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Drought Assessment in Greece Using SPI and ERA5 Climate Reanalysis Data

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Abstract: The present work aims to assess the spatial variability and the trends of the annual rainfall and meteorological drought in the entire territory of Greece utilising the ERA5 reanalysis precipitation dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF), which spans from January 1940 to December 2022 (an 83-year period). Drought assessment took place based on the Standardized Precipitation Index (SPI) for timescales ranging from 1 month to 12 months. Evaluation was carried out by calculating SPI using observed rainfall data from five meteorological stations. The annual rainfall and drought severity trends for timescales of 1 (SPI-1), 3 (SPI-3), 6 (SPI-6) and 12 (SPI-12) months were analysed using the Theil–Sen slope method and the Mann–Kendall trend test. The results indicate significant, both increasing and decreasing, annual precipitation trends at the 95% significance level for the Aegean Islands, western Crete and western mainland of Greece. The results also indicate significant drought trends for SPI-12 for the Aegean Islands and western Peloponnese. Trend analysis for SPI-1, SPI-3 and SPI-6 indicate a mixture of non-significantly increasing wetting trends and increasing drought trends at the national scale. In conclusion, the ERA5 dataset seems to be a valuable tool for drought monitoring at the spatial scale.

Keywords: meteorological drought; Standardized Precipitation Index (SPI); Theil–Sen slope estimator; Mann–Kendall trend; monthly ERA5 reanalysis data

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1. Introduction

Climate change is foreseen to increase the risk of natural hazards and extreme events (floods, droughts, etc.), thus posing an additional risk for the economy, health and life [1]. Several researchers have assessed the impacts of climate change on different regions around the globe [2–17]. In addition, various studies have assessed rainfall trends for different regions around the world (e.g., [18–31]).

Drought is among the most common and disastrous natural hazards, having direct and/or indirect economic, social and environmental impacts. Moreover, it is highly related to the United Nations Sustainable Development Goals, especially SDGs 1, 2, 6, 10, 13 and 15. In addition, climate change may have adverse impacts on the hydrological cycle, resulting in more frequent weather extremes (floods and droughts). According to Tabari and Willems [1], "*Sustainable development would reduce population exposure to drought by 70% compared to fossil-fueled development. Furthermore, it halves the number of countries facing a fivefold increase in drought risk*". As a result, understanding droughts and the mitigation of adverse impacts of drought phenomena, as well as sustainable drought proactive planning [32], constitute important aspect of sustainable development in the new era. To this

end, drought monitoring using reanalysis data at the regional scale can be a valuable tool in the new era.

Researchers have claimed that both drought hazards and risks will intensify as a result of the projected climate change (e.g., [33,34]). However, drought quantification constitutes a rather difficult task as it is based on various meteorological variables (e.g., precipitation and temperature; [35–37]). To assess drought, these meteorological variables are used as an input to estimate drought indices, which constitute "numerical representations of drought severity" [38].

In recent years, various researchers have applied well-established and newly developed drought indices for assessing meteorological, hydrological and agricultural drought in different areas around the globe (e.g., [39–67]). Depending on the purpose of the drought analysis, different drought indices can be selected to assess and characterise drought with adequate accuracy (e.g., [39,45]). Complex and data-demanding indices may be suitable for specialised tasks, for instance, the recently proposed Modified Palmer Drought Severity Index (MPDSI) for monitoring agricultural drought by Yu et al. [39] and the integrated remote sensing drought monitoring indices proposed by Zhang et al. [45]. Both indices have been extensively tested across China. However, simple indices can provide sufficiently accurate and comprehensible results for a wide range of drought analyses (e.g., [68–70]).

The Standardized Precipitation Index (SPI) is a typical example of a simple drought index, since it only requires precipitation data for its application. SPI has been used in a wide variety of drought studies for analysing all the aforementioned types of drought. Another popular and well-tested index is the RDI [71,72], which, in addition to precipitation, requires evapotranspiration data, so it is more advanced.

According to the World Meteorological Organization [73], drought assessment should take place based on a complete timeseries comprising at least 30 years of monthly data, with the optimum being 50 to 60 years of monthly data. In recent years, due to the lack of continuous, long-term, adequate spatial coverage and reliable meteorological measurements, a growing number of studies have used satellite and/or reanalysis datasets for ungauged and/or purely gauged regions (e.g., [74–77]). For instance, Vangelis et al. [77] used the CMORPH rainfall reanalysis dataset of the National Oceanic and Atmospheric Administration for assessing the relationship of flood discharge probabilities with extreme rainfall probabilities. Varlas et al. [74] employed the ERA5 monthly precipitation dataset for a 71-year period (1950 to 2020) to conduct a trend analysis of annual precipitation over Greece. The most widely used reanalysis datasets are CMORPH, ERA-Interim, ERA5, NCEP CFSR, JRA55 and MERRA-2 [75,78].

Several researchers around the world have utilised the ERA5 reanalysis dataset for drought assessment and monitoring and for the development of global monitoring systems (e.g., [35,75,79–81]). For instance, Zhang et al. [81] used the ERA5 dataset for the estimation of the Soil Water Deficit Index (SWDI) in four provinces of China. Lee et al. [79] assessed meteorological drought for the Korean Peninsula using seven drought indices that consider only precipitation. They also used observational data to verify the accuracy of drought detection, concluding that the SPI and Rainfall Anomaly Index (RAI) constitute the most accurate drought indices for the study area. Torres-Vázquez et al. [80] reported a good agreement between the ERA5 reanalysis dataset and the observed data reported by the Spanish Meteorological Agency. They also employed the ERA5 dataset for seasonal drought prediction in Spain. Vicente Serrano et al. [35] utilised the ERA5 reanalysis dataset for the development of a global monitoring system of drought. The developed monitoring system was based on the Standardized Precipitation Evapotranspiration Index (SPEI). Finally, Tladi et al. [75] assessed two reanalysis products, namely the rainfall data of the National Centers for Environmental Prediction–Climate Forecast System Reanalysis (NCEP-CFSR) and the ERA5 dataset for a basin in South Africa in terms of meteorological drought monitoring, concluding that the ERA5 dataset outperformed NCEP-CFSR for the study area.

The goal of the present work is threefold: (i) to assess precipitation over Greece based on monthly ERA5 reanalysis data for an 83-year period (January 1940 to Decem-

ber 2022) and identify annual trends; (ii) to assess meteorological drought over Greece calculated based on SPI using the ERA5 reanalysis dataset, identifying drought trends in different timescales; and (iii) to evaluate the suitability of the ERA5 reanalysis dataset for drought characterisation. Evaluation took place using observed rainfall data from five meteorological stations. Trend analysis for precipitation and SPI was performed based on the widely used Mann–Kendall trend test and Sen's slope method using a MATLAB code developed in-house. The manuscript has the following structure: Section 2 describes the methodological framework and the data used; Sections 3 and 4 present and discuss the results of our analysis, respectively; and Section 5 follows with a summary and concluding remarks.

