

SUMMARY

Northern Africa (NA) encompasses diverse climate types, from Mediterranean woodlands to arid deserts, making it one of the most water-stressed regions globally. Water availability in the soil is crucial for the socioeconomic activities and ecosystem resilience of this region. This study utilises soil water content (SWVL) datasets from the European Space Agency (ESA) and the ERA5-Land reanalysis (1980–2023) to investigate the response of three soil layers: 0–7 cm, 7–28 cm, and 28–100 cm, to changes in dry conditions, considering precipitation and atmospheric evaporative demand. By integrating 3-month standardised indices for precipitation (SPI3), evapotranspiration (SPEI3), and soil moisture (SSMI3), we build a comprehensive drought typology and map monthly compound-drought hazards. Typologies are defined using mutually exclusive logical rules and strict thresholds (< -0.84) to identify four distinct categories: Compound (simultaneous SPI, SPEI, and SSMI deficits), Hydrological, Evapotranspiration-driven, and Soil-anomaly hydrology. Validation results show that ESA and ERA5-Land soil moisture data are strongly correlated in the first layer, with maximum coherence in the northwestern region for deeper layers. Trend analysis also reveals a significant decrease in soil water content, particularly in the top and intermediate layers of the Maghreb belt. Multiple regression attribution analysis demonstrates that trends in the first layer are dominated by SPI evolution, confirming NA as a primarily water-limited region. The results identify pronounced compound drought hotspots over Morocco, northern Algeria, and Tunisia. While the hydrological type is spatially dominant along the Mediterranean margin, evapotranspiration-driven and soil-anomaly types are more episodic, consistent with localized heat-demand effects and soil–land-use controls. A coherent hazard belt is observed across all seasons, with peak intensity during winter and spring in Northwestern Africa. By distinguishing physical drought manifestations (typology) from multivariate co-occurrence frequency (hazard) and their underlying drivers (attribution), this framework delivers a diagnostics to support risk-informed decision-making in water allocation, rain-fed agriculture, and the stewardship of Mediterranean forests.

