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Characterization of agricultural drought propagation on the Iberian Peninsula through non-parametric indices

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Drought

Fig. 11: Example of dry cracked area affected by extreme heat events. Source: *https://public.wmo.int/en/resources/world-meteorological-day/previous-world-meteorological-days/climate-and-water/drought.*

- Definition

- A costly natural hazard with impacts on agriculture, ecosystem, water supply and socio-economy due to slow onset and extended periods
- Impacts have a **multi-scalar nature** ⟶ different systems have distinct response times to precipitation deficit
- 55 million people/year affected by droughts
- Droughts are projected to be larger in frequency and intensity with every additional increment of global warming

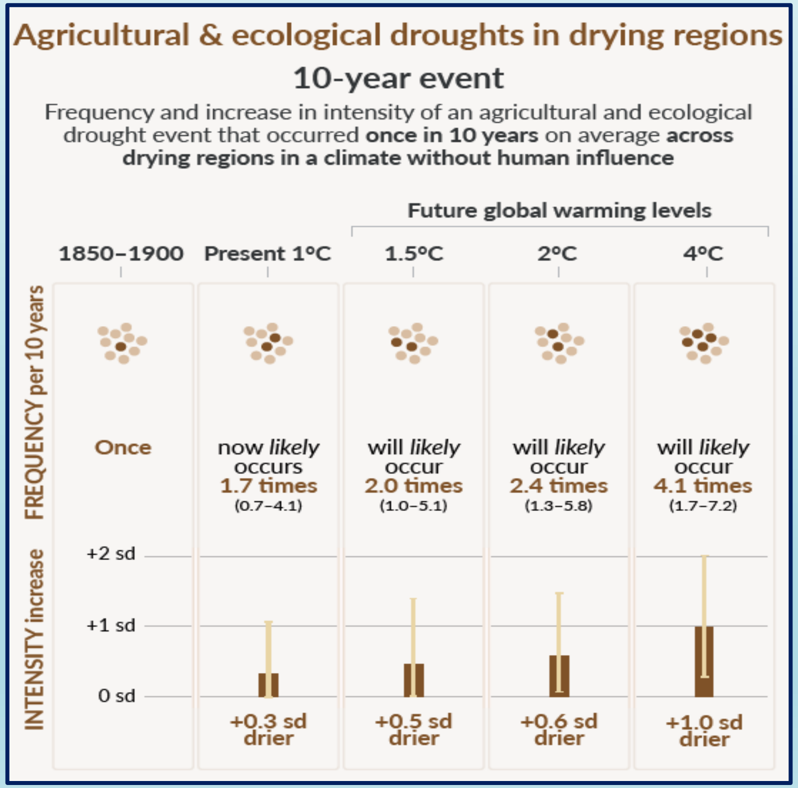

Fig. 12: Projected changes in the intensity and frequency of agricultural and ecological droughts in drying regions. From *IPCC AR6 (2021)*.

- Classification

5 categories of drought exist:
- **Meteorological**: region specific extended period of **dry weather** patterns
- **Agricultural**: agricultural impacts of precipitation shortage, especially linked to **evapotranspiration**, **soil water** deficits
- Hydrological: associated with the effects of periods of precipitation shortfalls on surface/subsurface water supply (streamflow, reservoir and lake levels, groundwater)
- Socioeconomic: water shortage affects the supply and demand of drought commodities
- Ecological: prolonged deficit in naturally available water supplies that create multiple stresses across ecosystems

Different drought types are studied through different **drought indices**

Research question

- Interaction between types of drought

- Drought **propagation** is related to changes in the anomalies of hydroclimatic signals

→ drought moves through the hydrological cycle

- Drought originates from precipitation deficits (meteorological drought), induces soil moisture deficits (agricultural drought) and low streamflow leading to hydrological drought

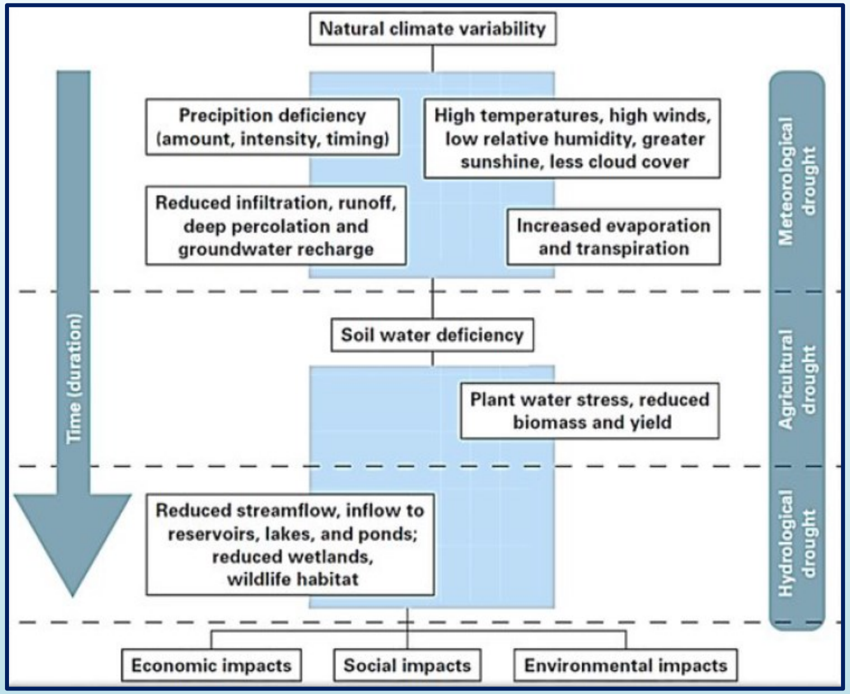

Fig. 13: Diagram showing the sequence of drought occurrence and impacts of the drought types linked with physical drivers. From *Wilhite et al. (2006).*