2. Materials and Methods

The framework of the study is presented in the workflow of Figure 1 and comprises the following parts: (i) monthly precipitation data acquisition for Greece from ERA5 reanalysis precipitation data, (ii) calculation of the SPI meteorological drought index for Greece based on the monthly precipitation data, (iii) analysis of trends of both precipitation and drought and (iv) evaluation of the ERA5 dataset. All computations were undertaken in the MATLAB computing environment using the Climate Data Toolbox (CDT; [82]) and in-house developed MATLAB codes (e.g., [83]).

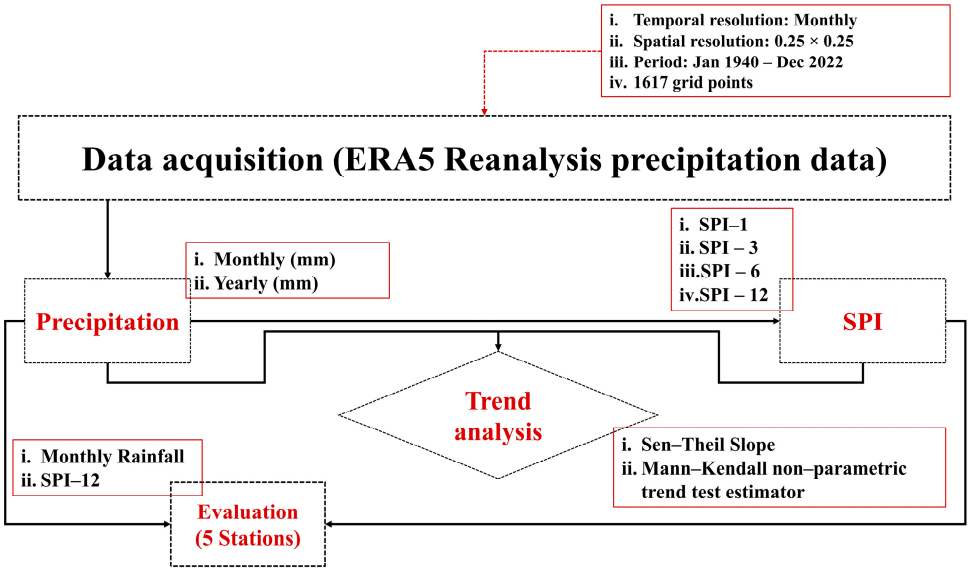


Figure 1. Workflow of the study methodology.

2.1. Climate Data and Study Area

To assess meteorological drought, we used historical reanalysis monthly precipitation data obtained from the ERA5 reanalysis dataset [84]. The analysis took place at the national level, and more specifically, the domain under study was the entirety of Greece; thus, monthly ERA5 precipitation data of the European Centre for Medium-Range Weather Forecasts (ECMWF) were acquired for a region between 18.00 W–30.00 E and 34.00 N–42.00 N with a spatial resolution of 0.25° × 0.25°. ERA5 monthly precipitation data were downloaded (https://cds.climate.copernicus.eu, accessed on 4 June 2023) for each month for all 1617 grid points used over the 83-year period spanning from January 1940 to December 2022. Monthly precipitation values were then used to calculate the total annual precipitation (i.e., sum of monthly values) and conduct trend analyses. Monthly precipitation values for each grid point of the domain under study were also employed to calculate the SPI for 1-, 3-, 6- and 12-month timescales and for drought trend analysis using SPI.

2.2. The SPI Drought Index

The SPI is a well-established drought index that has been used in numerous studies around the world over the last three decades. The index is usually preferred due to its simple, customisable and solid structure; low data requirements; worldwide use and recognition; and comprehensible outcomes with universal interpretation.

The index was introduced by McKee et al. [85] based on a standardisation approach fitting the precipitation timeseries accumulated for specific intervals of time (timescales) to a proper statistical distribution (typically gamma) and further transformed into standard normal distribution.

The probability density function (p.d.f.) for the gamma distribution is:

$$g(x) = \frac{1}{\beta^{\alpha}\,\Gamma(\alpha)} x^{\alpha-1}\, e^{-x/\beta} \tag{1}$$

where α is a shape parameter ($\alpha > 0$); β is a scale parameter ($\beta > 0$); x is the precipitation value ($x > 0$); and $\Gamma(\alpha)$ is the gamma function, expressed as $\int_0^{\infty} y^{\alpha-1}e^{-y}dy$.

According to Thom [86], the α and β parameters are assessed as follows:

$$\alpha = \frac{1+\sqrt{1+\frac{4A}{3}}}{4A} \quad , \quad \beta = \frac{\overline{x}}{\alpha} \tag{2}$$

where $A = \ln(\overline{x}) - \frac{\sum \ln(x)}{n}$ and n is the number of observations in the timeseries.

A precipitation event has a cumulative probability $G(x)$ given by:

$$G(x) = \int_0^x g(x)dx = \frac{\int_0^x x^{\alpha-1}\, e^{-x/\beta}dx}{\beta^{\alpha}\,\Gamma(\alpha)} \tag{3}$$

By letting $t = x/\beta$, Equation (3) becomes the incomplete gamma function:

$$G(x) = \frac{\int_0^x t^{\alpha-1}\, e^{-t}dt}{\Gamma(\alpha)} \tag{4}$$

Since the gamma distribution is not defined for $x = 0$, the cumulative probability of zero precipitation (q) is taken into account separately; the final cumulative probability is then calculated using the following formula [87]:

$$H(x) = q + (1-q)G(x) \tag{5}$$

For assessing SPI, the approximation proposed by Abramowitz and Stegun [88] can be used to transform the cumulative probability distribution of Equation (5) into standard normal distribution:

$$\text{SPI} = -\left(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right), \quad 0 < H(x) \le 0.5 \tag{6}$$

where $t = \sqrt{\ln\left(1/H(x)^2\right)}$.

$$\text{SPI} = t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\,, \quad 0.5 < H(x) \le 1.0 \tag{7}$$

where $t = \sqrt{\ln\left(1/\left[1-H(x)^2\right]\right)}$ and the values of the various constants are $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.43278$, $d_2 = 0.189269$ and $d_3 = 0.001308$.

The intensity of drought events based on SPI can be classified according to the value of SPI. The most typical classification is presented in Table 1.

Table 1. Classification of drought intensity based on SPI values.

SPI Value	Category
≥2.00	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0 to 0.99	Near normal (mildly wet)
0 to −0.99	Near normal (mild drought)
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
≤−2	Extreme drought

The proper selection of timescales, depending on the aim of the study, is critical for getting meaningful and adequately interpretable outcomes. Several factors, including the system under study, the climatic characteristics of the area, data availability and others, should be considered to select the appropriate timescale for drought analysis [70]. Indicatively, for SPI and similar multi-scalar drought indices, the 1-month timescale may represent the monthly percentage of monthly precipitation, the 3-month and 6-month timescales are suitable for agricultural drought identification and the 12-month timescale can represent drought impacts on various systems within the entire hydrological year (WMO [73]). Although timescales greater than 12 months can also be used, these require careful analysis to avoid misinterpretations [73]; therefore, these were not included in the present study. The SPI values for the selected timescales are usually plotted on drought maps to assess the areal extent of drought [89].