1. STUDY AREA

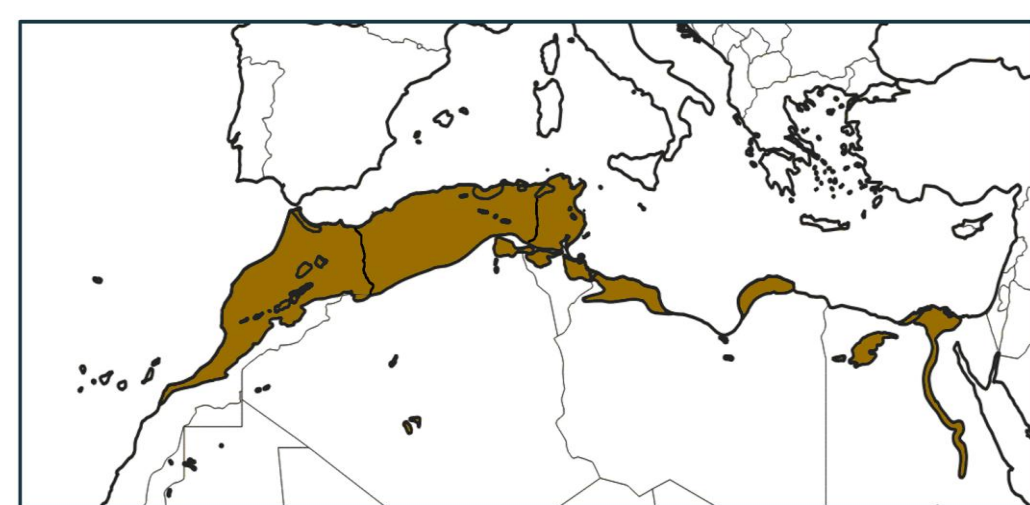


Figure 1. The Northern Africa

2. METHODOLOGY

- **Data Sources:** Precipitation data were obtained from the ERA5 reanalysis [1], covering the period from 1950 to 2022.
- **Drought Indices:** The Standardised Precipitation Index (SPI), Standardised Precipitation–Evapotranspiration Index (SPEI) and the Standardised Soil Moisture Index (SSMI), to first build a drought typology and then map the monthly compound-drought hazard.
- **Drought Typologies.**
 1. Compound (SPI3, SPEI3 and SSMI3 all below drought threshold)
 2. Hydrological (SSMI3 and SPI3 < -0.84 , SPEI3 > 0.84)
 3. Evapotranspiration-driven (SSMI3, SPEI3 < -0.84 ; SPI3 > 0.84)
 4. Soil-anomaly hydrology (SSMI3 < -0.84 , SPI3 and SPEI > 0.84).
- **Drought hazard:** Empirical frequency that SPI3, SPEI3 and SSMI3 fall below -0.84 . Very Low ($\leq P_{20}$); Low (P_{20} – P_{40}); Moderate (P_{40} – P_{60}); High (P_{60} – P_{80}); Very High ($> P_{80}$).
- **Granger causality:** tests whether past values of one time series help predict another, allowing the inference of directional causal influence over time.

- **Frequency of drought (per grid cell)**

$$F(x, y) = \frac{\text{Number of months under drought conditions}}{\text{Total months considered}}$$

$$H(x, y) = f(F(x, y), \{P_{20}, P_{40}, P_{60}, P_{80}\})$$

3. RESULTS AND DISCUSSION

The spatial distribution of dominant drought typology (left) and compound drought hazard (right) across the Mediterranean sector of North Africa for February, May, August and November, is shown in Figure 2. In these months, the SPI/SPEI3 allows for the quantification of dry/wet conditions at the seasonal scale. Compound drought conditions clearly dominate along the study region throughout the year, indicating a strong coupling between meteorological deficits, atmospheric demand and soil moisture anomalies in this semi-arid transition zone. Seasonal differences are evident, with more fragmented patterns in winter and late autumn, reflecting the higher variability of Mediterranean precipitation, whereas spring and summer exhibit a more spatially coherent signal. The compound typology remains consistently elevated along the Maghreb corridor, with areas of hydrological but also soil anomaly-driven drought typology, suggesting increased persistence of hydroclimatic stress and enhanced water demand for human use or even irrigation practices.

