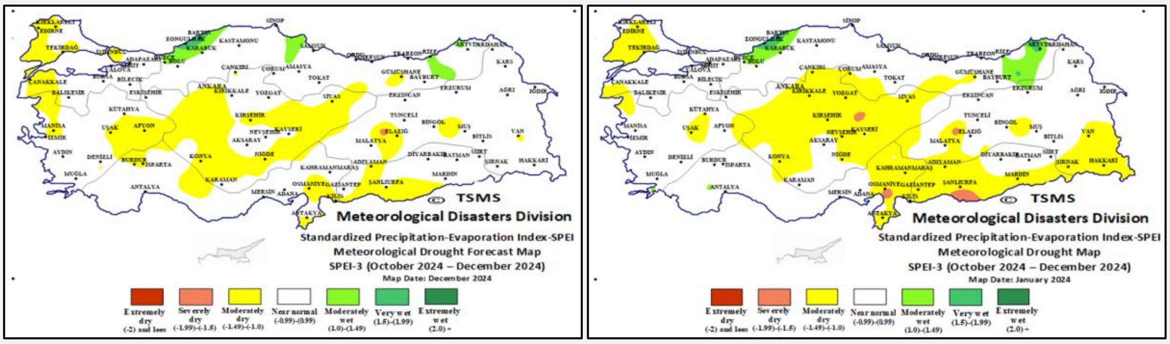


Figure 26. December SPEI-3 Forecast and Observation Meteorological Drought Map.

Annual Spatial and Temporal Variation in Türkiye

Since 2005, Türkiye has experienced a noticeable increase in temperatures without a corresponding significant change in precipitation, which has led to more frequent and severe drought conditions from that year onward. Analysis of the 12-month Standardized Precipitation-Evapotranspiration Index (SPEI-12) reveals that droughts of varying intensities occur in different months (Figure 27). Drought periods lasting 12 months were detected during 1973–1974, 14 months during 1989–1990, 11 months during 1990–1991, 8 months in 1994, 24 months during 1999–2001, 26 months during 2007–2009, 3 months in 2011, 14 months during 2013–2015, 34 months during 2016–2018, and 48 months during 2020–2023. Additionally, a 9-month drought was observed in 2024. (Drought durations were evaluated such that the drought period begins when SPEI ≤ –1 and ends when SPEI = 0.) The most severe drought was recorded in May 2021.

In terms of annual temporal variation, ten years (1989, 1990, 1999, 2008, 2013, 2017, 2020, 2021, 2022, 2024) experienced drought conditions. Among these, seven years were classified as moderately drought-affected (1989, 1990, 1999, 2013, 2017, 2021, 2022) and three years as severely drought-affected (2008, 2020, 2024). The driest year was 2008, with 2024 being the second driest. Over the period 1971–2024, Türkiye experienced normal conditions 65% of the time, drought conditions 19% of the time, and humid conditions 16% of the time.

According to the 2024 annual meteorological drought map based on the SPEI-12 (January–December), varying intensities of drought were evident in the Marmara, Aegean (excluding Çeşme), Central Anatolia, Mediterranean (excluding the coasts of the Western and Eastern Mediterranean), the interior parts of the Western Black Sea, the Central Black Sea, as well as in the Erzincan, Malatya, Bingöl, Arapgir, Çemişgezek, Solhan, and Keban areas of Eastern Anatolia, and in the western part of the Southeastern Anatolia region.