2.3. Trend Analysis

The Theil–Sen slope (Sen's slope) estimator and the non-parametric Mann–Kendall statistical test [90–93] are widely used for testing and quantifying trends in hydrometeorological timeseries (e.g., [94]). Based on the Mann–Kendall non-parametric statistical test, the null hypothesis (H_0) assumes that the data ($x_1, \ldots, x_n$) denote a sample of n independent and randomly ordered variables. The null hypothesis implies that there is no trend against the alternative of the trend. The Theil–Sen calculator (Sen's slope; [90,91]) constitutes a widely used approach for linear regression [61]. Based on this method, the median slope is calculated among all pairs of two-dimensional sample points ($i = 1, \ldots, N$). The statistic S of the Mann–Kendall test can be calculated as follows [92,93]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{8}$$

where n is the number of data points, x_i and x_j are the data values in the time series i and j for every $j > i$, and $\operatorname{sgn}(x_j - x_i)$ is the sign function computed as:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} +1, & if \;\; x_j - x_i > 0 \\ 0, & if \;\; x_j - x_i = 0 \\ -1, & if \;\; x_j - x_i < 0 \end{cases} \tag{9}$$

Variance ($Var(s)$), standard deviation (sd) and the Z_S (standard normal test variable) are computed as follows:

$$Var(S) = \frac{n \cdot (n-1) \cdot (2 \cdot n + 5) - \sum_{i=1}^{k} tg_i (tg_i - 1) \cdot (2tg_i + 5)}{18} \tag{10}$$

$$sd = \sqrt{Var(S)} \tag{11}$$

$$Z_S = \begin{cases} \frac{S-1}{sd}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{sd}, & \text{if } S < 0 \end{cases} \quad (12)$$

where n is the number of data points, k is the number of tied groups and t_{gi} is the number of ties of extent i. Negative values of Z_S indicate a decreasing trend, while positive values of Z_S indicate an upward trend. The trend is examined based on a predefined significance level p (e.g., 1%). In case Z_S is greater than $Z_{1-p/2}$, where $Z_{1-p/2}$ can be obtained from the standard normal distribution table, then it can be concluded that the null hypothesis can be rejected and there is a significant trend in the data examined.

Sens's slope can be calculated as:

$$S = \text{median}(\frac{X_j - X_i}{j - i}) \quad (13)$$

where X_j and X_i are the data values at times j and i ($j > i$), respectively.

3. Results

3.1. Precipitation and Precipitation Trend Analysis

The spatial distribution of mean annual precipitation for the period of 1940–2022 in Greece is presented in Figure 2. It can be observed that the highest precipitation values are depicted in western Greece (e.g., Epirus, western Peloponnese and Ionian Islands), ranging from 1000 to 1400 mm (Figure 2). The lowest values of precipitation range from 300 to 600 mm (Figure 2) and are depicted in eastern Greece (e.g., Athens, eastern Crete, Peloponnese and the Aegean Sea). The results are in accordance with the results presented by other researchers (e.g., [74]). It is seen that a special hydrological regime prevails in Greece; the western part of the country receives the majority of the precipitation (1200–1400 mm/year; Figure 2), while in the eastern part of the country, along with the Aegean Islands and eastern Crete, the precipitation is almost three times lower (400–700 mm/year; Figure 2).

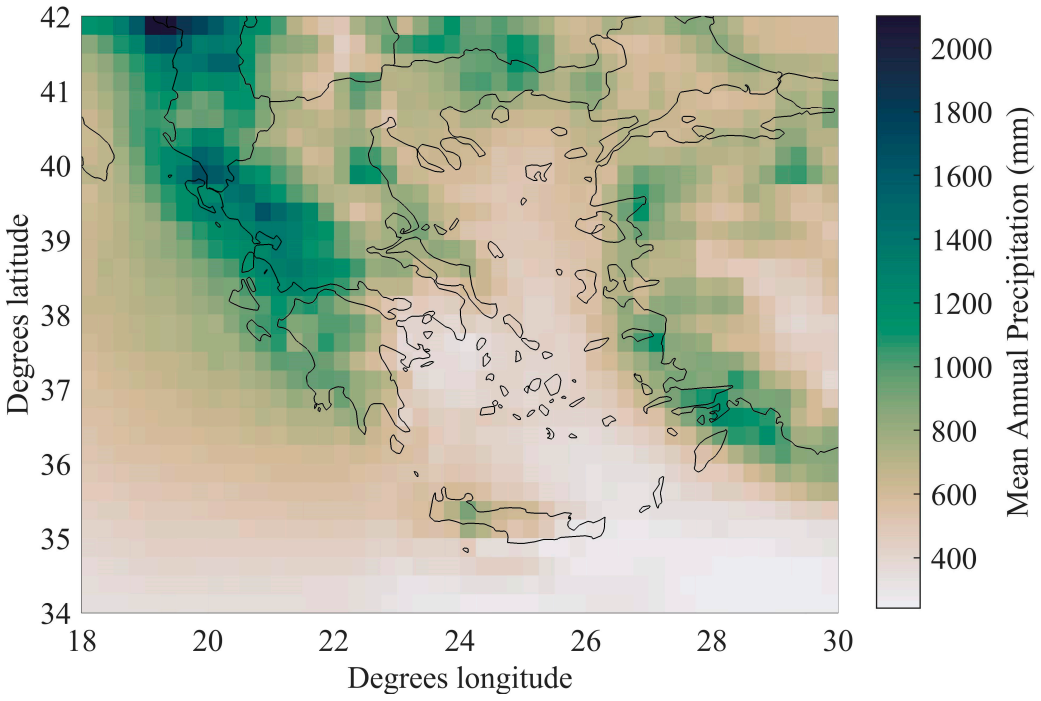


Figure 2. Mean annual precipitation for the period of 1940–2022.

Figure 3 presents the results of the trend analysis for annual precipitation based on the linear trend analysis (Theil–Sen slope) and the Mann–Kendall significance trend test. Black dots on the map indicate a statistically significant trend estimated using the Mann–Kendall trend test at the 95% significance level. Although a declining trend in precipitation for the greater part of Greece can be observed, a statistically significant trend can be observed in the Aegean Sea, western Crete and western Greece (as indicated by the black dots in Figure 3). On the other hand, it must be noted that in northwestern Greece, the Attica region, Euboea Island and northeastern Peloponnese, non-significant increasing trends can be observed.