- Issues and research gaps

- Propagation **from meteorological to agricultural** drought is rarely investigated considering different indices and time-scales
- *Zhang et al.* (2022) highlights research gaps about:

1) Long-term data: focus on studies regarding **long multi-year datasets** with multiple drought events
2) Multi-variable indices: consider impact of indices involving **other variables** than soil moisture

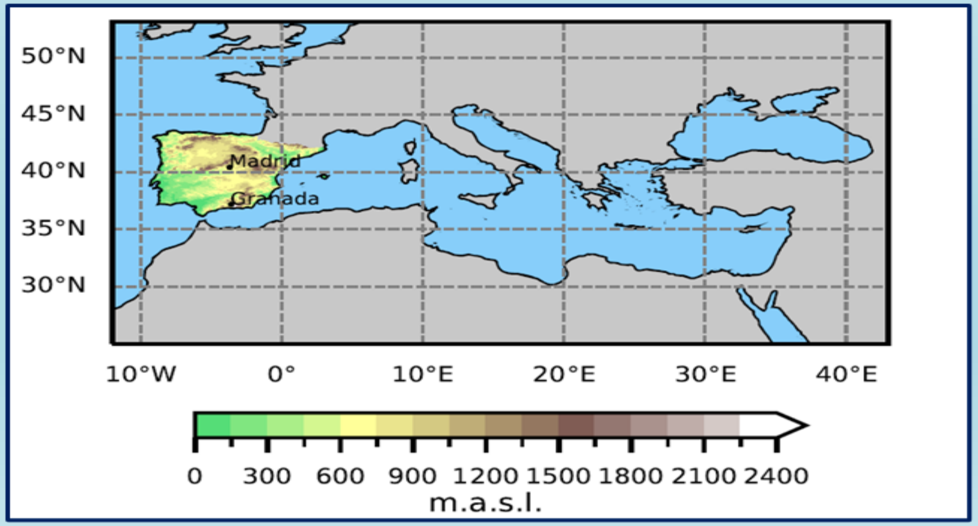

Fig. 14: Location of the Iberian Peninsula within the Mediterranean.

- Purpose of this study

- Fill research gaps analyzing drought propagation on **Iberian Peninsula** (IP), well recognized drought hotspot
- Evaluation of effects of using multivariate indices at various time-scales

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Methodology

- Drought indices

Selected **non-parametric** versions of drought indices computed as in *Hao et al.* (2014), at **1**, **3**, **6** months timescale

- For meteorological droughts:
  Standardized Precipitation-Evapotranspiration Index (SPEI)
- For agricultural droughts:

1) *Standardized Soil Moisture Index* (SSI)
2) *Multivariate Standardized Drought Index* (MSDI)
3) *Standardized Precipitation, potential Evapotranspiration and Soil Moisture Index* (SPESMI)
4) *Combined Agricultural Drought Index* (**COMB**), adapting the combined meteorological index proposed by *Spinoni et al*. (2016) with a refined classification

Drought Index	Structure	Variables	Type of Drought
SPEI	Multivariate	P-E	Meteorological
SSI	Univariate	SM	Agricultural
MSDI	Multivariate	P, SM	Agro-Meteorological
SPESMI	Multivariate	P-E, SM	Agro-Meteorological

Drought Indices (SSI, MSDI, SPESMI)	COMB	Conditions
2+ indices $\in (-\infty, -2]$	-2	Extreme Drought
2+ indices $\in (-2, -1.5]$	-1.5	Severe Drought
2+ indices $\in (-1.5, -1]$	-1	(Moderate) Drought
2+ indices $\in (-1, 0]$	-0.5	Dry
2+ indices $\in (0, +\infty)$	1	Normal/wet

Tables 2-3: Description of the non-parametric drought indices. P stands for Precipitation, SM for Soil Moisture and E for Evapotranspiration.

- Dataset

- Monthly **ERA5-Land** reanalysis data (11x11 km) for period 1950-2021 ⟶ Total Precipitation, Evapotranspiration, Soil Moisture
- **Fraction of Absorbed Photosynthetically Active Radiation** (FAPAR) anomalies from EDO re-standardized as *Peng et al* (2019)

⟶ evaluate drought indices accuracy to detect vegetation stress

- Methods of analysis

- Drought events detection: Application of **run theory** ⟶ drought event duration depends on drought index threshold
- Characterization of droughts: Temporal evolution over IP and average drought characteristics over the entire period
- Drought Propagation:

a) Computation of **Response Timescale** and Propagation rate

b) Analysis of 2005 drought event ⟶ Propagation Probability and Lag time

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Analysis of agricultural drought propagation

Drought events on Iberian Peninsula

- Temporal evolution of drought indices

- SPEI trend indicates **increase** of periods with **precipitation deficit**

→ large area affected by severe events (index < −1.5) more frequent in last 2 decades

- Good agreement between agricultural indices with some differences:
  1) SSI detects most rainy periods
  2) MSDI/SPESMI detect driest periods
  3) COMB detect an average of the others