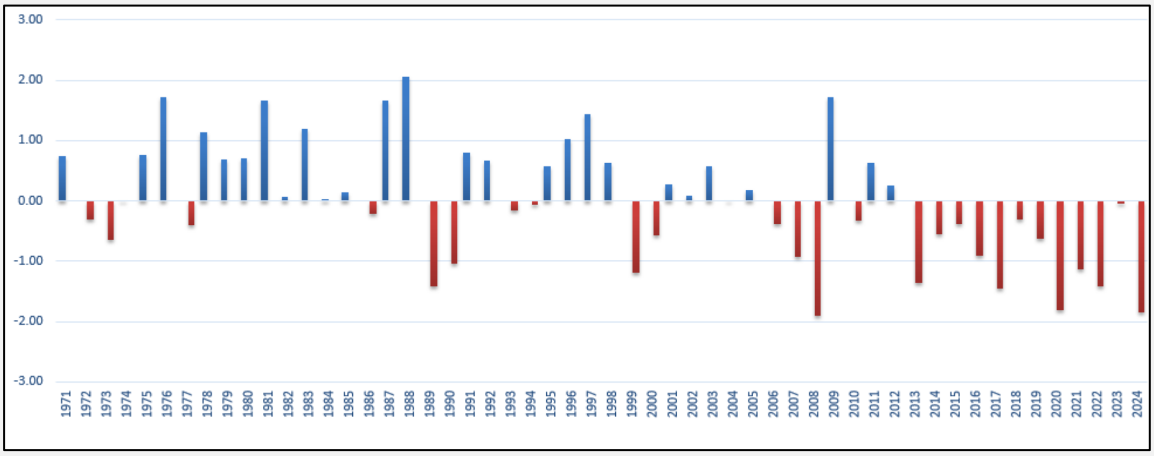


Figure 27. Temporal Variation of Annual SPEI-12 in Türkiye

Verification Results of SPEI-3 Drought Events

The verification results for the 2024 SPEI-3 monthly drought events, based on a categorical approach, are presented in Table 3. In this analysis, observed and forecasted drought events were evaluated using a binary classification (drought/no drought, defined by SPEI ≤ -1) without subdividing them into classes. The table reports the performance metrics of the model for each month, including accuracy and other indices that assess drought forecast performance. Verification provides insights into the model's reliability and highlights areas for potential improvement.

According to the performance scale, April, June, July, and August stand out due to their high detection rates and low false alarm rates, while March and May also exhibit commendable performance. Although September shows a balanced performance, its rate of missed detections is slightly elevated. In October, the model clearly underestimates drought events. For February, although the false alarm rate is very low, many drought events are missed, as indicated by low POD (Probability of Detection) and BIAS values. In November, despite a good detection rate, the occurrence of false alarms and overpredictions is notable. December and January are generally balanced, albeit with moderate detection rates.

Overall, the model exhibits high drought forecast accuracy, with satisfactory HIT and POD values in most months. However, there is a tendency to underestimate drought events, particularly in October and February. This is also reflected in the monthly average consistency between SPEI-3 forecasts and observations (across all moisture conditions: humid/normal/drought), which are calculated as follows: 84% in January, 72% in February, 78% in March, 83% in April, 82% in May, 89% in June, 83% in July, 93% in August, 75% in September, 59% in October, 74% in November, and 77% in December. Monthly correlation values exceed 83% in all months except October, which remains at 64%. The performance of the SPEI-3 and SPEI-12 drought forecasts is directly dependent on the accuracy of the ECMWF SEAS5 seasonal precipitation and temperature forecasts, which positively influence the drought predictions. In conclusion, although the overall forecast performance of the model is high, improvements are required for certain months.

DISCUSSION

The analysis of drought events in Türkiye using the Standardized Precipitation Evapotranspiration Index (SPEI) has provided critical insights into the temporal and spatial variations of drought conditions across the country. The findings indicate a notable increase in the frequency and severity of drought periods, particularly since the late 1990s, with the most severe and prolonged drought occurring in the water year 2020-2021, where "severe drought" conditions persisted for twelve consecutive months (Erlat & Güler, 2023).

Table 3. Distribution of SPEI-3 (SPEI ≤ –1) Drought Events and Categorical Approach Performance Scale

			Observed		SPEI-3 Drought				
Total number of events: 190			Yes	No	FAR	POD	HIT	BIAS	TS
January	Prediction	Yes	10	4	0.29	0.53	0.93	0.74	0.43
		No	9	167					
February		Yes	23	3	0.12	0.38	0.78	0.43	0.36
		No	38	126					
March		Yes	37	14	0.27	0.73	0.85	1.00	0.57
		No	14	125					
April		Yes	113	2	0.02	0.78	0.83	0.80	0.77
		No	31	44					
May		Yes	77	18	0.19	0.86	0.84	1.06	0.71
		No	13	82					
June		Yes	141	2	0.01	0.88	0.89	0.89	0.87
		No	19	28					
July		Yes	102	16	0.14	0.94	0.88	1.09	0.82
		No	6	66					
August		Yes	148	10	0.06	0.98	0.93	1.05	0.92
		No	3	29					
September		Yes	51	11	0.18	0.7	0.83	0.85	0.61
		No	22	106					
October		Yes	42	5	0.11	0.41	0.66	0.46	0.39
		No	60	83					
November		Yes	64	39	0.38	0.94	0.77	1.51	0.60
		No	4	83					
December		Yes	38	17	0.31	0.63	0.79	0.92	0.49
		No	22	113					