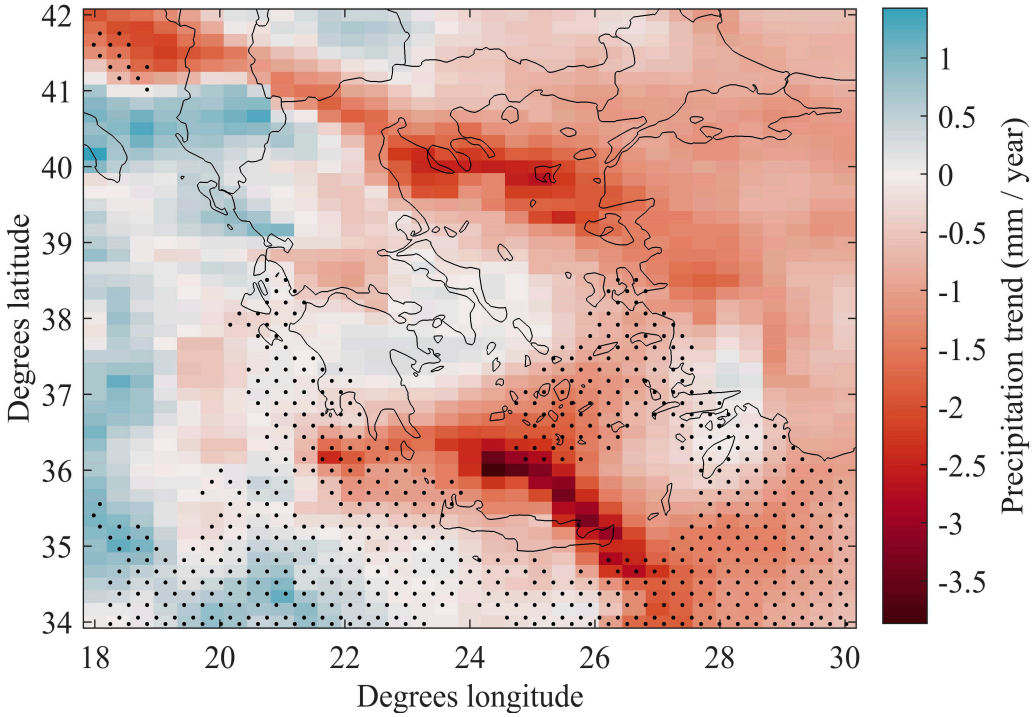


Figure 3. Trend of annual precipitation for the period of 1940–2022. Black dots indicate statistically significant trends at the 95% significance level.

3.2. SPI and Drought Trend Analysis

The SPI for different timescales (1 month, 3 months, 6 months and 12 months) was estimated for the entire study region. Indicatively, Figures 4–6 present the results for a period of low precipitation (Figure 4), a wet period (Figure 5) and a near-normal period (Figure 6).

Figure 4 presents the SPI results for 1-month (SPI-1 January 1990; Figure 4a), 3-month (SPI-3 January to March 1990; Figure 4b), 6-month (SPI-6 January to June 1990; Figure 4c) and 12-month (SPI-12 October 1989 to September 1990; Figure 4d) reference periods. It can be observed that during the specified hydrological year, the country experienced a meteorological drought of significant magnitude and areal extent, as indicated by the negative SPI values which fall under the severe or extreme drought categories (Table 1) for the selected reference periods and for almost the entire country.

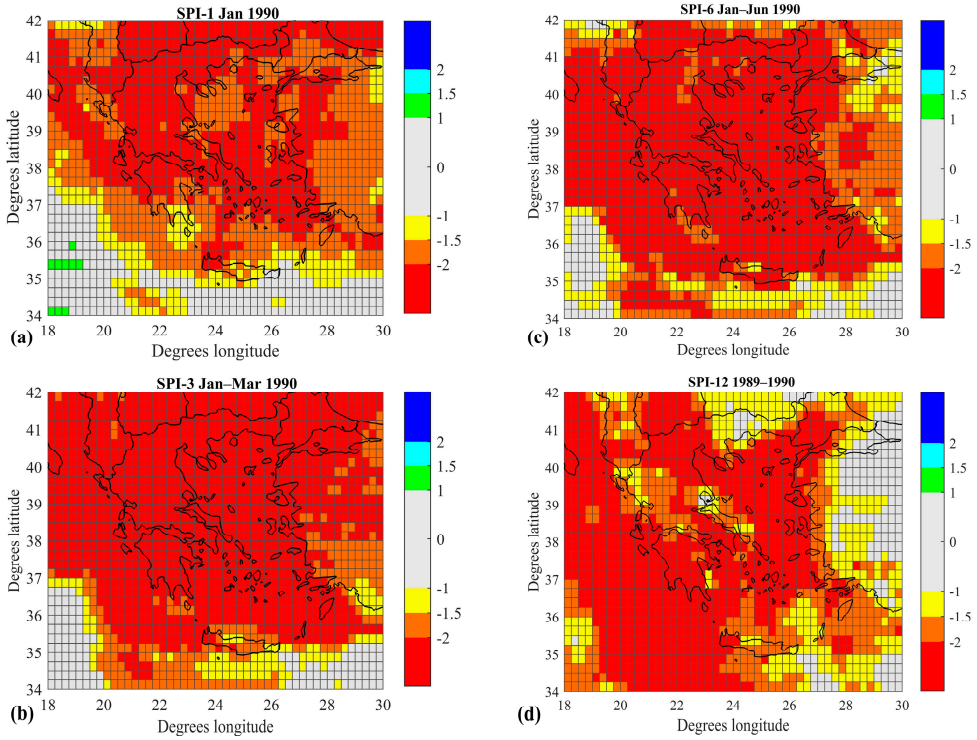


Figure 4. SPI for Greece for a dry hydrological year (1989–1990).

Figure 5 presents indicative SPI results for 1-month (SPI-1 July 2002; Figure 5a), 3-month (SPI-3 July to September 2002; Figure 5b), 6-month (SPI-6 July to December 2002; Figure 5c) and 12-month (SPI-12 October 2002 to September 2003; Figure 5d) reference periods.

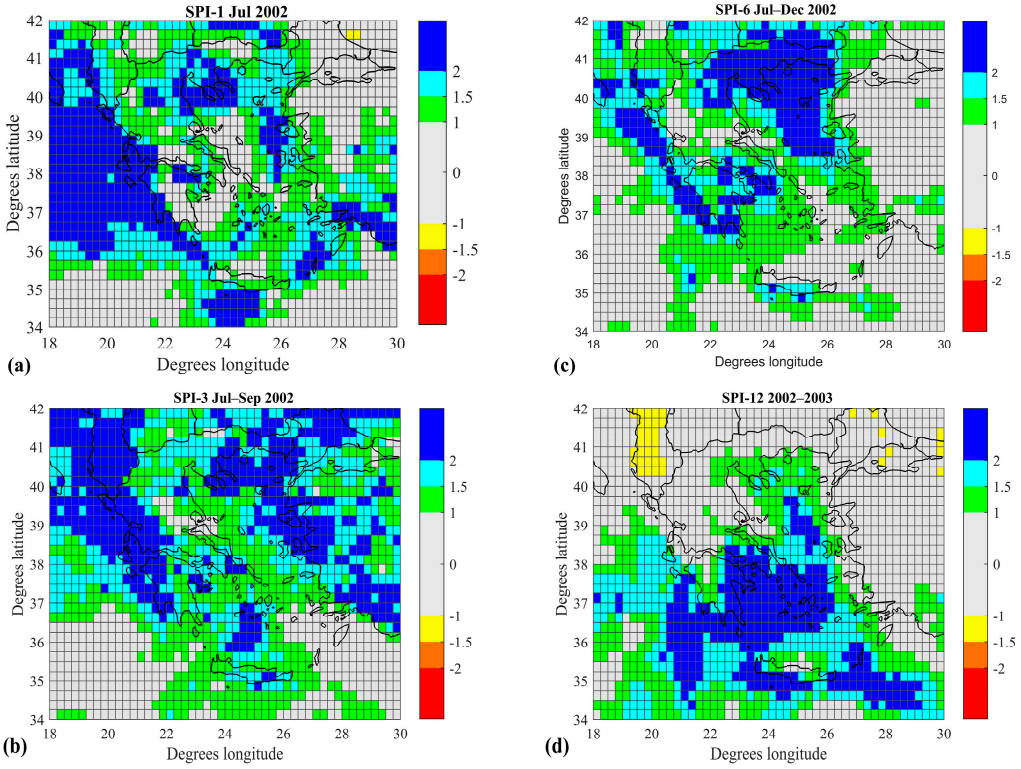


Figure 5. SPI for Greece for a wet hydrological year (2002–2003).