- Comparison with FAPAR anomalies

- Taking FAPAR anomalies as reference, computation of *Probability of Detection* (POD), *False Alarm* (FAR), *Critical Success Index* (CSI) and *Effect of Drought* (EOD)
- POD ~ 1 → all indices can successfully **monitor** areas of **vegetation stress** due to agricultural drought
- FAR ≠ 0 → some areas dominated by vegetation stress cannot be well monitored by indices
- CSI and EOD not close to 1 → some areas in no drought conditions but with high vegetation stress

→ AD indices efficient in assessing vegetation stress related to drought, but **not sufficient** to distinguish all areas with stress due to other factors

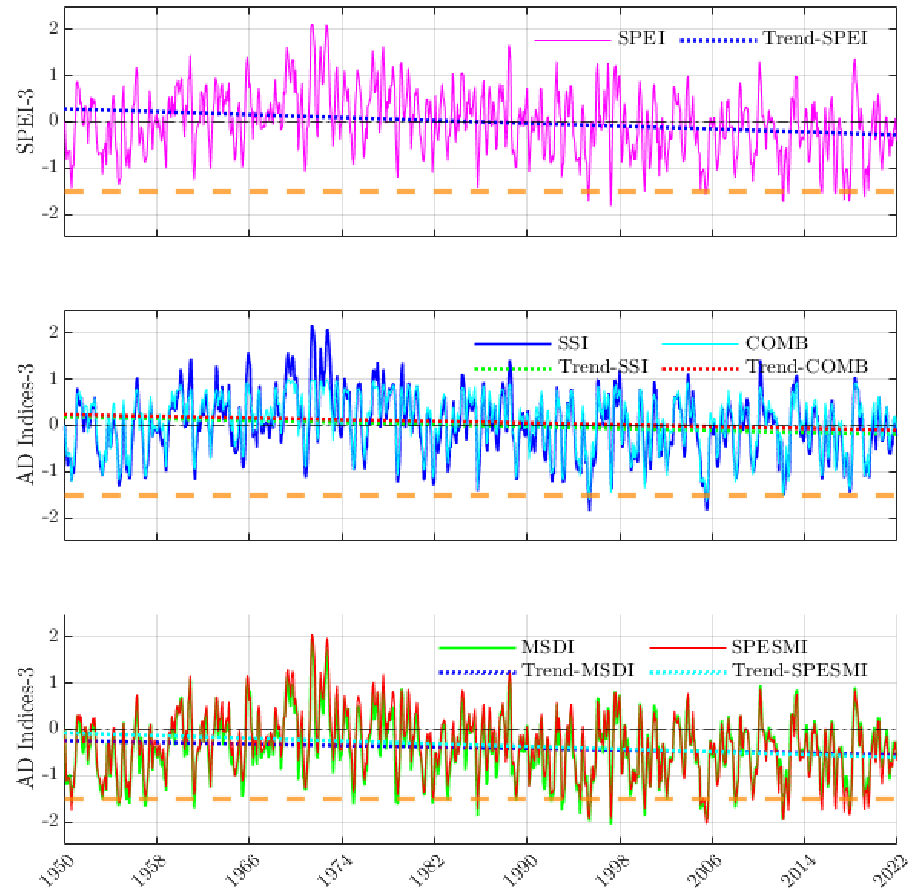

Fig.15: Temporal evolution of Iberian Peninsula averaged SPEI and agricultural drought (AD) indices at 3-month time scale for the period considered. The linear trend is represented for each index, and the orange dashed line indicates the -1.5 threshold for severe drought events.

Analysis of agricultural drought propagation

Drought characteristics comparison

- Characteristics of droughts

- Area coverage ⟶ soil moisture not sufficient to detect areas affected by agricultural droughts, while multivariate indices are more sensitive (more than 70% of Peninsula)
- Frequency and Duration ⟶ highest frequency for MSDI and lowest for SSI, average duration similar for all indices
- Magnitude and Severity ⟶ MSDI detects more intense droughts, COMB hardly reaches considerable severity values

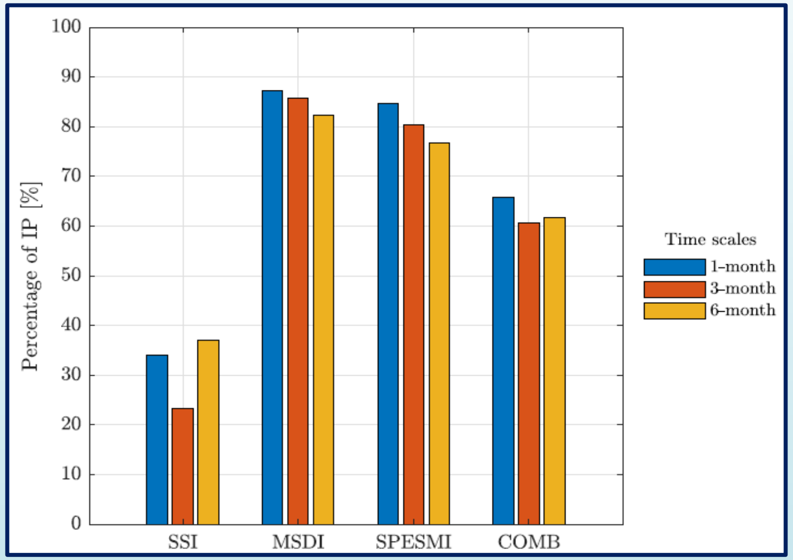

Fig. 16: Percentage of IP affected on average by severe droughts according to different scales indices.