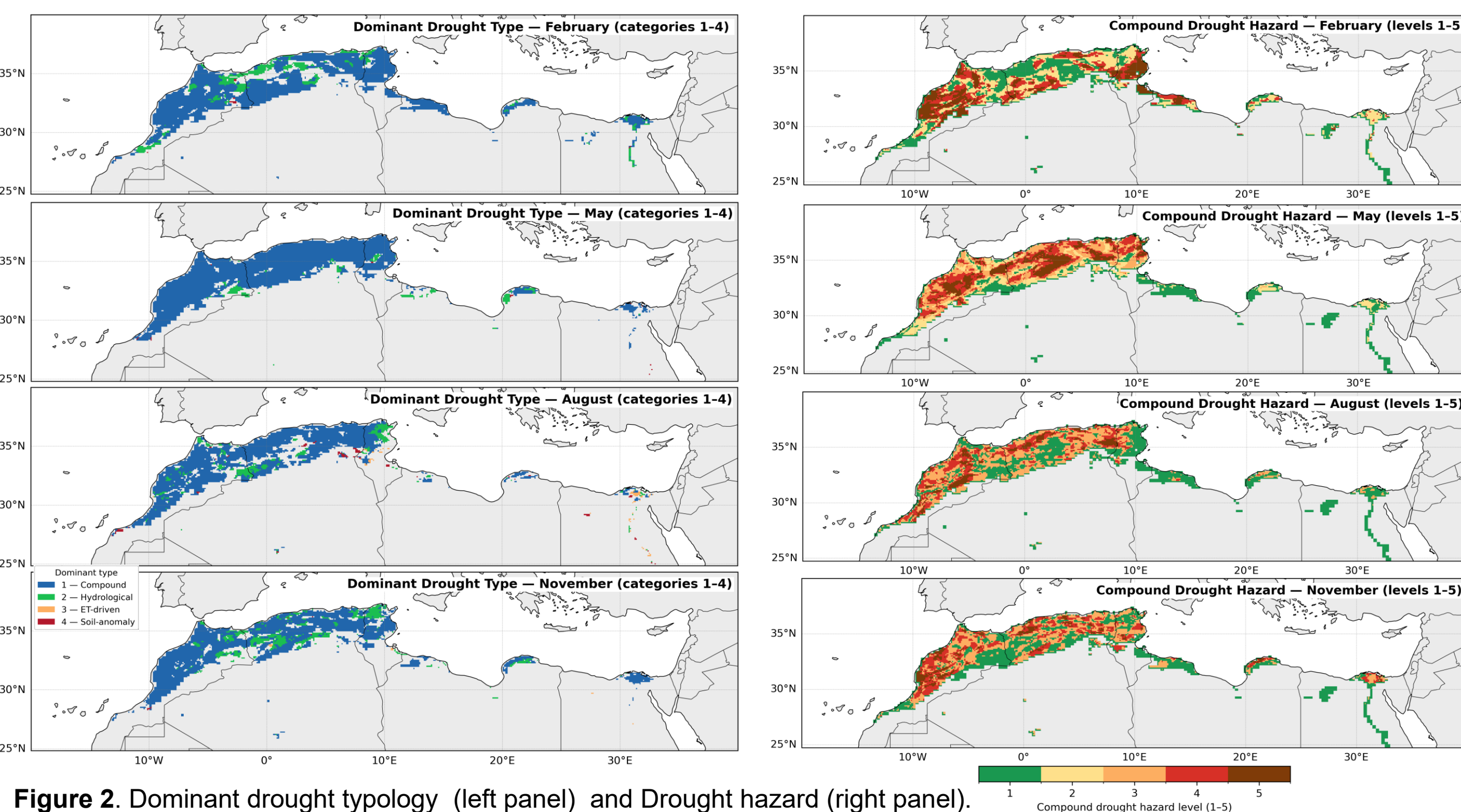


Figure 2. Dominant drought typology (left panel) and Drought hazard (right panel).

Causality analyses reveal a clear hydroclimatic contrast in the response of soil moisture to meteorological forcing across Mediterranean North Africa (Fig. 3). The SPI–SSMI relationship is dominated by very short optimal timescales (1–3 months), indicating a rapid transfer of precipitation deficits to the upper soil layer, consistent with the limited storage capacity and shallow soil profiles typical of semi-arid environments. This fast response suggests that soil moisture variability is strongly controlled by short-lived rainfall anomalies, particularly along the Atlantic–Maghreb corridor.

In contrast, when atmospheric evaporative demand is incorporated through SPEI, the optimal causal scales shift markedly towards longer periods (4–8 months and locally up to 9–12 months), especially across northern Morocco, Algeria, Tunisia and the Nile corridor. This spatial pattern highlights the increasing role of temperature-driven processes, radiative forcing and persistent evaporative stress in modulating soil moisture dynamics beyond immediate precipitation variability. The longer timescales observed in SPEI-driven causality reflect a stronger hydroclimatic memory, whereby cumulative energy balance anomalies prolong drought conditions even in the absence of sustained rainfall deficits.

4. CONCLUSIONS

Overall, the results show that drought dynamics across Mediterranean North Africa are strongly compound and multi-scale. Precipitation variability drives rapid soil moisture responses at short timescales, while evaporative demand introduces longer-term persistence and hydroclimatic memory. Together, these processes highlight the key role of thermodynamic forcing in amplifying drought impacts in semi-arid Mediterranean environments. This integrated perspective provides new insight into how short-lived rainfall deficits and sustained atmospheric warming jointly shape drought propagation across the region.

REFERENCES

- [1] Copernicus Climate Change Service (2022): ERA5-Land monthly averaged data from 1950 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.68d2bb30 (Accessed on 01-12-2025)
- [2] McKee, T.B., Doesken, N.J., Kleist, J. The relationship of drought frequency and duration to time scales. In Proceedings of the Eighth Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; pp. 179–184.

Figure 3. Optimum scale of the correlation between the SPI/SPEI from 1 to 12 months with the SSMI from the soil layer 1 (0–7 cm), and soil layer 2 (7–28 cm).

Acknowledgements: This research was financed by the project MARINA: Mapping Drought Risks in Water-Stressed Regions of North Africa: An Integrated Approach. Reference 04_MARINA_EG_ES_EOAC3. Financed by the European Space Agency (ESA). Duration: 01/12/2024 – 31/03/2026. In addition, this work was possible because of the computing resources and technical support provided by the Centro de Supercomputación de Galicia (CESGA). R.S., M.S., A.P.A., R.N., and L.G. acknowledge the APALPADOR project PID2024-155515NB-I00, funded by the Ministerio de Ciencia, Innovación y Universidades, Spain (MICIU/AEI/10.13039/501100011033) and by “ERDF/EU”.