Figure 6 presents the indicative SPI results for 1-month (SPI-1 June 2018; Figure 6a), 3-month (SPI-3 April to June 2018; Figure 6b), 6-month (SPI-6 July to December 2018; Figure 6c) and 12-month (SPI-12 October 2018 to September 2019; Figure 6d) reference periods.

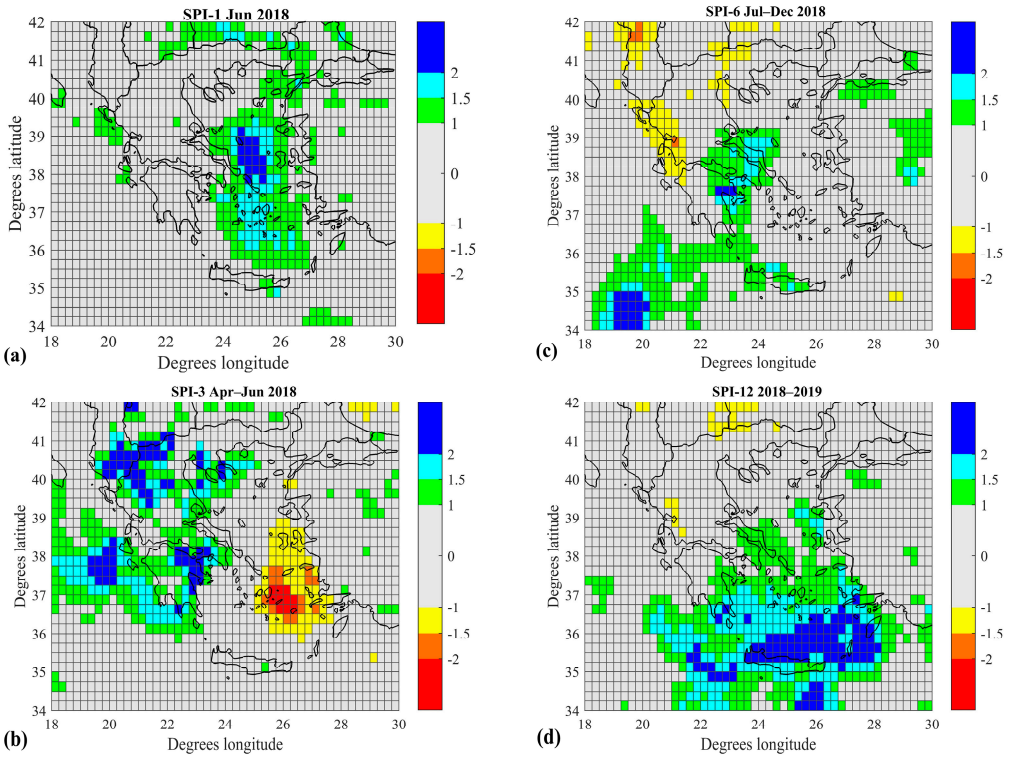


Figure 6. SPI for a hydrological year under near-normal conditions (2018–2019).

Finally, Figure 7 presents the spatial distribution of drought severity trends for the different timescales of SPI for the entire study region. Trend analysis was performed using the Theil–Sen slope estimator and the Mann–Kendall trend test. According to the results, the trend for SPI-3 October–December (Figure 7a), SPI-3 April–June (Figure 7b), SPI-6 July–December (Figure 7c) and SPI-12 October–December (Figure 7d) was not significant at the 95% confidence level in most parts of the study area. A statistically significant drought trend appears in the major agricultural area of Thessaly in the first trimester of the hydrological year (October–December), while a wetting, though non-significant, trend appears in most parts of the country in the spring period (April–June). According to the 6-month (Jul–Dec) SPI, a significant drought trend appears in the Cyclades region and a wetting trend is present in western parts of the country. The results of SPI-12 reveal a mixture of both an increasing wetting trend (western Greece, western and northern Crete and Peloponnese) and an increasing drought trend (Aegean Islands, eastern Crete and northern Greece). A significant trend at the 95% confidence level is exhibited in the Aegean Islands and western Peloponnese.