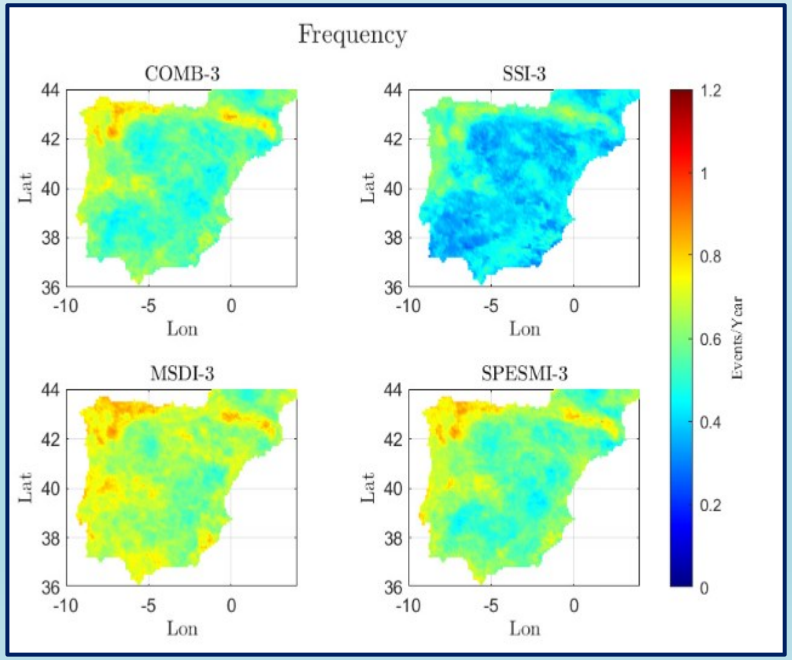

Fig. 17: Pattern of frequency of severe drought events per year on IP according to 3-month indices.

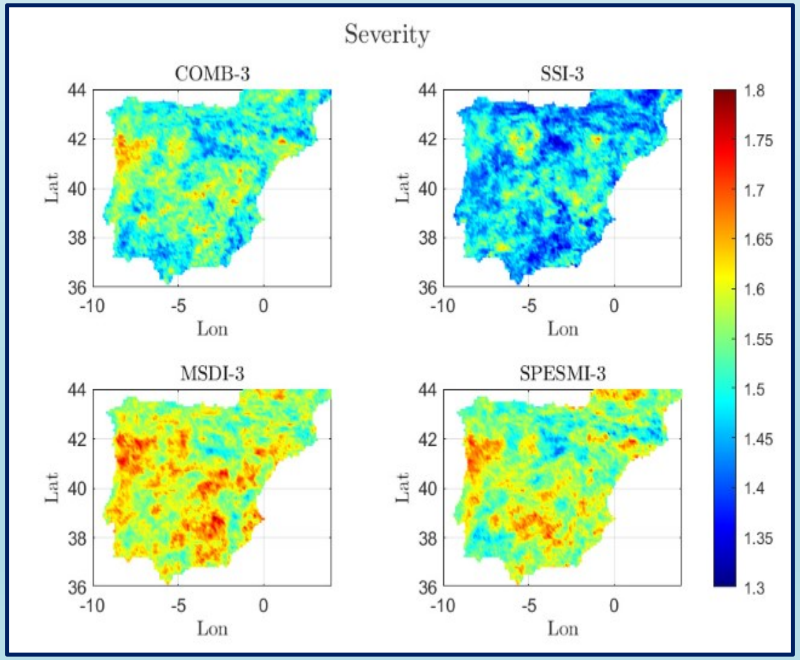

Fig. 18: Pattern of average severity on IP according to 3-month indices.

Overall:

- **Multivariate** indices identify **more frequent and intense** drought events
- **Combined index** is a **compromise** between SSI and multivariate indices
- More variability in severity values at longer time scales

Analysis of agricultural drought propagation

Propagation from meteorological to agricultural droughts -1

- Response timescale (RT)

- Time for accumulated deficit in meteorological drought to propagate to agricultural drought
- Computed as **highest correlation** between 1-month AD indices and 1 to 48-month SPEI over the whole period
- Short RT accordingly to global studies (*Zhou et al.* (2021))
- RT = 1 month for MSDI, SPESMI, COMB while 2-2.5 months for SSI ⟶ other variables **accelerate** response

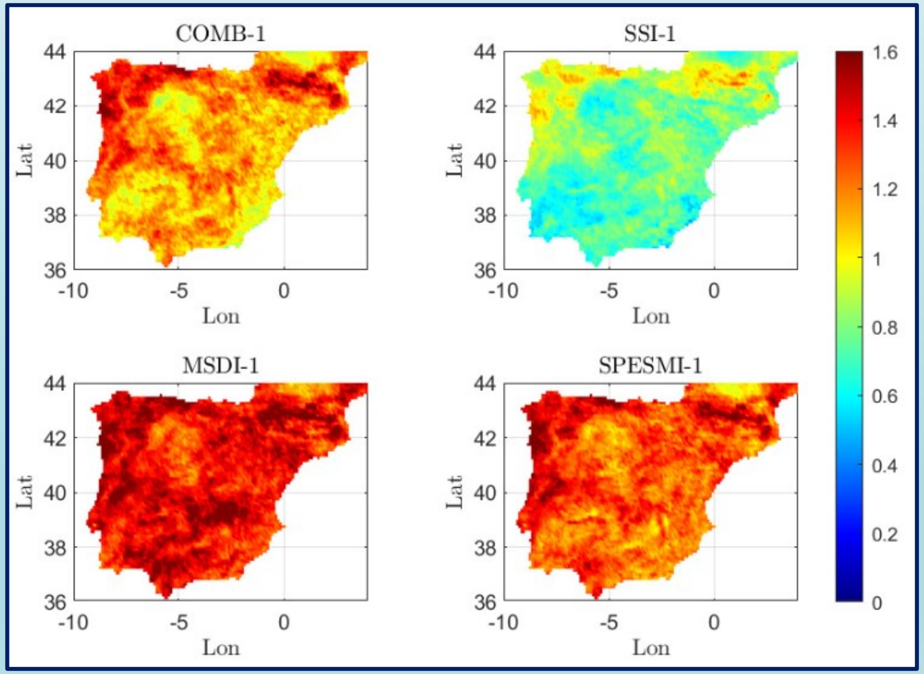

Fig. 20: Propagation rate considering 1-month SPEI and 1-month AD indices.