These results are consistent with previous studies that have reported a rising trend in drought occurrences in Türkiye. For instance, research analyzing data from 1951 to 2022 revealed a shift in SPEI values from "normal" to "moderate and severe drought" classes over the past 72 years. Similarly, an analysis of drought intensity and frequency using SPEI over a 50-year period identified a noticeable increase in drought periods, with the most widespread event observed in 2001 (Serkendiz et al. 2024).

The regional distribution of droughts also aligns with findings from other studies. The identification of drought hotspots in Western Anatolia, Central and Southern Anatolia, Southeastern Anatolia, and Eastern Anatolia corresponds with previous research highlighting these regions as particularly susceptible to drought conditions. The increasing trend in drought events can be attributed to several factors. Rising temperatures and increasing evapotranspiration rates have been identified as significant contributors to the intensification of droughts and the extension of dry periods. Additionally, changes in atmospheric circulation patterns, such as the weakening of the Siberian anticyclone and the strengthening of the Azores anticyclone, have led to increased winter droughts in the eastern Mediterranean region (Türkeş, 2020). A critical limitation encountered in the application of ECMWF SEAS5 for Türkiye is the reduced skill in seasonal precipitation forecasts, particularly in semi-arid and topographically complex regions like Central and Eastern Anatolia. The model's 36 km resolution, while suitable for large-scale circulation, fails to capture localized convective precipitation patterns and orographic effects prevalent in these regions. This spatial under-resolution contributes to discrepancies between forecasted and observed drought intensities in the SPEI-3 assessments for months such as October and February. Moreover, the simplified representation of regional atmospheric circulation, including the Mediterranean storm tracks and continental air masses, likely reduces SEAS5's ability to predict precipitation anomalies driven by local dynamics. Integrating downscaled or bias-corrected forecasts could enhance drought prediction performance in Anatolian subregions.

These findings underscore the necessity for comprehensive water resource management strategies and adaptive measures to mitigate the adverse impacts of increasing drought frequency and severity in Türkiye. Future research should focus on developing predictive models that incorporate climate change projections to better anticipate and manage drought risks.

CONCLUSION

In this study, seasonal drought forecasts for Türkiye in 2024 were evaluated using the Standardized Precipitation Evapotranspiration Index (SPEI) method for 3-month accumulation periods. Additionally, trends in annual total precipitation and average temperature series, along with annual spatial and temporal drought analyses, were examined.

Since 2005, Türkiye has experienced a significant increase in temperatures without substantial changes in precipitation levels. This trend has led to more frequent and severe drought events between 2005 and 2024. Rising temperatures accelerate evaporation from vegetation and soil surfaces, increasing total evapotranspiration. During periods of extreme heat, potential evapotranspiration (PET) values rise markedly, causing rapid depletion of soil moisture and heightened water demand from plants, thereby elevating the risk of hydrological and agricultural droughts. In regions where precipitation remains constant or becomes irregular, increased temperatures exacerbate water deficits, hastening the progression from meteorological to hydrological and agricultural droughts. Furthermore, heightened evaporation due to rising temperatures accelerates the depletion of existing water resources, disrupting the water balance. These interactions are particularly critical in semi-arid and arid regions like Türkiye, where they significantly intensify the severity and frequency of drought events. Over the past 54 years, at the SPEI-12 monthly scale, Türkiye experienced normal conditions 65% of the time, humid conditions 16%, and drought conditions 19%. The years 2008, 2020, and 2024 were classified as severely dry, while 1989, 1990, 1999, 2013, 2017, 2021, and 2022 were moderately dry. The driest year was 2008, with 2024 recorded as the second driest year.