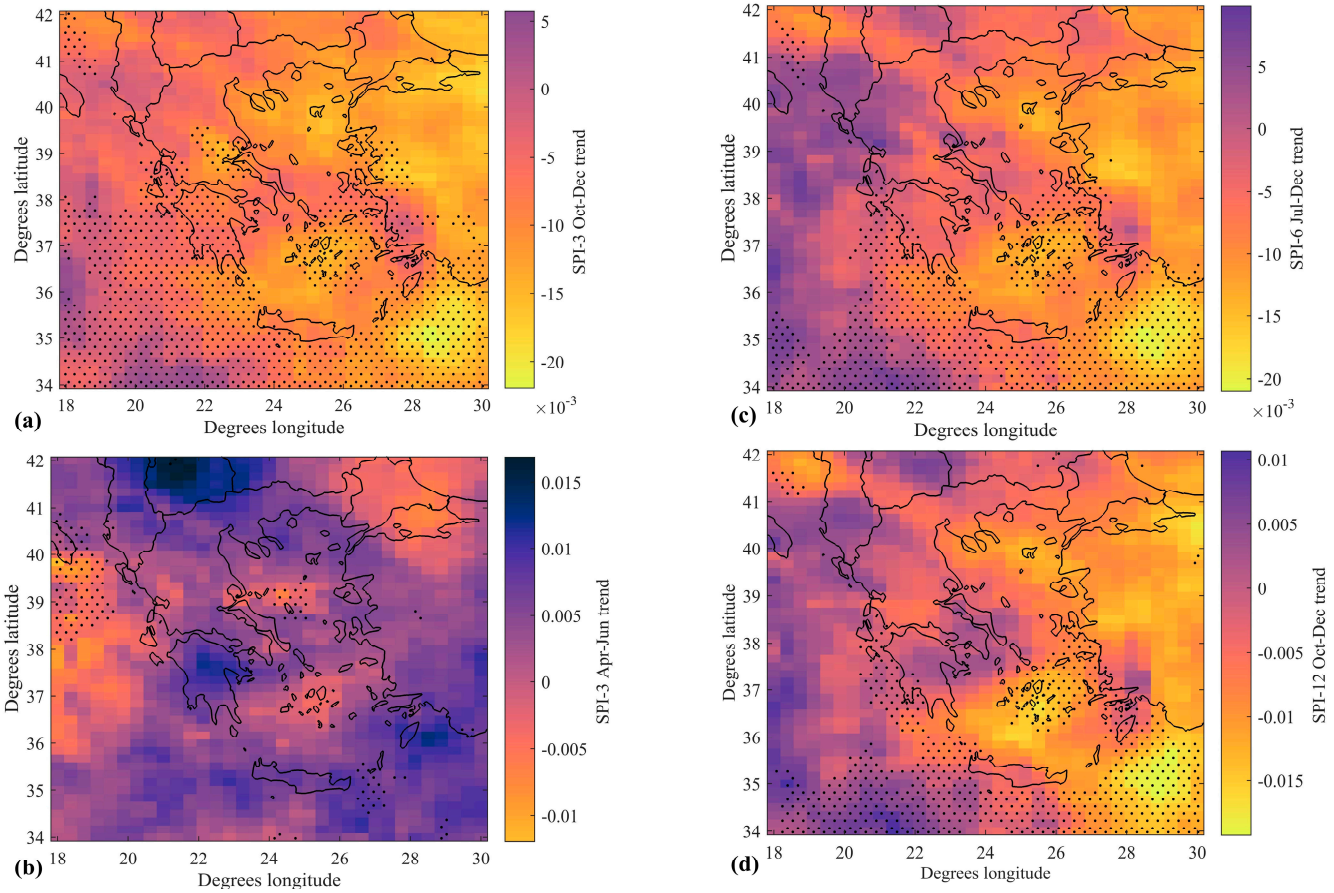


Figure 7. SPI trend analysis for (**a**) SPI-3 October–December, (**b**) SPI-3 April–June, (**c**) SPI-6 July–December and (**d**) SPI-12 October–December. Black dots indicate statistically significant trends at the 95% significance level.

4. Discussion

The suitability of the ERA5 reanalysis dataset for characterising drought using the SPI index was qualitatively evaluated based on studies and reports from the literature regarding the historical conditions and drought events in the study area. In addition, the ERA5 reanalysis dataset was also quantitatively evaluated using observed rainfall from five meteorological stations in Greece.

A well-reported drought event that affected Greece was the multiyear drought during the period of 1989 to 1993. The specific drought event caused significant losses in agricultural production and major water scarcity issues, jeopardising the security of the water supply even in the capital of the country (Athens Metropolitan Area; [95]). The characteristics of drought magnitude, duration and areal extent of this event have been reported in several studies (e.g., [95–98]). The outcomes of the present study based on the ERA5 dataset are in line with these studies, indicating the accuracy and suitability of the approach for depicting this severe drought event.

Apart from this specific event, the outcomes of this study agree with the results presented in other drought studies in Greece, covering the entire study area or specific regions of the country, regarding the evolution of the magnitude and spatial distribution of the phenomenon. Indicatively, similar results have been reported in studies for several regions in Greece (e.g., [97,99,100]). Furthermore, similar outcomes have been reported by Caloiero et al. [101] regarding drought trends in the entire study area.

Quantitative evaluation of the ERA5 dataset in terms of drought characterisation was performed using observed precipitation data from five indicative meteorological stations located in north, west, east and south Greece [102]. The 12-month time scale was used for

this comparison to take into account the conditions of the entire hydrological year. Details on the stations used are presented in Table 2. The closest ERA5 grid cell to each station was selected using the nearest neighbor approach. Evaluation of the ERA5 reanalysis dataset in terms of drought characterisation was accomplished using the following six metrics: (i) the Pearson correlation coefficient (r), (ii) Nash–Sutcliffe efficiency (NSE), (iii) the Root Mean Square Error (RMSE), (iv) R-squared (R^2), (v) the Index of agreement (d) and (vi) the Mean absolute error (MAE). Finally, it must be noted that the ERA5 precipitation reanalysis dataset was also compared with monthly values of observed precipitation for the aforementioned stations. Comparison took place only in terms of R-squared, as the ERA5 precipitation dataset, at different spatiotemporal scales, has already been extensively assessed by various researchers (e.g., [103–105]). The ERA5 reanalysis dataset was selected and preferred over other reanalysis datasets as it has been evaluated and its capability in simulating monthly rainfall in the Extratropics has been corroborated [105].

Table 2. Stations used for evaluation of the ERA5 dataset.

a/a	Station	Longitude	Latitude	Elevation
1	Chrysoupoli	24.6232	40.9183	4.2
2	Ioannina	20.8193	39.6949	474.7
3	Mytilini	26.6038	39.0541	4.2
4	Souda	24.1454	35.5288	147.6
5	Sitia	26.1029	35.2156	113.6

Figure 8 presents the comparison of the observed monthly precipitation with the ERA5 monthly reanalysis precipitation for the period of 1979–1980 and 2021–2022 for the five stations, namely Chrysoupoli (Figure 8a), Ioannina (Figure 8b), Mytilini (Figure 8c), Souda (Figure 8d) and Sitia (Figure 8e). A relatively good agreement for monthly precipitation for the five stations can be observed, with the R-squared ranging from 0.69 to 0.84. It should be acknowledged that the evaluation of the ERA5 gridded dataset against point observations (i.e., stations) may lead to representativeness errors [106]. However, it must be noted that a dense network of stations for upscaling precipitation data at the grid cell size is not available in our study area; therefore, upscaling to the model grid could not take place.

Table 3 and Figure 9 present the performance of the ERA5 reanalysis dataset in terms of drought severity. The Pearson correlation coefficient (r) ranges of 0.62 to 0.85 indicate a moderate to strong correlation between the observed and the modelled annual drought (SPI-12) based on the station assessed. The other metrics, NSE, RMSE, R^2, d and MAE, range from 0.22 to 0.69, 0.55 to 0.91, 0.38 to 0.70, 0.79 to 0.92 and 0.43 to 0.75, respectively. Overall, the data present variations in the assessment metrics across different regions of Greece. Figure 9 presents the comparison of SPI-12 calculated based on observed data and ERA5 reanalysis data for the periods of 1979–1980 and 2021–2022 for Chrysoupoli (Figure 9a), Ioannina (Figure 9b), Mytilini (Figure 9c), Souda (Figure 9d) and Sitia (Figure 9e).

Table 3. SPI-12 metrics calculated based on observed data and ERA5 reanalysis dataset for the periods of 1979–1980 and 2021–2022 for the five stations.

a/a	Station	r	NSE	RMSE	R^2	d	MAE
1	Chrysoupoli	0.73	0.49	0.81	0.53	0.85	0.66
2	Ioannina	0.85	0.69	0.55	0.73	0.92	0.43
3	Mytilini	0.78	0.61	0.82	0.61	0.88	0.45
4	Souda	0.66	0.28	0.83	0.44	0.81	0.66
5	Sitia	0.62	0.22	0.91	0.38	0.79	0.75