- Propagation rate (PR)

- Defined by *Sattar et al*. (2019) as the ratio between the agricultural drought events and the meteorological droughts
- High values of PR indicate **high sensitivity** of agricultural drought to meteorological drought
- Lowest values for SSI, max for MSDI
- Values ≥ 1 for all multivariate indices

⟶ a single meteorological drought capable of generating multiple agricultural drought events

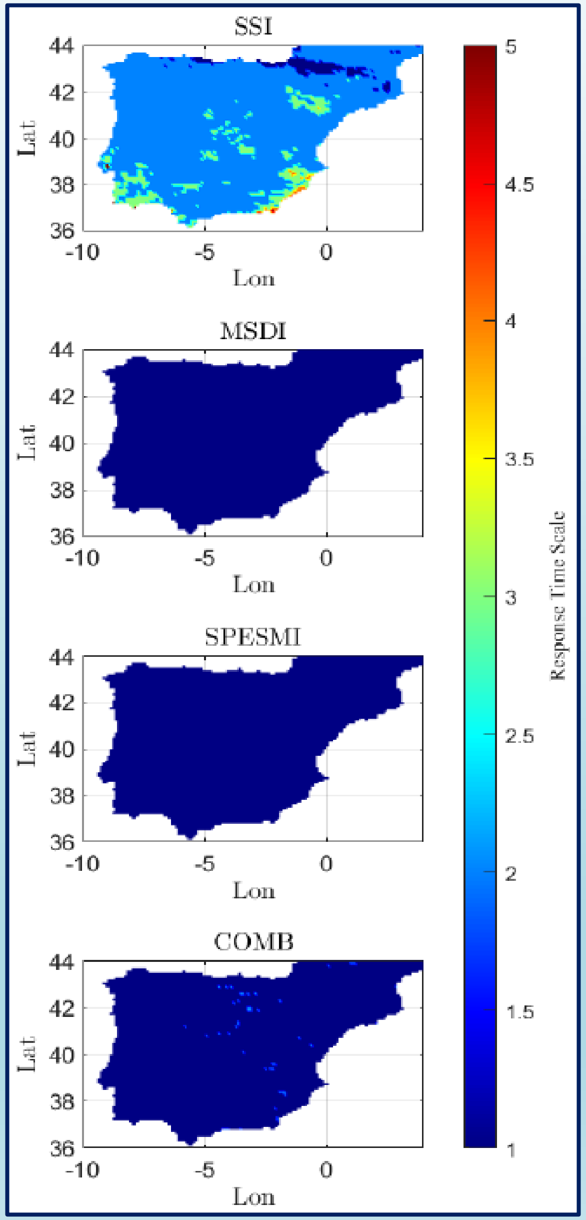

Fig. 19: Pattern of RT in months for IP.

Analysis of agricultural drought propagation

Propagation from meteorological to agricultural drought -2

- 2005 drought event

- Severe drought event documented by *Spinoni et al* (2016), EDO and EM-DAT
- Dry conditions from February to September 2005
- Similar patterns between meteorological and agricultural drought (max correlation at 3-month timescale)
- All agricultural indices detect drought on average in Iberian Peninsula 2005
- SPESMI/MSDI → **extreme drought** July 2005
- SSI → less severe droughts and 1-month **delayed**
- Prolonged effects of precipitation deficit

