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Future Drought Variability in Greece: A Regional Assessment Based on PCA-Derived Spatial Patterns

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INTRODUCTION & AIM

The Mediterranean basin is among the most climate-vulnerable regions globally, experiencing a temperature increase 20% faster than the global average and notable declines in precipitation [1]. As a result, droughts are becoming more frequent, prolonged, and spatially extensive, exhibiting complex and unpredictable patterns. These conditions present ongoing challenges in assessing drought dynamics, making it difficult to anticipate their impacts on water resources, ecosystem biodiversity, and human well-being. Greece, as part of the eastern Mediterranean, is particularly vulnerable, with critical sectors such as agriculture, tourism, and energy production exposed to water scarcity. Moreover, the increasing frequency of wildfires across the country in recent years has accelerated desertification processes. This study aims to evaluate future drought variability across Greece for the late 21st century (2071–2100), combining Principal Component Analysis with Run Theory as an alternative approach for spatial drought characterization. The findings are expected to inform effective water management and adaptation strategies under a warmer and drier climate, enhancing resilience to future drought conditions in highly susceptible regions such as Greece.

METHOD

Data and Model Performance

Daily precipitation data (1971–2100) from 58 meteorological stations across Greece were obtained from the RCA4 regional climate model (EURO-CORDEX) at ~12.5 km resolution, under the IPCC's future emission scenarios RCP4.5 (intermediate, moderate) and RCP8.5 (high-emission, extreme).

The climate model's performance was evaluated using statistical metrics—RMSE, MAE, MSE, and WAPE—and by comparing the frequency distributions of observed and simulated precipitation for the reference period (1971–2000). Overall, the model showed satisfactory performance, with small biases detected in western and eastern insular areas, likely due to complex topography and localized rainfall variability, while central lowlands exhibited the highest accuracy.

Standardized Precipitation Index (SPI)

The impact of climate change on the adequacy of water resources was assessed for the period 2071–2100, taking into account the 12-month Standardized Precipitation Index (SPI-12) [2], clearly identifying drought episodes of prolonged duration (medium-term drought conditions). The SPI is based entirely on precipitation data and offers a straightforward and flexible approach to monitor dry and wet periods.

Computation of the SPI involves fitting precipitation data to a theoretical probability distribution, typically the gamma distribution, and then transforming it into a standard normal distribution Z with mean value μ = 0 and standard deviation σ = 1. [3]. Since the gamma distribution is undefined for x=0, a modified expression of the gamma cumulative probability can be applied, solving the problem with the possible zero values in our monthly precipitation data.

$$H(x) = q + (1-q)G(x)$$

where q is the probability of no precipitation and $G(x)$ the cumulative probability of the incomplete gamma function.

Hydrological events can then be classified into categories representing dry and wet climatic conditions in a similar way. Positive SPI values correspond to wetter-than-average conditions, while negative values correspond to drier-than-average conditions, allowing the characteristics of desirable events to be compared across different time periods and diverse climate regimes.

Table 1. Classification of SPI Values

SPI	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Very wet	4.4
1.00 to 1.49	Moderately wet	9.2
-0.99 to 0.99	Near Normal	68.2
-1.49 to -1.00	Moderately dry	9.2
-1.99 to -1.50	Severely dry	4.4
-2 or less	Extremely dry	2.3

Principal Component Analysis (PCA)

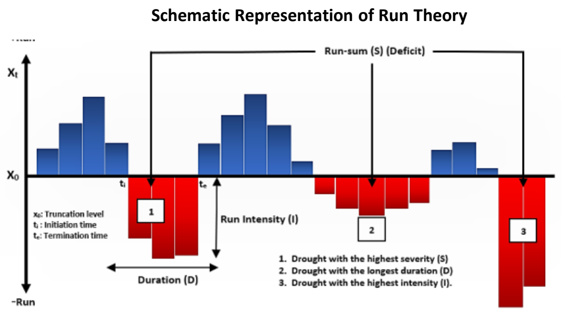
Principal Component Analysis (PCA) was employed on the SPI values under the high-emission scenario, facilitating the interpretation of spatial drought patterns through a more manageable dataset. In general, PCA constitutes a statistical procedure that linearly transforms an original set of interrelated variables $(X_1, X_2, \dots, X_p)$ into a substantially smaller set of uncorrelated variables $(Z_1, Z_2, \dots, Z_p)$, according to the following relationship:

$$Z_1 = a_{11}X_1 + a_{12}X_2 + \dots + a_{1p}X_p, \qquad \sum_{j=1}^{p} a_{1j}^2 = 1$$
$$\vdots$$
$$Z_p = a_{p1}X_1 + a_{p2}X_2 + \dots + a_{pp}X_p, \qquad \sum_{j=1}^{p} a_{pj}^2 = 1$$

The coefficients a_{ij}, or loadings, reflect the contribution of each original variable to the principal components. Loadings near ±1 indicate a strong correlation, while values near 0 can be disregarded.
Eigenvalues represent the variance explained by each component. Components with eigenvalues ≥ 1 were retained according to the Kaiser-Guttman criterion, ensuring that only the most meaningful components were considered.
Finally, a Varimax rotation was applied to maximize the variance of squared loadings, enhancing the identification of distinct spatial drought patterns.