In 2024, at the SPEI-3 monthly accumulation scale, droughts affected different regions of Türkiye during various periods, with certain months experiencing more intense conditions. April, June, and August were identified as the driest months nationwide, with June witnessing the most severe drought conditions. The winter season of 2024 was moderately dry across Türkiye, notably impacting the Aegean and Central Anatolia regions. During spring, moderate drought conditions prevailed nationwide, with the Marmara and Mediterranean regions exhibiting similar patterns; however, the Aegean region experienced severe drought conditions. The summer season was characterized by extreme drought conditions throughout Türkiye: the Aegean, Marmara, Mediterranean, and Southeastern Anatolia regions faced extreme droughts, Central Anatolia experienced severe drought, and the Black Sea region encountered moderate drought conditions. In the autumn season, the Aegean region faced severe drought, while the Marmara and Mediterranean regions experienced moderate drought conditions.

The accuracy of drought forecasts at the SPEI-3 and SPEI-12 monthly accumulation scales is directly dependent on the precision of ECMWF SEAS5 seasonal precipitation and temperature forecasts. The reliability of these forecasts positively influences the accuracy of drought predictions. The ECMWF seasonal forecasting system, operating on a global scale with a surface grid resolution of 36 km, primarily represents large-scale weather systems. However, the consistency of SEAS5 seasonal forecasts, particularly for precipitation and temperature in mid-latitudes, varies. Precipitation forecasts are generally less accurate due to their sensitivity to atmospheric chaos and regional factors such as topography and local cyclonic/anticyclonic systems. In contrast, temperature forecasts are relatively more consistent, being more directly related to large-scale atmospheric patterns (e.g., ocean surface temperatures and high-pressure systems). While the model's overall drought forecasting performance is high, accuracy declines in certain months, indicating a need for further improvements. Specifically, the model tends to underpredict drought events in October and February. Factors limiting forecast accuracy include the model's 36 km surface grid resolution, the extended range of seasonal forecasts, the complexity and variability of the atmosphere, the movement of air masses, latitudinal effects, temperature variability, the low consistency of long-term precipitation forecasts, and insufficiently detailed consideration of topography.

In conclusion, the increase in temperatures and the prevalence of drought conditions underscore the escalating risks associated with climate change and the necessity for effective adaptation strategies. Variability in precipitation data and the occurrence of regional droughts necessitate a reevaluation of agricultural and water management policies. In this context, more accurate modeling of future climate projections and extreme weather events is crucial for mitigating future risks and enhancing societal resilience. Incorporating these improvements will enhance both the scientific robustness and societal applicability of seasonal drought forecasts in Türkiye. By addressing resolution limitations, strengthening statistical and contextual analysis, promoting transparency, and reinforcing policy integration, future research can further optimize early warning systems and support sustainable drought management strategies in a changing climate.

Lessons for Policy

Early Warning System Enhancement: The demonstrated utility of SEAS5 in capturing drought trends supports its integration into national drought early warning systems (DEWS). Operationalizing seasonal forecasts for agriculture and water planning can help mitigate socioeconomic impacts.

Drought-Responsive Agricultural Planning: Policymakers should prioritize crop insurance schemes and adaptive planting calendars informed by seasonal drought forecasts, especially in high-risk regions such as the Aegean and Southeastern Anatolia.

Investment in Forecast Downscaling: To overcome spatial resolution limitations, investment in regional climate modeling or statistical downscaling techniques is recommended, particularly for provinces prone to convective or orographic rainfall.

Limitations and Recommendations for Future Research

This study provides a comprehensive assessment of meteorological drought forecasts in Türkiye using ECMWF's SEAS5 model and the SPEI drought index. While the model demonstrated high predictive skill in several months, especially during the summer season, there remain several areas for methodological and operational enhancement. Based on this evaluation, we recommend the following improvements. These findings underscore the necessity for methodological and operational enhancements in meteorological drought forecasting in Türkiye, suggesting that future research should focus on enhancing model resolution through downscaling, refining statistical rigor with multi-class drought classifications and ensemble forecasting, deepening contextual analysis by linking forecast errors to underlying physical processes and interdisciplinary impacts, improving reproducibility and transparency through open data and code, and strengthening policy linkages to integrate forecasts into national drought information systems and develop cost-benefit tools for early warning interventions.

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