→ SSI remains ~ -2 even in areas with less intense SPEI

- Higher severity values for AD indices compared to SPEI

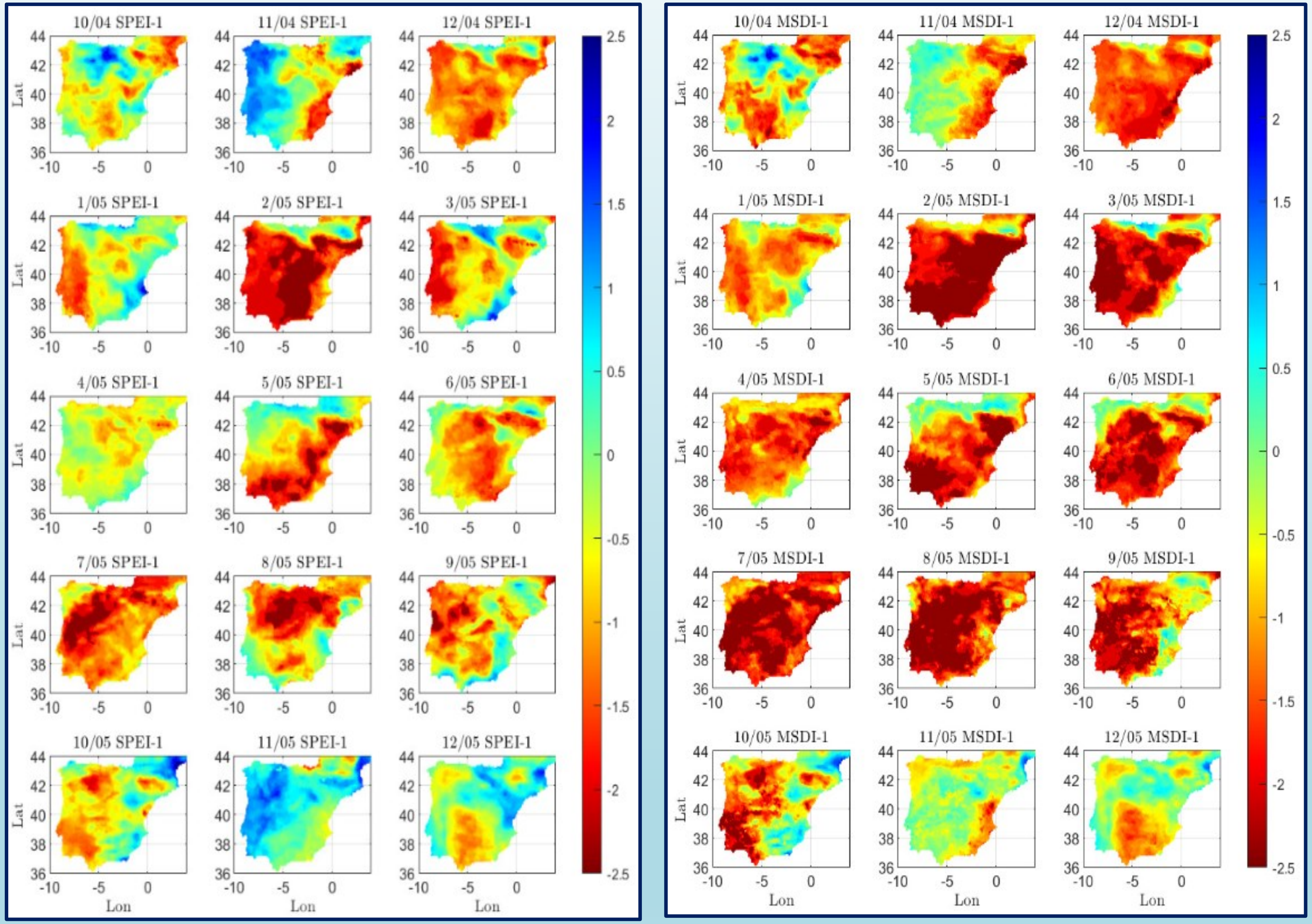

Fig. 21: Temporal evolution pattern of SPEI-1 and MSDI-1 indices over IP from October 2004 to December 2005 .

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Analysis of agricultural drought propagation

Propagation from meteorological to agricultural drought -3

- Propagation probability (PP) during 2005 event

- Similarly to *Zhu et al*. (2021), probability of drought propagation from meteorological to agricultural systems under different levels of severity
→ **fraction of IP** experiencing agricultural drought conditioned on the occurrence of meteorological drought
- All AD indices display **growth** in PP for increasing severity levels of meteorological drought
- MSDI and SPESMI highly sensitive to moderate agricultural drought propagation and less prone to severe and extreme propagation
- SSI generally lower PP than multivariate indices

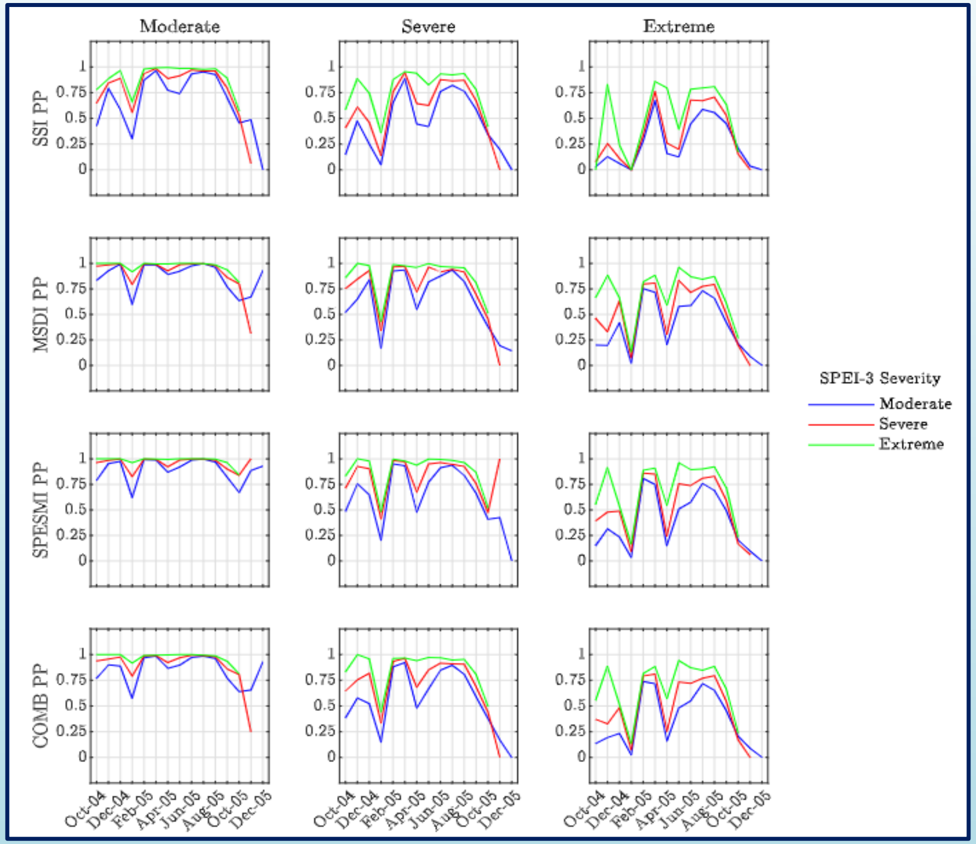

Fig. 22: PP from meteorological drought detected with SPEI-3 to agricultural drought of different severity levels according to 1-month time scale AD indices. The colors distinguish the severity of generating meteorological drought.