Theory of Runs (ToR)

Schematic Representation of Run Theory



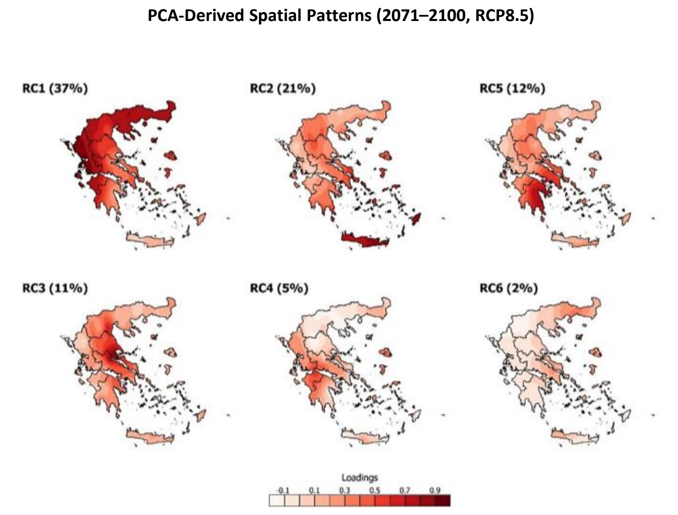
In this study, Run Theory [4] a probabilistic method with broad applicability for time series analysis, was applied to extract the statistical properties of hydrological drought. According to this method, a drought event is defined as a consecutive period during which values of the selected variable (here **SPI**) fall below a predefined threshold, forming a negative run. Each drought event is quantified by its main characteristics:

- **Duration (D)** – the continuous period when the drought parameter remains below a threshold.
- **Severity (S)** – the cumulative deficit over that period.
- **Intensity (I)** – the average deficit per time unit, calculated as **Severity** divided by **Duration**.

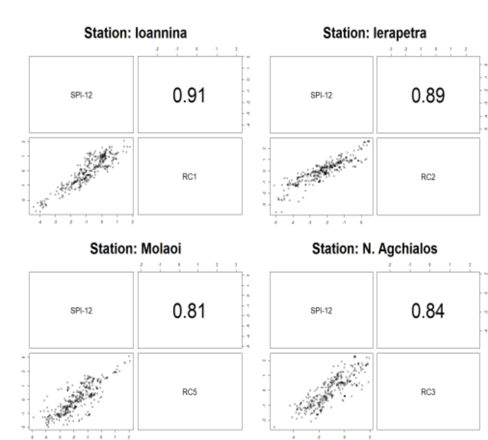
A threshold value of –1, based on the SPI classification, was used to define the onset of water deficit. Drought characteristics were further examined at representative stations corresponding to spatial clusters identified by PCA under the high-emission scenario, emphasizing regions with the highest drought susceptibility and enabling a comparative analysis between RCP4.5 and RCP8.5.

RESULTS & DISCUSSION

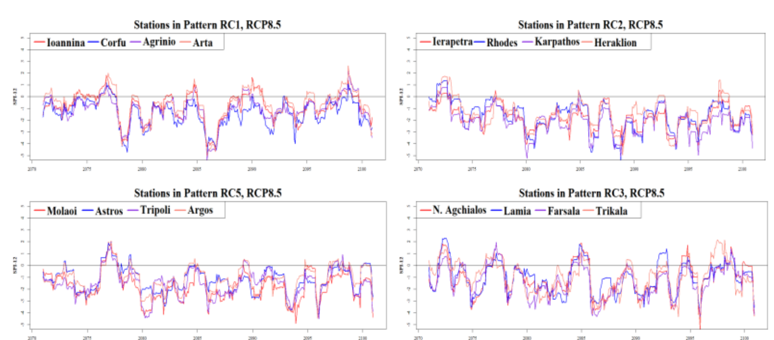
PCA-Derived Spatial Patterns (2071–2100, RCP8.5)



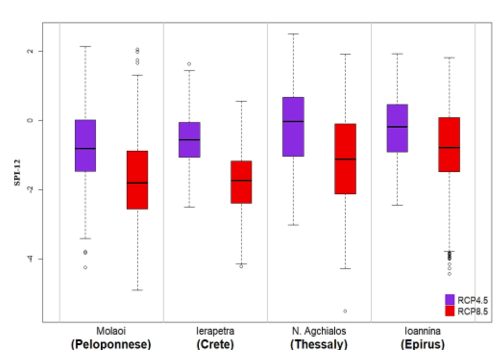
Strongest Correlation between SPI-12 and Components (2071–2100, RCP8.5)



Time Series of SPI-12 at Highly Correlated Stations, (2071-2100, RCP8.5)