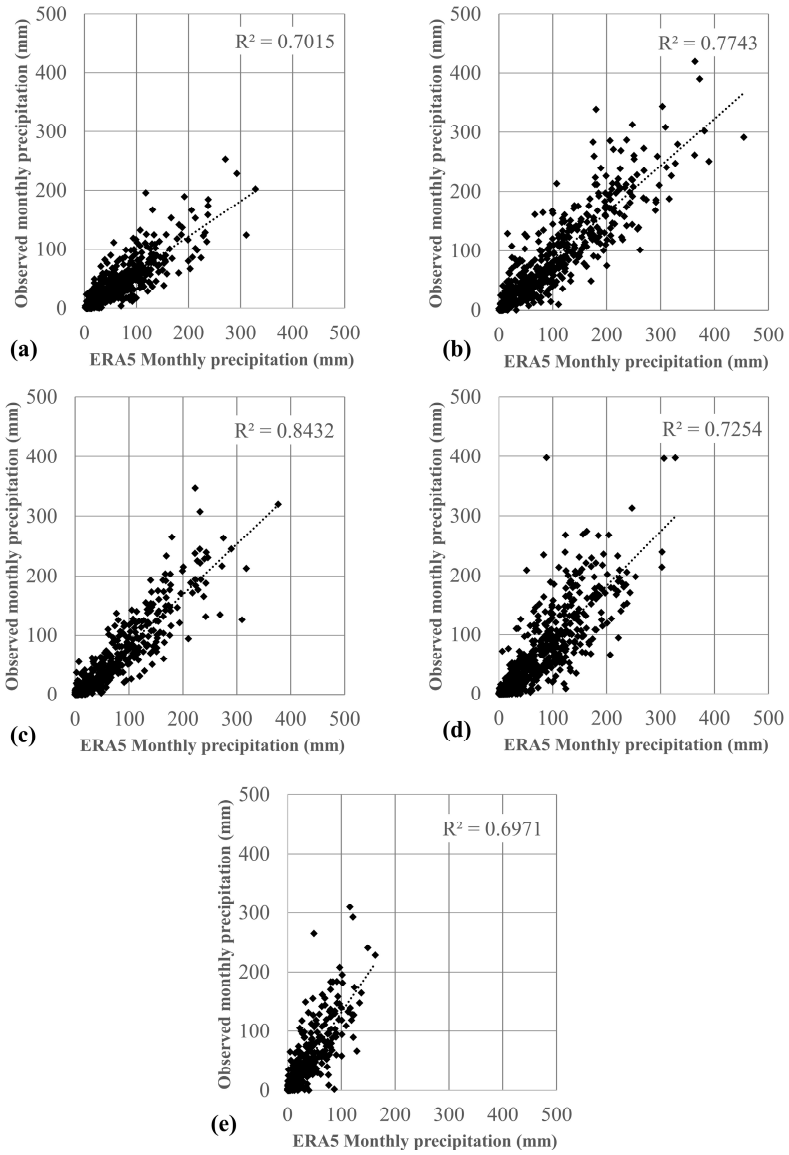


Figure 8. Comparison of observed and ERA5 monthly rainfall for the periods of 1979–1980 and 2021–2022 for (**a**) Chrysoupoli, (**b**) Ioannina, (**c**) Mytilini, (**d**) Souda and (**e**) Sitia.

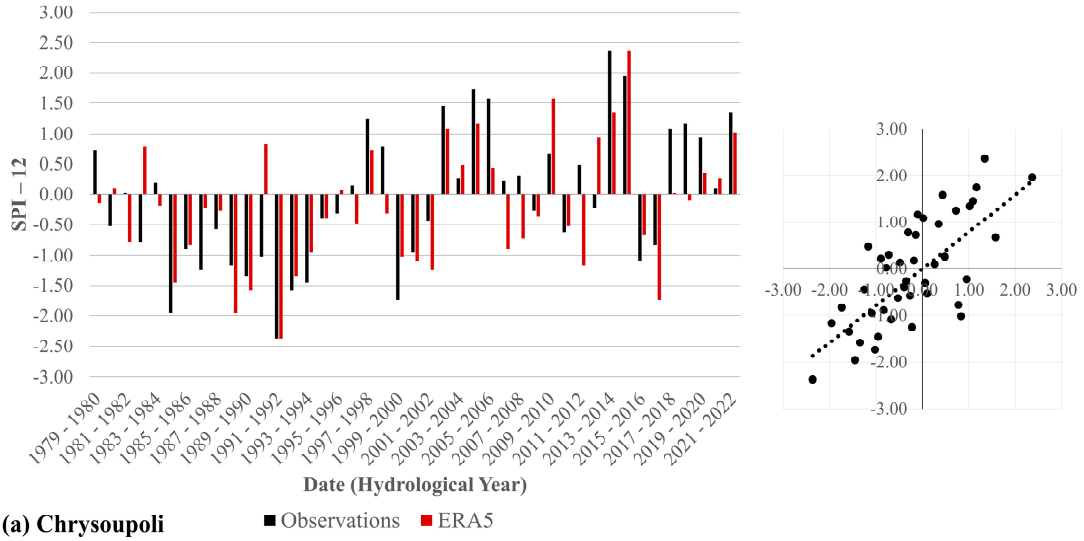
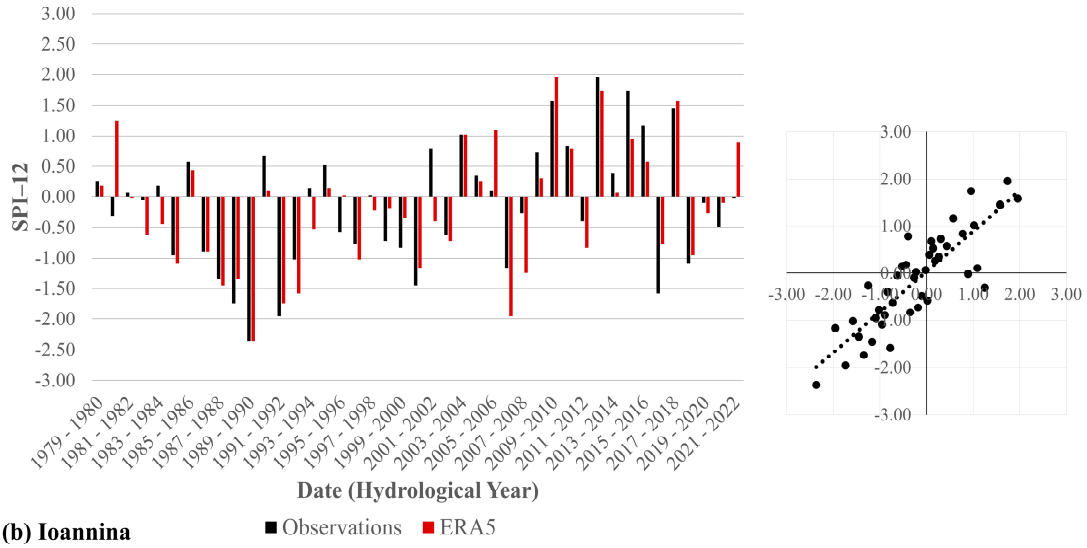
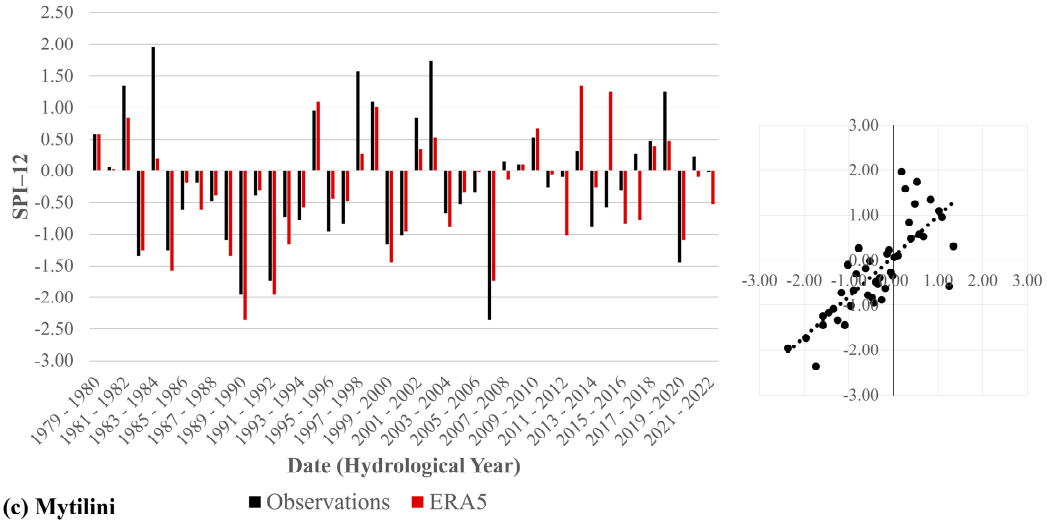