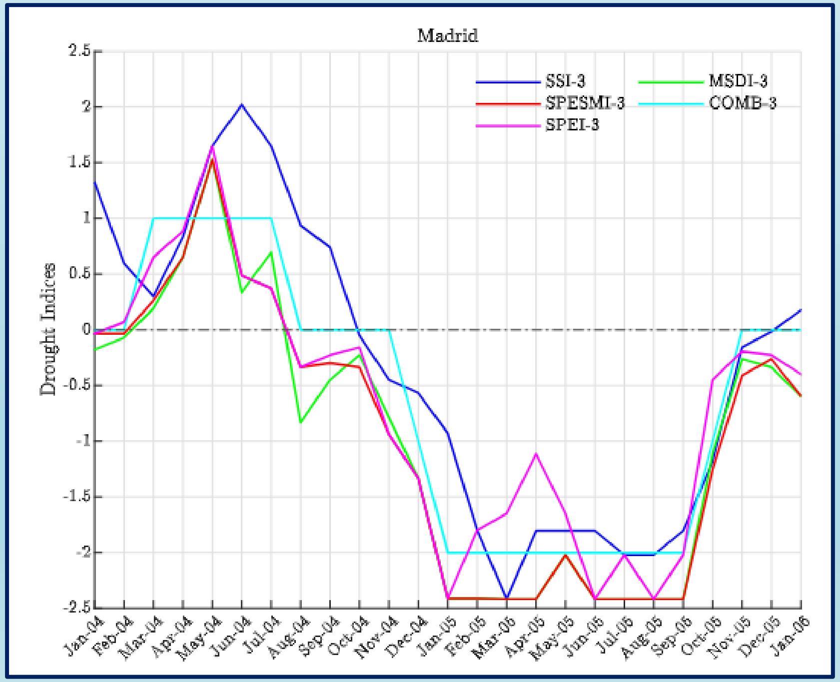

Fig. 23: Temporal evolution in Madrid of different drought indices at 3-month time scale.

- Lag time (LT)

- Difference of **onset time** between meteorological and agricultural drought
- Multivariate indices show LT ~ 0, while **LT ~ 2** months for SSI
- Depends on the location but always near 0

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Conclusions and next developments

- Summary of main results

- Slight trend towards increased dryness over the last two decades as in *Coll et al.* (2017)
- Multi-variate AD indices **more effective** in identifying severe drought events compared to the uni-variate SSI index
- More severe and extensive agricultural drought impacts than meteorological
- Novel COMB **balances** the characteristics of other indices ⟶ valuable resource for future investigations
- Accelerated response timescale when water balance is involved compared to the effect of soil moisture alone
- 2005 episode reveals a **higher propagation probability** depending on severity of originating meteorological drought

- Related article

- Possega, M.; García-Valdecasas Ojeda, M.; Gámiz-Fortis, S.R. (2023) *Multi-Scale Analysis of Agricultural Drought Propagation on the Iberian Peninsula Using Non-Parametric Indices*. Water, 15(11), 2023. DOI 10.33w1511203290/

- Future developments

- Extend the study to other techniques of drought propagation analysis:

a) Probabilistic approach proposed by *Wong et al*. (2013)
b) Evaluate how lead time between meteorological and agricultural drought onset depend on type of crop and location

- Study of drought propagation in **future projections**

References

1) Zhuang X et al. *Drought propagation under global warming: Characteristics, approaches, processes, and controlling factors*. Science of The Total Environment, 2022;
2) Zhu Y, Liu Y, Wang W et al. *A global perspective on the probability of propagation of drought: from meteorological to soil moisture*. J. Hydrol, 2021;
3) Spinoni J et al. *Meteorological droughts in Europe: events and impacts-past trends and future projections*, 2016;
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Thanks for your interest

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Supplementary material

Empirical MSDI

X = monthly accumulated precipitation
Y = monthly accumulated soil moisture
Joint Probability: $P(X \leq x, Y \leq y) = p$

Gringorten plotting position formula:

$$P(x_k, y_k) = \frac{m_k - 0.44}{n + 0.12}$$

where n = n° of observation,
m_k = n° of occurrences of (x_i, y_i) for $x_i \leq x_k$ and $y_i \leq y_k$ $(1 \leq i \leq n)$

$$\boldsymbol{MSDI} = \phi^{-1}(p)$$

where ϕ = standard normal distribution function

Table T1: Method to compute non-parametric indices.