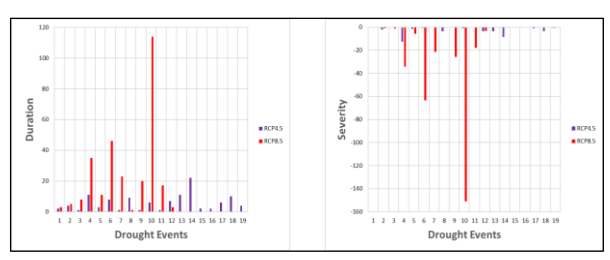
Boxplots of SPI-12 under RCP4.5 & RCP8.5 (2071-2100)



- **PCA**: A total of six principal components were extracted based on the Kaiser-Guttman criterion, representing 88% of the total variance. The first principal component explained 63% of the total variance, with high loadings (>0.7) in 49 of 58 stations, reflecting the general temporal evolution of droughts across most of Greece.
- **Varimax**: An orthogonal rotation of the axes was performed, redistributing variance among the principal components generating six newer (rotated) components that accounted for 37–2% of the variance, improving the interpretability of spatial patterns.
- **Spatial drought patterns**: Analysis of the rotated components shows that RC1 is indicative of drought conditions in western Greece, with high loadings at stations including Ioannina (0.91) and Agrinio (0.89). RC2 is representative for eastern Crete and the southeastern Aegean islands, with strong loadings at regions such as Ierapetra (0.89) and Rhodes (0.87). RC5 characterizes temporal drought variability across southeastern continental areas (Molaoi: 0.81, Astros: 0.76), while RC3 reflects conditions in Thessaly and northern Central Greece (N. Agchialos: 0.84, Lamia: 0.80). RC4 and RC6 contributed minimally (<5%) with low loadings (<0.6), indicating limited influence on overall spatial variability.

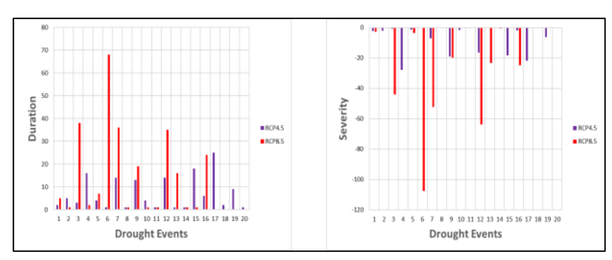
Station Ierapetra (2071-2100, RCP8.5)

Classification	RCP4.5 %	RCP8.5 %
Extremely Wet	0 %	0 %
Severely Wet	0 %	0 %
Moderately Wet	1 %	0 %
Normal	68 %	20 %
Moderate Drought	22 %	18 %
Severe Drought	6 %	21 %
Extreme Drought	3 %	41 %



Station Molaoi (2071-2100, RCP8.5)

Classification	RCP4.5 %	RCP8.5 %
Extremely Wet	1 %	0 %
Severely Wet	1 %	1 %
Moderately Wet	3 %	1 %
Normal	56 %	26 %
Moderate Drought	15 %	14 %
Severe Drought	8 %	13 %
Extreme Drought	16 %	45 %



- **Drought characteristics—severity (S)** and **duration (D)**—were further analyzed using Run Theory at representative stations from PCA-derived patterns, enabling a comparative evaluation between RCP4.5 and RCP8.5. Under the high-emission scenario (RCP8.5), eastern Crete (Ierapetra) and southeastern Peloponnese (Molaoi) experience prolonged and severe drought events, with wet (SPI ≥ 1) to mildly wet conditions (0 ≤ SPI ≤ 0.99) almost completely absent, indicating a high risk of desertification. Over 50% of monthly SPI values correspond to severe or extreme drought events. Furthermore, the most extreme negative SPI value was recorded for the region of Thessaly (N. Agchialos). By contrast, under the moderate RCP4.5 scenario, especially in western and northern stations, droughts are shorter, less intense, and wet periods are more frequent, mitigating the prevalence of dry conditions.

CONCLUSION

Greece's climate is projected to become significantly drier by the end of the 21st century, with longer and more intense droughts, particularly under the high-emission scenario RCP8.5. By applying Principal Component Analysis (PCA), four homogeneous regions in terms of drought variability were identified for further analysis. Run Theory revealed prolonged and severe drought episodes across most of the country, with the strongest impacts expected in southern Greece, particularly in eastern Crete and the southeastern Peloponnese. These projections imply an increased risk of desertification and wildfire occurrence, with higher pressure on water resources and negative consequences for agriculture and tourism. Although climate modeling carries inherent uncertainties, these findings highlight the urgent need for sustainable water management and long-term adaptation planning in view of a warmer and drier future.

REFERENCES

[1] IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
[2] McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference on Applied Climatology (Vol. 17, No. 22, pp. 179-183).
[3] Edwards, D. C., & McKee, T. B. (1997). Characteristics of 20th century drought in the United States at multiple time scales (Vol. 97, p. 155). Fort Collins: Colorado State University.
[4] Yevjevich, V. M. (1967). An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology paper 23, Colorado State University, Fort Collins, Colorado.