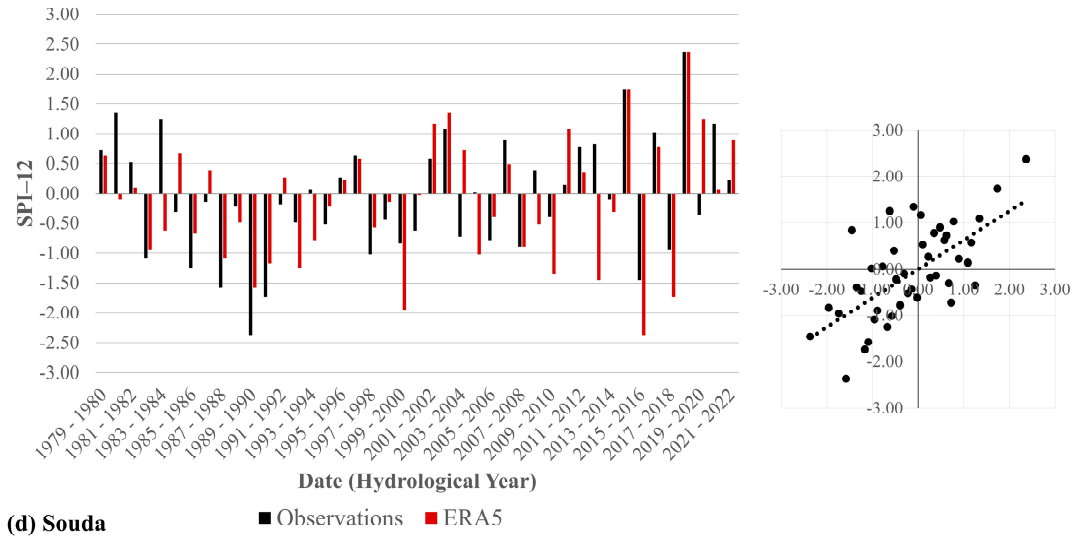
Figure 9. *Cont.*



(b) Ioannina



(c) Mytilini



(d) Souda

Figure 9. *Cont.*

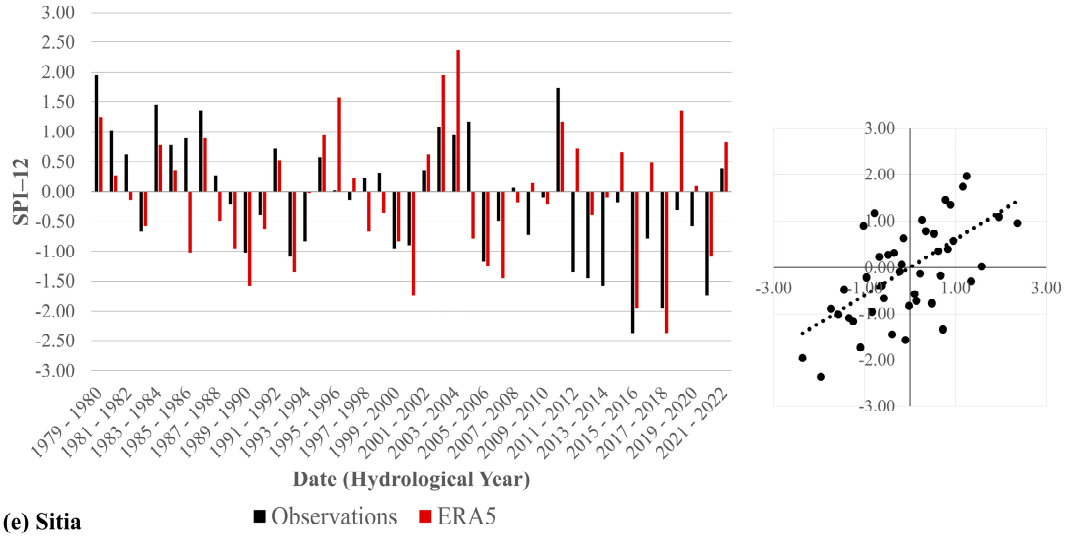


Figure 9. Comparison of SPI-12 calculated based on observed data and ERA5 reanalysis data for the periods of 1979–1980 and 2021–2022 for (**a**) Chrysoupoli, (**b**) Ioannina, (**c**) Mytilini, (**d**) Souda, and (**e**) Sitia.

As can be seen, the results are comparable in terms of drought characterisation between the two datasets. For instance, the extreme drought that affected Greece during the hydrological year of 1989–1990 (e.g., [95,98]) is well represented by the ERA5 reanalysis dataset. In general, the results suggest that the specific reanalysis dataset is able to detect drought events at the annual scale; thus, it can be used for drought characterisation across the Greek territory.

5. Conclusions

Spatial variability and annual rainfall and drought trends in Greece were analysed using rainfall from a reanalysis dataset spanning from 1940 to 2022 (83 years). Specifically, we utilised the ERA5 precipitation data of the European Centre for Medium-Range Weather Forecasts (ECMWF). Drought was analysed by means of the Standardized Precipitation Index (SPI) for different timescales (i.e., 1 month, 3 months, 6 months and 12 months). Trend analysis was carried out utilising the Theil–Sen slope estimator and Mann–Kendall trend test at the 95% significance level. The results revealed non-significant declining trends in annual precipitation at the national scale, but significant trends were evidenced for the Aegean Islands, western Crete and western Greece. Regarding drought analysis, the results are in line with those of previous drought studies in specific parts of the country, which used non-remote sensed precipitation data and applied different drought assessment methods. This reveals that the ERA5 dataset can reproduce past drought events and can be a valuable tool for drought identification. Furthermore, trend analysis for drought revealed non-significant drought severity trends for timescales of 1-, 3- and 6-month reference periods. On the other hand, significant drought severity trends for the 12-month timescale were detected for the Aegean Islands and western Peloponnese. Overall, it can be concluded that the ERA5 dataset can be a useful tool for drought identification and monitoring at the national scale and can be possibly incorporated into and used for the development of a drought forecasting and early warning system.

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