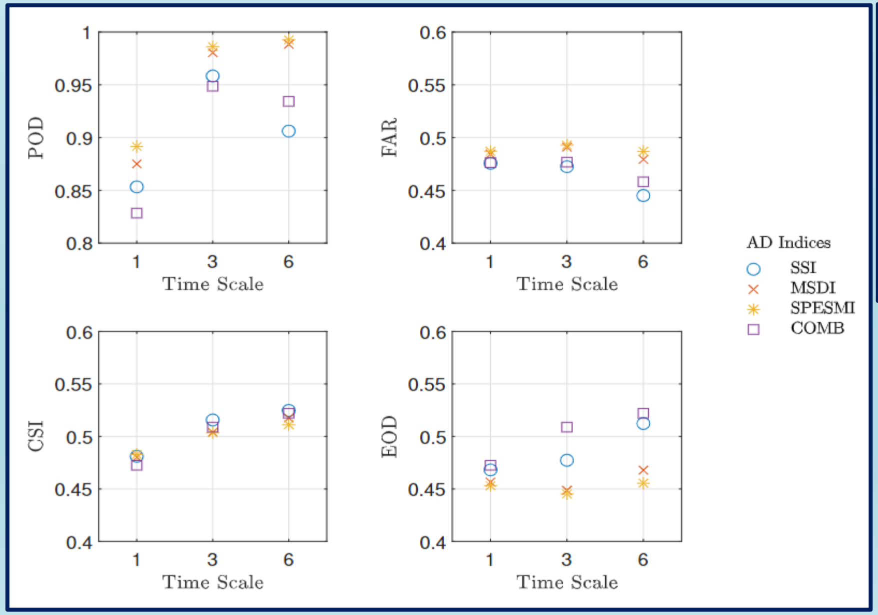

Fig.S1: Skill score metrics regarding FAPAR anomalies for AD indices at the 1-, 3-, 6-month time scales.

$$POD = H/(H+M)$$

$$FAR = F/(H+F)$$

$$CSI = H/(H+M+F)$$

$$EOD = (H+H_N)/(M+F+H+H_N)$$

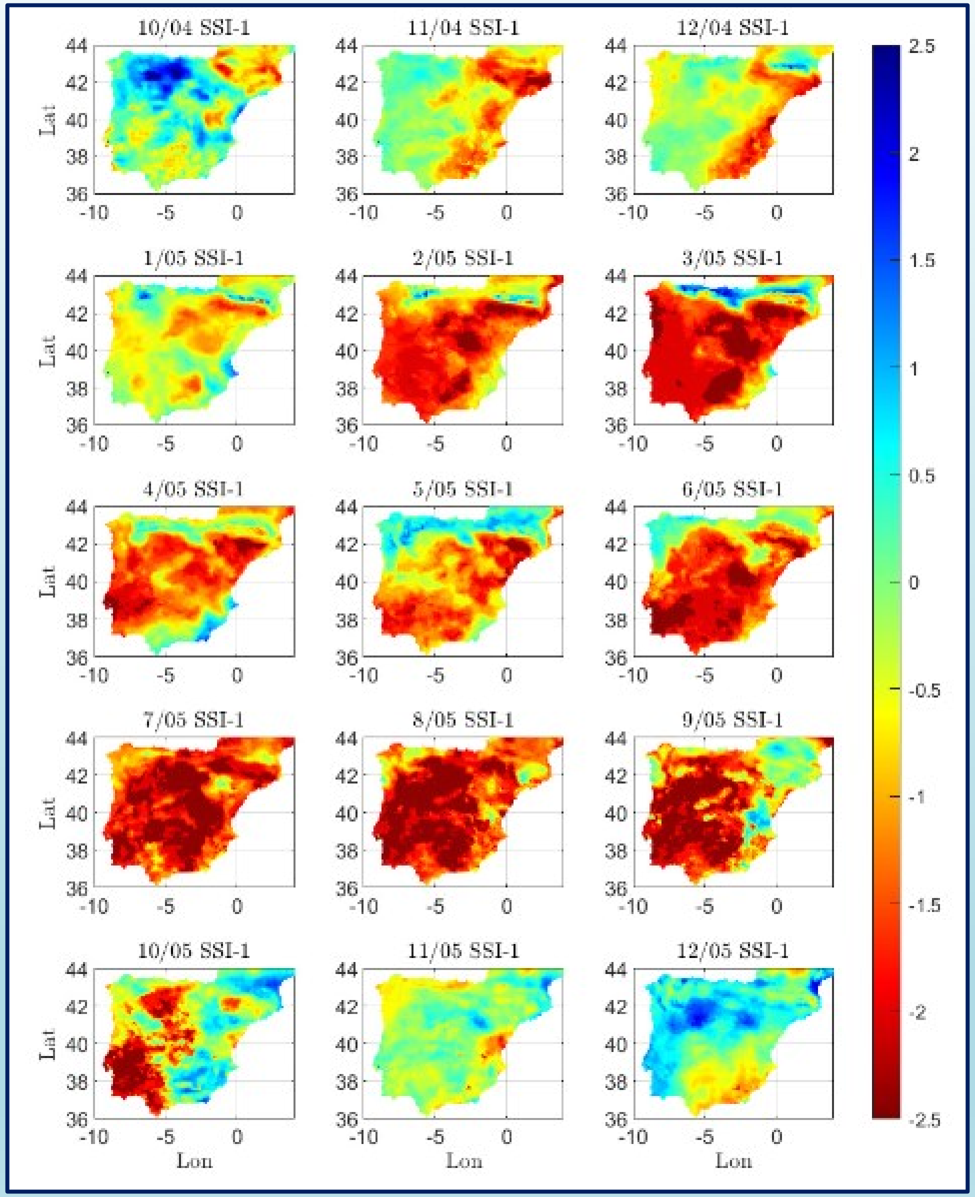

Figure S2. Temporal evolution of drought pattern over the IP according to the SSI at 1-month time scale from October 2004 to December 2005.